The Cambridge Handbook of the Neuroscience of Creativity

Historically, the brain bases of creativity have been of great interest to scholars and the public alike. However, recent technological innovations in the neurosciences, coupled with theoretical and methodological advances in creativity assessment, have enabled humans to gain unprecedented insights into the contributions of the brain to creative thought. This unique volume brings together contributions by the very best scholars to offer a comprehensive overview of cutting-edge research on this important and fascinating topic. The chapters discuss creativity's relationship with intelligence, motivation, psychopathology, and pharmacology, as well as the contributions of general psychological processes to creativity, such as attention, memory, imagination, and language. This book also includes specific and novel approaches to understanding creativity involving musicians, polymaths, animal models, and psychedelic experiences. The chapters are meant to give the reader a solid grasp of the diversity of approaches currently at play in this active and rapidly growing field of inquiry.

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Introduction

Rex E. Jung and Oshin Vartanian

In 1950, J. P. Guilford raised the clarion call for creativity research in psychology – a clear voice to contrast the predominant focus on intelligence as the main driver in the understanding of the elusive genius (Guilford, 1950). He noted that creativity is difficult to study due to several factors, including: (1) the rare incidence of extremely creative acts, (2) the "accidental nature" (i.e., environmental influence) of many discoveries and inventions, and (3) the possible overlap between notions of intelligence and creativity. Unlike IQ tests, which had been well established for nearly 50 years, there were no similar reliable and valid tests of creative cognition. It was difficult (if not impossible) to observe, quantify, and measure creative behavior and/or moments of insight in lower animals, making comparative studies incredible to even imagine. And yet, he noted the importance of discovering the mechanisms relevant to unleashing, developing, and even growing creative potential in individuals and society as critical to education, industry, and government.

How have we done since Guilford's call? At the time of his American Psychological Association Presidential Address, he stated that he had conducted a search of the index of *Psychological Abstracts* for the terms "creativity, imagination, originality, thinking, and tests in these areas." He found that, of 121,000 titles listed, only 186 were within this search criteria – a measly two-tenths of 1%. We conducted a search in Scopus of all studies which extended from 1960 to the present using the same terms, and found 5481 documents subsequent to his call [creativity or originality or imagination or thinking (in article title) and psychol* (in article title, abstract, keywords)]. Of the 1,401,060 total (with psychol* in article title, abstract, keywords), the 5481 reflect .0039% of all psychological research: nearly four-tenths of 1% – or a 100% relative increase from before the call. We do not pretend that this is a strict "apples to apples" comparison, but we do note a clear increase in the study of creativity in the psychological sciences, with particular acceleration since 1995 (Figure 0.1).

The 1990s was the decade when creativity experienced a renaissance of sorts – when Jamison and Rothenberg independently noted that individuals with certain mental illnesses had a higher incidence of creativity (Jamison, 1993; Rothenberg, 1990); when Robert Sternberg emerged as a major voice in the field, formulating several theories of creativity (e.g., investment, propulsion) (Sternberg, 1999a; Sternberg & Lubart, 1996) and edited the landmark *Handbook of Creativity* toward the decade's end (Sternberg, 1999b; see also Kaufman & Sternberg, 2010); when the importance of personality in creative expression was highlighted again (Eysenck, 1995; Feist, 1998); and when the cognitive components of creativity began to emerge as tractable by rigorous empirical approaches (see Runco & Chand, 1995), among other notable developments. In large part this greater empirical rigor was made possible by largescale adoption of the *creative cognition approach* to research in creativity. The aims of this approach were described as follows by Ward, Smith, and Finke (1999):

> Creative cognition is a natural extension of its parent discipline, cognitive psychology, and it has two major goals. The first is to advance the

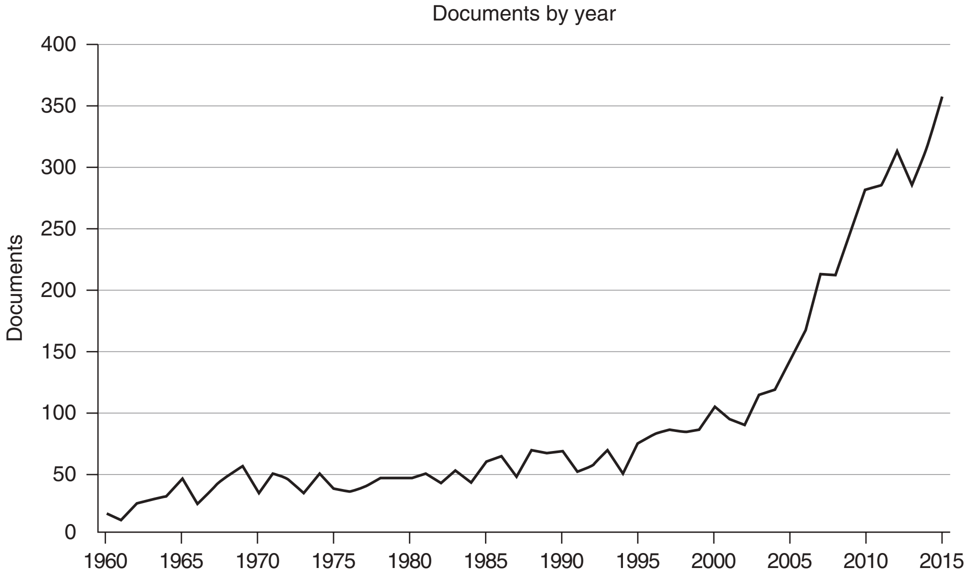

Figure 0.1 Frequency of studies of creativity in the psychological sciences. For a color version of this figure, see the color plate section.

> scientific understanding of creativity by adapting the concepts, theories, methods, and frameworks of mainstream cognitive psychology to the rigorous study and precise characterization of the fundamental cognitive operations that produce creative and noncreative thought … The second goal is to extend the scientific understanding of cognition in general and conducting experimental observations of the cognitive processes that operate when people are engaged in plainly *generative* tasks (p. 189, italics added).

Studying the components of creativity using generative (rather than receptive) tasks within the larger framework of cognitive psychology was instrumental in the conceptual and methodological maturation of creativity as a scientific discipline, and in retrospect served to bring it in line with theoretical and experimental approaches in cognitive neuroscience that would otherwise have been difficult to bridge in the decades to come.

The 1990s was also a decade that saw the emergence of the magnetic resonance imaging (MRI) machine in the study of human behavior, allowing researchers to peer farther into the human brain than they ever had before in examining the biological correlates of this unique human capability. Key psychological constructs were isolated by pioneers of the psychological study of creativity – including Amabile, Martindale, Kaufman, Ward, Feist, Runco, Simonton, Sternberg, and others – forming the theoretical and methodological bases of investigation by a new set of explorers of the human brain including Bechtereva, Beeman, Carlsson, Chavez, Heilman, Fink, and others – neuroscientists who turned their powerful instruments and intellect toward studying a construct that, at the time, was not funded by any granting agency and was not rewarded with high citation rates.

So now let's hone in on *the neuroscience of creativity* by removing the term "thinking," which would appear to be overly broad, and add "brain" to the "title, abstract, keyword" search criteria. This produces 523 articles, beginning with the first EEG study published in 1975, of 32 normal male subjects, using the Remote Associates Test (RAT) and the Alternate Uses Test (AUT), two reliable and valid measures of creative cognition that emerged following Guilford's call

(Martindale & Hines, 1975). Basal alpha levels were found to relate to differential performance across creativity and intelligence measures. The first interventional study could be said to involve 19 boys with Attention Deficit Hyperactivity Disorder (ADHD), compared to 21 control boys, which found no significant difference between ADHD and controls on the Torrance Test of Creative Thinking (TTCT) at baseline, or after the ADHD boys were treated with methylphenidate (Funk, Chessare, Weaver, & Exley, 1993). Neurologists joined in, finding that high levels of artistic creativity emerged in certain cases of frontotemporal dementia (Miller et al., 1998). By the dawn of the twenty-first century, creativity studies were firmly established within the neurosciences, with every imaginable neuroscientific modality being utilized to better understand this elusive construct. Indeed, by 2015, neuroscientific studies of creativity (Figure 0.2) represented roughly 15% of all creativity studies in the psychological sciences, with a remarkable acceleration observable around the year 2000 (Figure 0.2).

Scientific progress in a field can be measured along a continuum from mere observations to the emergence of theoretical "consensus" supported by "normal" science (Kuhn, 1962). Along the way, various pitfalls and waystations can be expected, and the neuroscience of creativity has not escaped this natural progression. The brilliant mathematician, Poincaré, used introspection to determine the source of his own creative process, and discovered that it was not represented by one, nebulous construct, inscrutable to science, but that it consisted of several discrete stages – preparation, incubation, intimation, illumination, and verification – each independent of one another, yet working in harmony to produce creative achievement (Poincaré, 1913). Several "folk psychologies" emerged, each attempting to make sense of initial observations, but lacking the scientific basis necessary to hold up under increased scrutiny: right brain locus, "mad genius," creativity *as* divergent thinking, etc. These attempts at understanding creativity are akin to the tale of the blind man and the elephant, each being convinced that they are touching (variously) a wall, snake, spear, tree, fan, and rope (Saxe, 1872). Eventually, however, a sighted man comes along and sees the elephant

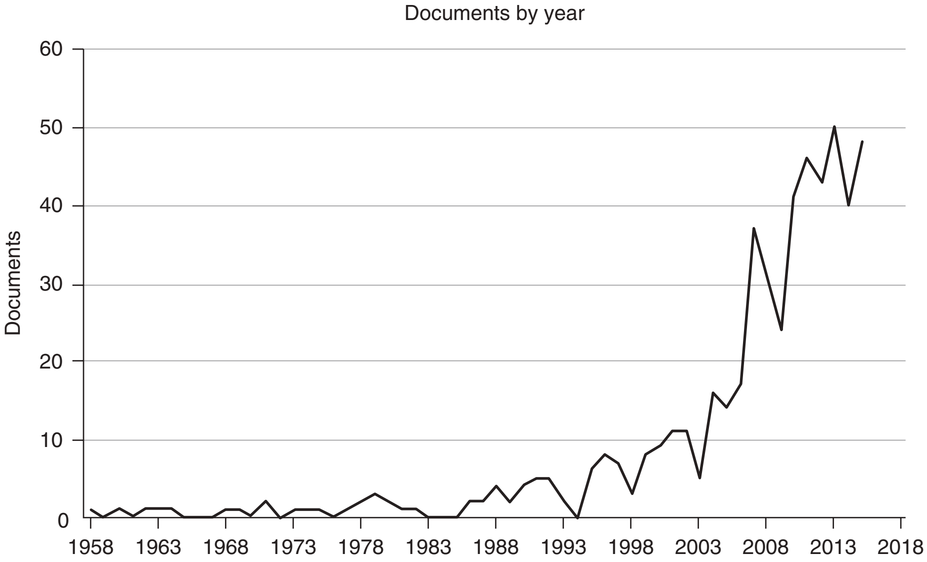

Figure 0.2 Frequency of studies on the brain bases of creativity. For a color version of this figure, see the color plate section.

in its entirety. It is our contention that the field has progressed to a point that we can leave such folk psychologies behind, and move firmly into a "normal" neuroscience of creativity.

Several hazards and pitfalls remain, however. If creativity is to be a viable neuroscientific construct it should conform to several scientific conditions. First, it should have a definition that lends itself to scientific inquiry. The production of something novel and useful (and perhaps surprising) is such a discrete definition. Importantly, it is not overly broad, and its components can have tractable neuronal correlates. Second, creativity should be explored in both human and non-human animals to determine whether creative cognition is a general brain "feature" or a more specific ability unique to higher mammals. Third, hypotheses should be generated regarding the emergence of creativity across evolutionary time: how and why might creative cognition have emerged to address environmental demands? Fourth, creativity should be explored as a dynamic interplay of multiple brain networks, engaged to serve context-specific demands, as opposed to "bits and pieces" of brain deemed "central" to creativity, the latter approach having the whiff of neurophrenology. With this basic framework, and a multimodal approach (i.e., both in terms of theoretically driven neuroimaging techniques, and their integration with behavioral, genetic, lesion, clinical, and intervention approaches), we can be hopeful in our ability to create a new and important discipline within the cognitive neurosciences.

We believe that the 30 chapters in this first *Cambridge Handbook of the Neuroscience of Creativity* represent the very best that the field has to offer. The chapters range widely in their scope, addressing general and long-standing questions about the nature of creative cognition. These include the overlap between intelligence and creativity, the association between psychopathology, pharmacology and creativity, the role of hemispheric asymmetry in creativity, the contribution of attention, memory, imagination, and language to creativity, as well as the questions of individual differences and domain generality vs. specificity in creativity. Other fundamental issues to be tackled in this book involve the relationship between motivations and drives with creativity, as well as the effect of the aging brain on creativity. There are also very specific (and novel) approaches to understanding creativity in musicians, polymaths, and animal models, as well as the introduction of new dynamic models to both intelligence and creativity.

We have gently edited all of the chapters, with our goal being to allow the voices and ideas of the authors to come through as distinctly and with as high fidelity as possible – which we feel is appropriate for a first volume in a nascent field. We have gently nudged all authors to adopt a "network" approach to their conceptualizations of creative cognition in the brain – which is the current state of the art within the neurosciences – and pulls the field away from the tendency to "localize" creativity within a distinct region or regions of the brain. We have been delighted by the novelty and quality of the chapters, and hope that you will find them to be useful in your work and thoughts regarding how creativity is manifested in the brains of humans and non-humans over evolutionary time. Some of the ideas might even surprise you. Finally, as editors of this volume, we are delighted to observe that within the span of only two decades a summary of the neuroscientific approaches to creativity requires an entire handbook rather than a single chapter in a handbook (see Martindale, 1999). We look forward to the future growth of this area with great excitement.

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Part I

Fundamental Concepts

00:09:17

1 Creative Ideas and the Creative Process: Good News and Bad News for the Neuroscience of Creativity

Dean Keith Simonton

Every neuroscientist is likely familiar with phrenology, the first science devoted to the proposition that the diverse psychological functions – or mental "faculties" – were located in specific parts of the brain. Who has not seen a phrenology chart with the borders between the various faculties precisely delineated on the cranium? To be sure, phrenology is now considered a notorious example of a pseudo-science. Yet that contemporary judgement often ignores the fact that phrenology was founded by a genuine scientist, Franz Joseph Gall. Although Gall's ideas about the localization of function were based on some erroneous assumptions – most notably a close congruence between cerebral cortex and cranium – phrenology probably deserves more respect than other pseudo-sciences of those times, such as Franz Mesmer's mesmerism. True or not, a creativity researcher like me might find it remarkable that the extensive list of faculties – dozens of them – does not include creativity! Nor anything similar, whether imagination, inventiveness, or originality. The closest faculty to creativity is perhaps wit (or "mirthfulness"), but surely that concept remains remote. Hence, are modern neuroscientists willing to rush in where phrenologists might have feared to tread?

In this chapter, I want to discuss why neuroscientists should tread carefully when studying creativity. Unlike such phrenological faculties as sight, hearing, taste, and smell, the psychology of creativity is necessarily riddled with complexities that must be deeply considered if the neuroscience of creativity is to become a cumulative and coherent science (cf. Arden, Chavez, Grazioplene, & Jung, 2010; Dietrich & Kanso, 2010; Gonen-Yaacovi et al., 2013; Sawyer, 2011). These complexities can be assigned to two big questions. First, what is a creative idea? Second, by what process are creative ideas produced?

Creative Ideas – What and Who?

Presumably, the creative *process* generates creative ideas, the creative *person* engages in the creative process producing those ideas, and the creative *product* contains the creative ideas that the creative person acquires through that creative process. But observe that these statements all suppose that we know what the adjective "creative" actually means. Without a definition, these seemingly obvious assertions actually become meaningless. It turns out that defining creativity is no simple task (Simonton, 2016). In fact, the definition requires that we address two independent questions. We should begin by asking: *What* criteria must be used in judging an idea's creativity? Once that issue is resolved, we then must inquire: *Who* evaluates those criteria in assessing the idea's creativity?

What Are the Creativity Criteria?

For a very long time, many creativity researchers subscribed to what has been called the "standard definition," namely, "Creativity requires both originality and effectiveness" (Runco & Jaeger, 2012, p. 92). Thus, two criteria are imposed, albeit different researchers might substitute approximate synonyms for either criterion: (a) novelty or uniqueness for originality; and

(b) usefulness, utility, value, appropriateness, or meaningfulness for effectiveness (Simonton, 2016). However, others have argued that a third criterion *must* be added. For instance, Boden (2004) stipulated that creative ideas must be novel, valuable, and surprising, a three-criterion definition that closely corresponds to that used by the United States Patent Office, namely, new, useful, and nonobvious (Simonton, 2012b).

Recently, the three-part definition has been formally expressed by the following equation (Simonton, 2013a, 2016, 2017): $c = (1 - p)u(1 - v)$. Here, c is creativity, p is the idea's initial probability, so that $(1 - p)$ gives its originality, u is the finally assessed utility or usefulness, and v is the prior knowledge of the idea's utility, which makes $(1 - v)$ a gauge of its surprise (i.e., how much new knowledge is gained). The values for c, p, u, and v, as well as $(1 - p)$ and $(1 - v)$, all range between 0 and 1, like probabilities or proportions. Hence, minimum = 0, maximum = 1, and middling ≈ 0.5. Moreover, because c is the multiplicative function of the three factors, $c = 0$ if any of its components equals 0. In words, a creative idea must be original *and* useful *and* surprising. Each separate criterion is thus rendered necessary but not sufficient. For example, an utterly useless idea cannot be creative no matter how original and surprising – such as constructing a bank vault out of cellophane.

This three-criteria definition is vastly superior to the standard definition (Simonton, 2016). Indeed, the latter definition makes no sense whatsoever. After all, the two-criteria definition can be expressed as $c = (1 - p)u$, indicating that the most creative ideas have a low probability but a high utility. This then leads to a paradox: How can a highly useful idea have such a low probability? The only rational answer to that enigma is that the creator does not already know the utility, necessitating that the prior knowledge value v approach zero. For any reasonable creature, if a highly useful idea was already known to be useful, then its probability would have to be high rather than low. This logical and psychological necessity then mandates that $(1 - v)$ be added as the third factor. The standard definition is plainly untenable.

Three critical consequences follow necessarily from the three-criteria definition. These consequences concern incubation periods, domain-specific expertise, and uncreative ideas.

Incubation periods. Wallas (1926) offered a stage theory of creative problem-solving that remains frequently cited nearly a century later: Preparation, Incubation, Illumination, and Verification. The creator starts by preparing an understanding of the problem, encountering difficulties that then lead to the incubation period in which the individual is not consciously thinking about the problem. With sufficient incubation the creator may have an insight, eureka, or "ah-ha" experience in which a solution flashes to mind (Hélie & Sun, 2010). Yet because such inspirations are by no means guaranteed to work, this illumination phase must be followed by the verification phase in which the idea is directly tested, whether externally or internally (cf. Dennett, 1995). If this test fails to confirm the idea's utility, then the cycle will continue in the hope that an effective solution is finally found.

Yet is the incubation period actually required? Might not the creative individual skip directly from preparation to illumination? That is, as soon as the problem is properly understood, the solution might come to mind without any need to work on irrelevant tasks in the meantime (cf. Boden 2004). The three criteria provide a precise answer to this question: Both yes and no! The precision of the answer comes from recognizing that the correct response depends on the magnitude of creativity. If we can assume that utility is high and prior knowledge low, then creativity obviously maximizes as the initial probability goes to zero (i.e., if $u \to 1$ and $v \to 0$, then $c \to 1$ as $p \to 0$). Hence, the most creative ideas under these conditions would have an initial probability of zero ($p = 0$). So the importance of incubation follows from the definition.

At the same time, even when the initial probability exceeds zero ($p > 0$), the creativity can still exceed zero ($c > 0$). To illustrate, suppose that after the requisite preparation the creator has an immediate but moderate hunch that a certain low-probability idea will solve the problem. The parameter values might be $p = 0.2$, $u = 1$, and $v = 0.5$ (for the "hunch"), which yields $c = 0.4$. A lot of ordinary creativity probably operates at this middling level, reasonably creative ideas emerging without any incubation whatsoever.

Yet given this direct implication of the definition, we might ask whether the *length* of the incubation period has any relevance for an idea's creativity. The definition makes no provision for this duration having any impact. This omission follows from the plausible assumption that the time elapsed before the response strength exceeds zero is most likely the function of random stimuli (cf. Seifert, Meyer, Davidson, Patalano, & Yaniv, 1995) and capricious trains of thought (cf. Mandler, 1995). The first recorded "Eureka!" moment in history occurred when Archimedes took a bath, yet the time that he waited before he felt he was (over)due for some personal hygiene should not determine the evaluation of the idea's creativity.

The good news: Researchers who study the neuroscience of creative insights are not wasting their time (e.g., Bowden, Jung-Beeman, Fleck, & Kounios, 2005). The incubation–illumination phase shift is not required for all creative ideas to emerge, but the cognitive shift is positively associated with the emergence of the most highly creative ideas.

Domain-specific expertise. Some researchers are inclined to believe that creativity is domain specific (Kaufman, Baer, & Glăveanu, 2017). Albert Einstein could no more paint *Guernica* than Pablo Picasso could work out the equations for the general theory of relativity. Yet such a belief conflates content with process. An analogy with language is useful here (Simonton, 2017). No doubt that someone who learns English cannot automatically speak Mandarin. Yet the kinds of psychological processes necessary to learn and apply either language must overlap considerably. Both languages require that the user recognize phonemes and morphemes, wrap the vocal apparatus around specific consonants, vowels, and tones, learn lexicons and master syntax, establish correspondences between the spoken and written word, and acquire the appropriate pragmatics of when to say this and when to say that to whom. If otherwise, then there would have to exist at least as many linguistics departments as there are world languages. We would also have to wonder why almost any *Homo sapiens* can master any human tongue on this planet, yet no non-human whatsoever can acquire even basic proficiency in any natural language. The human language "module" is generic, not specific.

Recall that the three-criteria definition parallels the standards used by the United States Patent Office to evaluate patent applications (www.uspto.gov/inventors/patents.jsp). In particular, the surprise criterion corresponds to the nonobvious criterion, the two just stressing different aspects of the prior knowledge value v. When $u = v = 1$, a useful idea is obvious, but when $u = 1$ but $v = 0$, the same idea is surprising. Significantly, when the Patent Office applies this criterion in evaluating applications, they refer not to the opinion of the average person on the street but rather to the judgment of somebody with "ordinary skill in the art" (www.uspto.gov/web/offices/pac/mpep/documents/2100_2141_03.htm). In other words, the idea cannot be derived directly from domain-specific expertise. A necessary even if not sufficient condition for $c \rightarrow 1$ is for $v \rightarrow 0$. This necessity does not mean that relevant expertise is absolutely irrelevant. On the contrary, such expertise is most often essential to constructing the utility criterion (Simonton, 2015). What does it actually signify to invent a better mousetrap or discover a cure for cancer? If a person has no knowledge of past solutions to the problem of invasive rodents or is completely ignorant of how various cancers appear and grow, then coming up with a highly effective device or medical intervention becomes impossible. It is just that knowing exactly what you're looking for does not ensure that you'll actually find what you're looking for.

Hence, more good news: Because creativity cannot just involve the direct application of domain-specific expertise, neuroscientists can concentrate their methods on whatever happens in the brain that produces surprising or nonobvious ideas. Creativity must be primarily domain-generic, not domain-specific (Simonton, 2017).

Uncreative ideas. According to the three-criteria definition, creativity can be optimized just a single way: Simultaneously maximize originality, utility, and surprise. If the idea is commonplace, useless, or obvious, or any combination of possible zero values, then an uncreative idea results. Each exerts veto power over the rest. In effect, this definition implies that ideas may be uncreative in multiple ways, seven to be exact (Simonton, 2016). Although not all possibilities are equally interesting or valuable, it is instructive to examine them all. So all eight potential outcomes are shown in Table 1.1.

The creative outcome is immediately followed by one representing routine, reproductive, or habitual thinking or behavior (e.g., $p = u = v = 1$). The idea is highly useful, that utility is known in advance, so that the initial probability is supremely high. Indeed, any rational creature would operate so that $p \to 1$ as $uv \to 1$ (aka "learning"). Closely related is the next outcome, rational suppression, in which the initial probability approaches zero because the idea is already known in advance to be useless (i.e., as $u \to 0$ and $v \to 1$, then $p \to 0$). These latter parameter values may have been "learned the hard way" through the extinction of maladaptive responses.

The next two outcomes both involve high-probability ideas but low prior knowledge values, with only the utilities differing. In the case of the fortuitous responses, the idea with the highest probability also has the highest utility, but the person is ignorant of the actual utility because the idea was just a "lucky guess" – such as winning the lottery using your mother's birthdate. In contrast, "problem-finding" occurs when a high probability idea is revealed to be useless, the individual having no prior knowledge of that inutility. This outcome can be considered a form of problem-finding because an idea that was expected to work based on past experience fails to work. The person is then

Table 1.1 *Creative and noncreative outcomes according to the three-criteria definition.*

Initial probability	**Final utility**	**Prior knowledge**	**Outcome**
$p \to 0$	$u \to 1$	$v \to 0$	Creative ideas or responses ($c \to 1$)
$p \to 1$	$u \to 1$	$v \to 1$	Routine, reproductive, or habitual ideas or responses
$p \to 0$	$u \to 0$	$v \to 1$	Rational suppression (e.g., extinguished responses)
$p \to 1$	$u \to 1$	$v \to 0$	Fortuitous responses (e.g., "lucky guesses")
$p \to 1$	$u \to 0$	$v \to 0$	Problem-finding (surprising expectation violations)
$p \to 0$	$u \to 1$	$v \to 1$	Irrational suppression
$p \to 1$	$u \to 0$	$v \to 1$	Irrational perseveration
$p \to 0$	$u \to 0$	$v \to 0$	Mind wandering or behavioral exploration

Note: The symbol "→" should be read "approaches." Table modified from Simonton (2016).

obliged to look for a different solution to the problem. An example would occur when a scientist makes a theoretical prediction that is contradicted by the data.

The next two outcomes should only be found in irrational thinking. On the one hand, "irrational suppression" entails having an idea with a very low probability despite having a strong prior expectation that the idea would be useful. On the other hand, "irrational perseveration" involves having an idea with a high probability even though the person already has prior knowledge that the idea will not work. If sufficiently frequent and pervasive, these two outcomes might be taken together as a definition of mental illness (Simonton, 2016).

The eighth outcome is perhaps the most curious: This has been called "blissful ignorance" (Simonton, 2016), but it might be better labeled either "mind wandering" or "behavioral exploration," depending on whether the response involves a thought or an action. In either case, the idea has a very low probability, but it does not really matter because the idea is likely useless, a fact unknown to the person anyway. The vague thoughts that drift by in dreams, daydreams, and drug trips fall into this category. Naturally, if the reverie just so happens to come up with a highly useful idea, the outcome is highly creative instead (Smallwood & Schooler, 2015). Similarly, a composer just absentmindedly tinkering at the keyboard may chance upon an original, surprising, and useful melody – as illustrated by the episode by which Edward Elgar discovered the theme for his popular *Enigma Variations*.

Why present all of these possibilities? Because they offer some bad news for any neuroscience of creativity. There is no such thing as a bipolar dimension with creative ideas at one end and uncreative ideas at the other end. Instead, creativity is multidimensional. Worse yet, the mental mechanisms for the diverse outcomes must be quite distinct. Rational suppression is just as uncreative as irrational perseveration, but the former indicates sanity, the latter insanity. Neuroscientists need to keep themselves ever aware of these niceties: Surely different areas of the brain will "light up" under the eight alternative scenarios! Indeed, under the eighth scenario, the brain may not show any localized activity, but rather might fall back on the "default mode network" recently associated with creativity (e.g., Kühn et al., 2014). Such a mental state allows the generation of ideas with the parameters $p \rightarrow 0$ and $v \rightarrow 0$, a tiny subset of which may have the parameter value $u \rightarrow 1$ (which can still be produced precisely because of the low prior knowledge value). This rare outcome then leads to a flash of insight that disrupts the random reverie and reverts the mind to concentrated attention once again.

Who Evaluates Those Creativity Criteria?

I received my PhD in social psychology, having written a doctoral dissertation specifically titled "The social psychology of creativity" (Simonton, 1974; cf. Amabile, 1983). That background has perhaps made me more sensitive to a critical distinction that is too often overlooked in creativity research, including in the neurosciences. The distinction is that between personal and consensual creativity, or what is sometimes called "little-c" and "Big-C" creativity (Simonton, 2013b; cf. Kaufman & Beghetto, 2009). The three-criteria definition discussed in the previous section quite literally concerned "little-c" or personal creativity. Not just c but also p, u, and v were all in lower case. That means that individual creators are basing the creativity assessment of an idea's initial probability, final utility, and prior knowledge value based on their own subjective experiences during a given episode, such as solving a particular problem. It matters not one iota if others would have a different opinion about these three criteria.

In stark contrast, consensual creativity does require the assessments of others besides the idea's creator, such as coworkers, supervisors, colleagues, referees, patent examiners, investors, critics, festival juries, curators, impresarios, consumers, audiences, connoisseurs, patrons, fans, scholars, and historians (the exact mix depending on the specific domain of achievement and the scope of the evaluation). To incorporate these judgments, we must revise the earlier definition by putting the parameters in uppercase: $C = (1 - P)U(1 - V)$, where P, U, and V represent some aggregate sum of numerous independent assessments using the three criteria (Simonton, 2013b). We now obtain (also literally) Big-C creativity.

Nonetheless, a problem emerges at once: Whose assessments should be averaged to produce a composite measure? By definition, a consensual evaluation should represent a consensus, yet seldom is that the case. For instance, research on cinematic creativity tends to use the evaluations of three different groups: moviegoers who buy tickets, film critics who write reviews, and industry professionals who bestow awards on their colleagues (Simonton, 2011b). Given that these three groups do not always agree with each other (e.g., blockbusters seldom earn critical acclaim), their separate opinions cannot just be averaged together. The resulting composite would suffer from prohibitively low reliability. So which of the three represents consensual creativity? Any choice must be arbitrary. It gets worse: Consensual evaluations can change radically over time. For example, the judgments of moviegoers, critics, and professionals may not correspond with much later identifications of “film classics” by, say, the American Film Institute (Ginsburgh, 2003). An infamous example is the 1941 *Citizen Kane*, now widely considered by film historians to be the greatest film to emerge out of Hollywood’s Golden Age.

Needless to say, a temporal shift in consensual evaluations is especially conspicuous in “neglected” or “rediscovered” geniuses, such as Gregor Mendel or Emily Dickenson. Obviously, if consensual creativity lacks any consensus or stability, it cannot be taken as representative of any corresponding psychological process. Mendel thought he had made an important scientific discovery, and Dickenson had faith that she was writing great poetry. No doubt they both were engaged in creativity during their respective lifetimes. Yet neither was considered highly creative until long after their deaths, when actual creativity must cease. The instability works in the other direction, too. The historical record is riddled with people who were once considered highly creative but who now are lucky to earn a footnote in an exhaustive history (Weisberg, 2015). Even earning a Nobel Prize is no guarantee. Today it boggles the mind that Nils Gustaf Dalén could get the 1912 Nobel Prize for Physics for his having designed automatic valves for use with the gas accumulators in buoys and lighthouses. Strikingly, Dalén received this high honor when Albert Einstein was already well overdue for the same Nobel after having revolutionized theoretical physics. Einstein did not receive that recognition until 1921, when the committee only explicitly honored his 1905 work on the photoelectric effect – ignoring his far more creative relativity theories!

Note that the problem raised by the personal–consensual creativity contrast permeates the actual “creativity” measures used in research, neuroscientific or otherwise. On the one hand, some instruments emphasize personal creativity, as evinced in those self-report measures that simply ask respondents to identify what they consider to be their creative accomplishments (e.g., Richards, Kinney, Lunde, Benet, & Merzel, 1988; cf. Silvia, Wigert, Reiter-Palmon, & Kaufman, 2012). On the other hand, some instruments stress consensual creativity, as seen in the Consensual Assessment Technique (Amabile, 1982). Yet complicating matters still more is that some instruments mix personal and consensual judgments, yielding hybrid measures with ambiguous implications. For instance, the Creative Achievement Questionnaire begins each creativity scale at the personal level but then switches to the consensual level, so that low but nonzero scores reflect little-c and high scores Big-C (Carson, Peterson, & Higgins, 2005; cf. Simonton, 2012a, 2013b). Even a putatively creative process measure like the Alternative Uses Test is somewhat of a mixed bag (Guilford, 1967). Scoring for originality, fluency, flexibility, and elaboration entails some consensual judgments, particularly given the prerequisite that the generated uses must be judged useful to count. However, those utility assessments might easily miss a genuine utility that is personally justified because the individual actually knows more than the judges about the potential functions of the given objects, whether brick or paper clip.

By now the bad news should be manifest: Neuroscientists must be cautious about the inferences they draw from any creativity tests they decide to use. Those measures that emphasize personal creativity will come closest to the creative process going on in a creator's head, whereas those that emphasize consensual creativity are contaminated with sundry social, cultural, economic, political, and historical factors that may have nothing to do with either psychology or neuroscience (see also Simonton, 2010). Caveat emptor!

Creative Process – or Processes and/or Procedures?

Earlier I offered the good news that creativity is not domain-specific. A creative idea cannot originate via the straightforward application of well-established disciplinary procedures. As seen in Table 1.1, such ideas must be considered routine, reproductive, or habitual rather than truly creative. So what neuroscientists must scrutinize is the creative process that applies to all domains of creativity. Now comes the bad news: There's no such thing as *the* creative process! At the very least we must speak in the plural, multiple processes rather than a single process. To appreciate this multiplicity, consider that creativity researchers have themselves identified the following processes: cognitive disinhibition (or defocused attention), intuition, remote association, imagination, divergent thinking (including originality, fluency, flexibility, and elaboration), overinclusive (allusive) thinking, and primary (or primordial) process (or "regression in the service of the ego"), such as occur in dreams, daydreams, and certain altered states of consciousness (Carson, 2014; Simonton, 2017; Simonton & Damian, 2013). Even if a few of these processes may overlap to some degree, that's still quite a sizable inventory! Many more than one, for sure.

The bad news gets yet worse: Creativity does not have to involve processes at all, but rather can entail specific procedures. By "procedure" I mean some conscious and deliberate tactic for producing creative ideas. Examples include analogy, conceptual reframing (frame shifting), finding the right question, broadening perspective, reversal, juggling induction and deduction, abduction, dissecting the problem, tinkering, and play as well as a toolkit of heuristic search methods, such as means-end analysis, hill-climbing, working backwards, and trial-and-error (Finke, Ward, & Smith, 1992; Ness, 2013; Newell & Simon, 1972; Simonton & Damian, 2013). To be sure, not only may some of these procedures overlap, but some processes can become procedures if applied deliberately rather than intuitively, such as divergent thinking and remote association. Indeed, Janusian, Homospatial, and Sep-Con Articulation thinking might go either way, process or procedure, according to the context (Rothenberg, 2015). Alternatively, some have demonstrated that creativity can involve just the application of ordinary thought, the thinking presumably indistinguishable by any brain imaging technique (Weisberg, 2014). As if the news could not get any more dismal, it must be acknowledged that many of these processes and procedures can operate across distinct modalities. For instance, divergent thinking can involve visual, verbal, kinesthetic, and gustatory/

olfactory imagery – as revealed in painting, poetry, choreography, and the culinary arts.

Does all this mental variety mean that creativity does not entail any generic process or procedure? No, not at all. These processes and procedures all represent alternative means to generate low probability ideas with comparably low prior knowledge values (Simonton, 2017). Because $p \to 0$, an incubation period will often be required, and because $v \to 0$, the idea is not guaranteed to be useful. The latter consequence is why Wallas (1926) added a verification stage after the illumination stage. Not all inspirations, no matter how exciting, actually pan out. Accordingly, the individual must engage in some "generation and test," "trial and error," or "blind variation and selective retention" or BVSR (Campbell, 1960; Nickles, 2003; Simonton, 2011a). Only when $u \to 1$ and $v \to 1$ is testing or selection not required. Yet in that case, as seen in Table 1.1, the only possible outcomes are either routine thinking (where $p \to 1$) or irrational suppression (where $p \to 0$). A highly creative idea is simply not an option under those parameters.

In truth, BVSR can operate at two levels (Simonton, 2011a). At one level, a creator might generate and test multiple analogies in the quest for that particular analogy that seems to work best. But at the other level, the creator may engage in trial and error to determine which procedure works best. For example, after despairing of using analogical reasoning to solve a problem, the person may try out alternative heuristics to see which one finds the solution, the application of each of those heuristics then entailing BVSR once more. Too often creativity researchers will overlook this critical necessity. Yet to the extent that an idea is truly creative, it should become impossible to pick the optimal process or procedure in advance (see the "No Free Lunch" theorem discussed in Nickles, 2003). Sometimes analogy will work, other times divergent thinking, and yet other times frame-shifting or some other approach. And if none of those work, perhaps the sole recourse is to "sleep on it" or to take a bath. Thus, the only genuine requirements for creativity are cognitive flexibility and motivational persistence. Highly creative people will attack a problem from many different angles, enduring many false starts and dead ends, before they finally complete their quest – if they manage to do so at all!

Apropos of the last unfortunate contingency, Einstein wasted the final three decades of his career on developing a unified field theory that absolutely *never* worked. As he himself admitted, "Most of my intellectual offspring end up very young in the graveyard of disappointed hopes" (www.aps.org/publications/apsnews/200512/history.cfm). He was still going over his notes on the subject the day before he died. Can the rest of us expect to do any better?

So are the foregoing points good or bad news for a neuroscience of creativity? The answer probably depends on the neuroscientist's aspirations. On the one hand, if the researcher wishes to identify *the* cerebral locus of creative ideas, that quest is necessarily quixotic. Presumably, cognitive mechanisms that produced Einstein's general theory of relativity were identical to those that generated his unified field theory, yet the former product was creative whereas the latter was not. On the other hand, if the goal is limited to the processes and procedures by which creators generate prospects for eventual test, whether or not the ideas survive those tests, then the neuroscience of creativity can operate on firmer ground (see, e.g., Jung et al., 2015). Nothing in the brain produces creativity like a gland secretes a hormone.

Conclusion

If the neuroscience of creativity is to make progress as a bona-fide scientific endeavor, then it must cope with the complexities of the phenomenon – a phenomenon far more complex than the norm for standard neuroscientific methods. This complexity was first seen in the discussion of what counts as a creative idea. The complexity was witnessed again in the treatment of the creative processes and procedures that produce those ideas. Given these real complications, sometimes the implications were good news, other times bad news. Nevertheless, when the positives and negatives are taken altogether, I believe that researchers should be optimistic about the field's future. Yet that optimism assumes that neuroscientists will deal adequately with the phenomenon's intricacies. Otherwise, the net result may be little more than a neophrenology that just rashly circles a section of the cortex and arbitrarily labels it "creativity."

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2 Homeostasis and the Control of Creative Drive

Alice W. Flaherty

Introduction

Because creative drive is a biological function of the human brain, the physical forces that affect motivation powerfully shape creativity. Most people doing creative work assume that more creative drive is always better. The first part of this three-part review describes some of the reasons for the brain's tight homeostatic control of drives, in which negative feedback loops produce inverted-U relations between motivation and other variables ranging from mood to dopaminergic tone to blood sugar. High motivation can be risky in some contexts. Plasticity genes can make creative people benefit more from resource-rich environments, but perform worse in harsh environments. Although overly negative feedback control restricts creative motivation unnecessarily, underactive control can deplete creative energy and paradoxically worsen performance. Feedback problems can make creative drive oscillate wildly, as can be seen in bipolar disorder. Nonetheless, because all negative feedback loops must oscillate, trying to flatten creative oscillations into a uniform constant output can be counterproductive.

The review's second part describes the brain's two major motivational systems, for approach and avoidance, and their effects on creativity. Dopamine stimulates goal-driven approach motivation and vivid mental imagery. Serotonin decreases fear-driven avoidance motivation. Norepinephrine boosts general arousal. The dominant left hemisphere aids approach motivation, and detection of familiar patterns. The right hemisphere fosters avoidance motivation, but also novelty detection. In creativity, these opposing systems coordinate to fit novel perceptions into new patterns.

The review's last two sections examine perturbations of motivation by disease and medical treatment. The link between specific brain disorders and creativity extends beyond "mental" and "neurological" illness, and provides more broadly applicable information about the risks that all people face when doing creative work. Interventions ranging from migraine medicines to treadmill desks have mixed effects on creative motivation of which their users are largely unaware. Creativity research should focus on real-world feedback signals that can help creators assess and correct their motivational levels.

Despite scientific training, researchers still find it hard to integrate psychological and biological discourse – mentalese and medicalese. This is especially true when the research subject is motivation. This difficulty may reflect the fact that, starting from infancy, and even with extensive scientific training, most humans are instinctive dualists who perceive motivated actions and mechanical events as very distinct (Forstmann & Burgmer, 2015; Mudrik & Maoz, 2014). The following review will nonetheless attempt to treat mentalese and medicalese as complementary vocabularies describing the same phenomena.

For example, a graduate student may describe a sudden boost to her creative motivation in psychological terms, as the result of an encouraging word from an advisor she admires – or she can describe it in biological terms, as the effects of certain sound waves on her tympanic membranes that change neuronal activity in her auditory cortex, which in turn increases the output of her midbrain dopaminergic system. The biological description, although clunky, provides a framework that accommodates physical influences on motivation. For example, it allows the realization that an encouraging word may have less effect on a creator who is using a migraine medicine that blocks dopamine. Thinking about the brain states that affect creativity can have great practical use even for creative people who might otherwise want nothing to do with science. Such knowledge can inform creators' daily choices, such as "Should I drink coffee or red wine before I settle down to write?"

Motivation and perseverance are psychological buzzwords currently. The work of Duckworth and others, showing that "grit" as a personality trait predicts long-term success, has seized the public imagination (Duckworth, 2016). Although creative work depends on talent as well as drive, talent is much harder to alter. In addition, the most creative people are not always the most skilled or the most intelligent. They are very often those with the strongest drive to create, who work at it constantly (de Jesus, Rus, Lens, & Imaginário, 2013). Above a certain IQ, typically estimated at around 120, personality factors such as motivation may have more effect than intelligence on creativity (Jauk, Benedek, Dunst, & Neubauer, 2013; Sternberg & O'Hara, 1999). Motivation can increase skill, because those who work hard at creative goals typically improve their execution through practice effects (Ericsson, 2006). Independent of skill, creative motivation can increase the number of creative ideas because it improves productivity, and chance ensures that the total number of creative ideas increases with the total number of ideas (Simonton, 1997).

The standard two-factor definition of "creative" as "novel and effective," (Runco & Jaeger, 2012) makes creative ideas valuable almost by definition. However, creativity, the collection of traits that produce more creative ideas, is dicier. The number of uncreative ideas increases along with the number of creative ideas. As W. H. Auden wrote, "The chances are that, in the course of his lifetime, the major poet will write more bad poems than the minor" (Auden, 1965, p. 115). The large number of failed attempts that all creative work generates is one reason that creative motivation can be risky. Motivation is also an energetically demanding brain function that drains resources – including blood glucose – needed for other functions such as attention and critical judgment (Gailliot & Baumeister, 2007; Kahneman, 2013).

Despite the energetic drain and creative risks of high motivation, most people doing creative work try to maximize their creative drive. The common belief is that creativity is a sign of the highest health. In theory we know that it is possible to have too much of a good thing; in practice, we tend to act as if there is no way we could have too much creative motivation.

Homeostasis and Motivation

The belief that more motivation is always better is an example of the monotonic assumption, namely that the relationship between two variables must always be positive (or always negative). The monotonic assumption can easily turn into the monotonic fallacy, because in nearly all biological and psychological states, the ideal level of a variable is a tipping point where more is no longer better; it is progressively worse (Figure 2.1). Staying alive requires homeostatic mechanisms, negative feedback loops that work to keep variables at the ideal set point.

When people are at their most creative, many influences are at near-ideal levels, and thus also near their tipping points. People with merely average creativity are further from those peaks. Consequently, standard laboratory studies of average subjects may show a monotonic relationship between creativity and its component traits, as on the left sides of the curves in

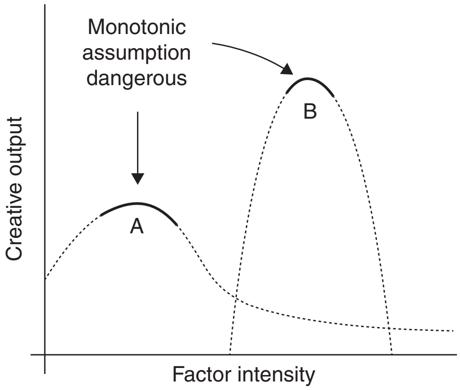

Figure 2.1 Near a factor's ideal value, more can be worse.

Notes. Let's say curves A and B represent novelty-seeking and attentional focus, respectively. Studying people with low novelty-seeking or focus would uncover nearly linear positive relationships between creativity and each variable. Studies of people with very high novelty-seeking or attentional focus would show a monotonic negative relationship with creativity. Applying either of those relationships to people working nearly at their peak creativity would be profoundly counterproductive.

Figure 2.1. That monotonic relationship would not apply to people working near their peak creativity, who may easily be pushed over the hump of a given curve. For instance, for a highly motivated, tightly wound academic, the added incentive of a possible $5,000,000 grant award may even cause creative block.

Researchers find the monotonic assumption tempting. Monotonic relations, especially linear ones, make predictions simpler. Creativity researchers rarely study subjects at the extremes of traits related to creativity, such as those who are clinically depressed or, conversely, in the midst of a breakthrough in their work. And if researchers examine a narrow-enough range of data, a line can approximate any data curve. Studies of average subjects may well apply to average business or academic settings. The monotonic assumption is so tempting that I will make it repeatedly in this paper, as in Tables 2.2 and 2.4.

Research on how creative people can maximize their creativity needs to focus on different questions than does research on how to make people of average creativity moderately more creative. Near a variable's tipping point, two important features have received little study. The first is signals that could tell creative workers whether they have strayed to the left or the right of their best level of a variable, whether the variable studied is job satisfaction or alcohol consumption, dopaminergic activity or the desire for fame. The second feature is corrective responses that could move them back toward their ideal set point. These signals and responses could allow conscious feedback control to help the brain's unconscious homeostatic controls of arousal, motivation, attention, and decision-making. Conscious control might also profitably suppress homeostatic regulation in some cases. Homeostatic mechanisms evolved in a world with different risks from the modern world. So, for instance, people whose creative drive is often interrupted by the desire for a snack might safely suppress it, as they are at lower risk of starvation than their ancestors were.

Negative feedback loops are stabilizing – as long as the feedback signal is accurate, and the corrective response is prompt. Two common feedback problems are excessive amplification of the feedback signal and delay of the corrective response. Both can contribute to feedback oscillation, as when a bad thermostat makes a house's temperature careen from hot to cold and back again.

The most accurate feedback signal for creative work – indeed, its gold standard – is the ultimate success of the completed work. That signal is far too slow, however, to help creators making hourly or daily decisions. The value of a creative product may not be apparent for years or decades after its completion. Instead, creators must typically assess the past hour's or day's productivity using other signals that are closer at hand. Excessive pessimism or grandiosity can distort their judgments, as can fatigue or unrelated influences on their mood. Creators whose love life is going well, for instance, may decide that their creative work is just as promising.

Even when people can quickly and accurately tell whether they are outside their most creative zone, they often cannot correct their state quickly. Arousal is a classic example. People doing creative work often tread a fine line between being too anxious to work and too sleepy. Many try to stay in their best state with alternate use of stimulants and sedatives. This is a common technique – more than 80% of people who take benzodiazepine tranquilizers also drink coffee (Cooper, Safran, & Eberhardt, 2004). It is also a tricky strategy that can contribute to counterproductive feedback oscillations of arousal and sedation.

For instance, consider a writer who wakes feeling groggy, and drinks coffee. When his sonnet starts to bore him, he drinks more. At the end of the day, he leaves his desk for a more stimulating environment, which, combined with the remaining coffee, makes him feel jittery. So he has a gin. It does not kick in fast enough, so he has another. The next morning, he wakes hung over as well as groggy, so he drinks coffee, and the oscillating feedback cycle begins again. On the second and subsequent days, however, his brain and liver have started to develop tolerance – he will need higher doses. After a few weeks, frustrated by his waning caffeine response, he may try to give up coffee – only to get rebound sedation that convinces him he needs more caffeine after all.

What if very fast-acting drugs were available to regulate arousal? That might prevent people from having a second shot of espresso or scotch while they are impatiently waiting for the effects of the first shot to kick in. However, faster-acting drugs typically have worse rebound symptoms, and are more addictive.

There are non-drug ways of controlling creative arousal. People who work using a computer may fight their work fatigue with a brief trip to a stimulating website, perhaps social media, e-shopping, or a video game. These activities can be highly addictive, however, and can take hours away from work. Some people instead try to raise low work arousal with brief bouts of exercise, such as walking down the hall and back, or doing 20 push-ups. These diversions, though stimulating, take willpower that most fatigued or bored workers cannot muster. Treadmill desks are a fast-growing alternative that can create a steady level of arousal that may increase creativity (MacEwen, MacDonald, & Burr, 2015). Unlike push-ups or commuting to a gym, home treadmill desks do not take time away from writing. Exercise triggers neurogenesis in animals and may benefit human cognition (Farioli-Vecchioli & Tirone, 2015; Vidoni et al., 2015). Although very rapid walking can create cognitive and energetic demands that compete with creative work, changing the treadmill's walking speed or incline can change a worker's level of arousal to suit different tasks. A writer who is able to answer unimportant emails at a rapid pace may need to slow down while editing a manuscript, and may have to sit down while writing the first draft of a difficult piece.

Diseases and other stresses can dysregulate goal-oriented drive or its homeostatic regulation. Mood disorders can make creative people overreact to others' positive and negative responses, causing crippling feedback oscillations. Patients with bipolar disorder, for instance, have higher emotional reactivity to both gains and losses (Meyer, Johnson, & Winters, 2001). When success dramatically raises motivation, it can generate a positive feedback loop that leads to mania. Likewise, a small failure can spiral out into depression (Johnson, 2005).

Creative ideas are often defined as having two factors: novelty and effectiveness. This definition points out a similarity between creativity and brain illness because both can produce novel, unusual behaviors. It also points out a difference: effectiveness. Producing ideas that are novel but useless – eccentric – is part of the vernacular conception of madness.

The wavery boundary between creativity and disease becomes clearer if we unpack the hidden third factor implicit in the two-factor definition: the crucial role of context. Communities judge an idea as creative if it is novel and effective in that community. Novelty is context-dependent. A Neolithic woman who realized that she could use a lever to move a boulder may have been creative, but a modern woman who uses a lever for the same task is not. Effectiveness is context-dependent, too. Thus an artist's work may be thought mad until it starts selling well or has influence on other artists. A Neolithic woman who tried using a lever to move a boulder between her and a fast-approaching predator would not be creative if her strategy was slow, and she was killed before she finished her defense. Her example reminds us that curiosity and experimentation tend to be healthier and more effective in safe environments, and unhealthy in dangerous ones.

Thus, an important way to foster creativity is to create environments that are safe for experimentation. In the case of the Neolithic inventor, her community could make a Neolithic think tank by bringing her food and keeping watch for predators so that she could safely experiment with levers. Modern environments are much safer for creativity, at least in developed countries. Inventors with no startup money now have access to crowdfunding (Kennedy, 2016), most budding artists have access to musical instruments or paint, and nearly everyone gets enough protein and vitamins for adequate brain development. This has contributed to a rate of creative innovation that is orders of magnitude higher in resource-rich communities than in resource-poor ones. In this respect, luxury, not necessity, is the mother of invention (Gopnik, 2009). This effect of permissive environments on creativity parallels recent evolutionary arguments that mild, hospitable environments foster genetic and species diversity, permitting the survival of mutants who may have high evolutionary fitness during the next environmental catastrophe (Deacon, 2010; Okanoya, 2015).

Why, then, do people so often say that necessity is the mother of invention? Often they are considering relatively low levels of necessity that are on the left half of the inverted-U relation between need and creativity. A small amount of necessity in a relatively safe and resource-rich environment can indeed spur creativity. Our bodies have a homeostatic drive to save energy when we can, and that makes most of us, when all our needs are satisfied, become contented and torpid. In such a context, a little necessity is a productive goad.

In resource-rich contexts, then, the most creative people may be ones who maintain high motivation even though all their needs are met. Working frantically when you already have enough is, of course, a little crazy – another link between creative motivation and brain disease. In resource-poor environments, frantic creators who don't pause to rest and refuel during times of plenty may not have the mental reserves or physical energy stores to survive the next famine. Creators' ability to respond to context is key.

Creators' background experience shapes their ability to respond to new environments; so does their genetic background. Researchers have identified "vulnerability genes" that are associated with maladaptive hypersensitivity to environmental stress, increasing the risk of depressed or violent behavior. Newer data, however, suggest that some of these genes might better be termed plasticity genes, because they also increase sensitivity to beneficial environments (Belsky et al., 2009; Kuepper et al., 2012). The proposal that some vulnerability genes are also plasticity genes raises the possibility that creative people are more susceptible to brain disorders than average people are, for the same reason that race cars break down on dangerously rough roads more than pickup trucks do. On safe, smooth roads, however, the race cars' highly tuned, responsive engines allow them to

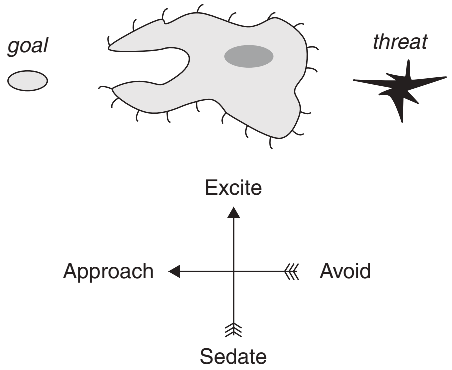

Figure 2.2 Two-axis "ameba" model of motivation.

Notes. All motivations, even of protozoa, are characterized by direction (toward or away from the motivation's trigger) and level of arousal. In humans and other mammals, approach (~ dopamine), avoidance (~ low serotonin), and arousal (~ norepinephrine) can be shaped not only by psychoactive drugs but common medicines like nausea pills and blood pressure treatments.

speed past pickups. The link between creativity and brain illness has been proposed as one reason why such illnesses are not quickly bred out of populations (Nettle, 2008). Reciprocally, genes promoting creativity must, at least in some contexts, be deleterious, or everyone would be highly creative.

The Two-axis Model of Creative Drive

All motivation has two qualities: intensity and goal. In creative motivation, that intensity has an inverted-U relation with its effect on creativity that is analogous to the Yerkes–Dodson law linking general arousal and performance (Yerkes & Dodson, 1908). Just as both low and very high arousal hinder the ability to successfully complete a task, both disinterest and an overintense desire to do creative work can inhibit the open-ended exploration needed for creativity.

If we represent motivation as a vector with intensity as its magnitude, then the motivation's goal is the vector's direction. Motivations drive a subject to approach or avoid a stimulus or outcome. Because this two-part intensity/direction model applies even to the behavior of very simple animals, it has been called the ameba theory of motivation (Figure 2.2). Approach motivation is typically linked to positive emotions, such as desire and curiosity, but predatory aggression and even anger also trigger approach behavior. Avoidance motivation typically accompanies negative emotions, such as fear, but can also accompany enjoyable emotions, such as group solidarity – and contempt.

A motivation's direction shapes the way in which it fosters or inhibits creativity. For average subjects, approach motivation and positive mood help creativity more than avoidance motivation does (Davis, 2009; De Dreu, Baas, & Nijstad, 2008). Approach motivation can improve the completion rate of creative projects, because approach motivation increases as it nears its goal whereas avoidance motivation decreases. The dominance of approach behaviors in creativity differs from the average motivational influence on human behaviors, in which people tend to have stronger motivation to avoid a negative outcome than to achieve a positive one. In economic decisions, for instance, loss aversion tends to be twice as powerful as desire for gain (Tversky & Kahneman, 1992). In marriages, research suggests that spouses must have five positive interactions to outweigh the corrosive effect of one negative interaction (Gottman, 2014).

However, the effect of avoidance motivation's intensity may occasionally outweigh the effect of its negative valence. Thus, high-energy negative states, such as fear, can drive more creative ideas than do low-energy positive states like contentment (Baas, Dreu, & Nijstad, 2008; Isen, Daubman, & Nowicki, 1987). In a business setting, moderately abusive supervisors may produce more creative work environments than

Table 2.1 *A first-approximation summary of neurotransmitter effects on motivational factors that play a role in laboratory creativity tests.*

	Transmitters	**Brain areas**	**Excess**	**Deficit**
Approach	High dopamine	Accumbens, tegmentum	Addiction	Apathy
Avoidance	Low serotonin	Raphe, anterior cingulate	Anxiety, OCD	Carelessness, risk-taking
Arousal	Norepinephrine	Retic. formation, thalamus	Insomnia, panic attack	Sedation
Satisfaction	Endorphins	Basal ganglia, Brainstem	Euphoria	Dysphoria

Notes. Effects on in-vivo high-level creativity are not necessarily similar to effects on lab creativity tests. This table neglects less-studied transmitters such as oxytocin, which promotes some forms of approach behavior, and endogenous cannabinoids, which modulate dopamine and attention.

either low- or high-abuse bosses (Lee, Yun, & Srivastava, 2013).

People attempting creative work sometimes wrongly privilege avoidance motivation, and underestimate or even forget about approach motivation. As a physician treating academics and artists, I often hear, when I suggest treating a creative person's anxiety, the reply "Oh, I have to stay anxious, or I'll stop working." Sometimes this reflects the creator's personality – some people have a higher negativity bias than others (Ito & Cacioppo, 2005). More often, creative overreliance on fear motivation shows the effect of academic and business environments. Teachers and supervisors typically find it easier to instill avoidance motivation than approach motivation in their charges. When creators spend years avoiding low grades or supervisors' scorn, their intrinsic interest in their work can wither. A final cause of creative people who rely too much on anxiety-provoking stimuli such as deadlines is the monotonic fallacy. People striving to be creative often think that if a little anxiety stimulates performance, more is better. That logic can cause creative block, of the deer-in-the-headlights variety.

Approach and avoidance motivations tend to inhibit each other. It is hard to be interested in an activity that produces fearful emotions, and it is hard to think of the risks of a strongly attractive goal. However, the two motivations are not mirror images of each other. The brain has anatomically and physiologically separate motivational systems for approach and avoidance behavior (Table 2.1). Simultaneous activity in the two systems does not completely cancel each other out either biologically or psychologically. The net effect of a goal that is equally desirable and terrifying is not calm disinterest, but agonized ambivalence.

Approach and avoidance motivations also have different consequences for action. If human approach and avoidance motivations were equal but opposite, then there would be no difference in describing a creative goal, such as writing a book, as either the result of approach motivation (such as the desire to understand a subject or to get tenure) or the result of avoidance motivation (such as the desire not to lose one's job). In practice, the psychological effects of the two motivations are quite distinct. With approach motivation, nearing a desired goal produces pleasure and increased effort, whereas failing to achieve a desired goal causes sadness, depression, or frustration. When avoidance motivation succeeds in moving a creator further from a feared outcome, it produces feelings of relief and decreased effort, whereas nearness to that outcome produces feelings of anxiety or shame.

There are, of course, many other features of motivation besides direction and intensity. One distinction that is important for creativity is that between intrinsic and extrinsic motivations. An approach motivation may be extrinsic (such as a cash reward) or intrinsic (such as curiosity). The latter more robustly produces creative works, whereas the former may be distracting – the subject may satisfice, working on the project only long enough to get the cash reward (Amabile, 1993). The intrinsic/extrinsic distinction doesn not fit well into the simple ameba model of motivation – or at least, humans have trouble imagining an ameba motivated by the joy of the chase, rather than by hunger. Some researchers have reformulated the intrinsic/extrinsic spectrum in terms of the approach/avoidance spectrum (Covington & Müeller, 2001), but to a first approximation it is easier to consider them as two separate axes.

Because motivation is a product of brain resources that have physical limitations, motivation is a limited resource too. The limitations vary with the timescale studied. On a timescale of minutes to hours, expending motivation in one domain, such as doing taxes or resisting the desire to watch videos, temporarily depletes motivation in other domains, such as problem-solving (Muraven, Tice, & Baumeister, 1998). One of the best-studied limits on motivation is blood glucose level. The brain has the highest glucose utilization of any bodily organ, and difficult mental work measurably depletes blood glucose. Reciprocally, even small changes in glucose within the normal range can change how long a subject works on a difficult math problem (Gailliot & Baumeister, 2007).

Because motivation is energetically expensive, creative workers should spend it wisely. One way to do this is to develop regular work habits, because habitual behaviors require less brain activity. In terms of Daniel Kahnemann's dual process theory of cognition, making routine decisions with fast, intuitive System 1 thought saves motivational resources needed for conscious, effortful System 2 thought (Kahneman, 2003). A writer who decides to work in the kitchen today will probably waste energy struggling to stay seated at the computer and not get up to snack. Context cues are far more powerful than motivation for habit formation, and far less energetically demanding (Gardner & Lally, 2012). Consciously creating recurrent triggers and rewards for a behavior can help it become habitual. Thus, the writer could instead develop a habit of bringing breakfast and coffee to a hotel or office lobby to work in an environment with far fewer distractions – especially if it does not have free wifi. Hunger for breakfast is the trigger that drives the writer to the workplace each day, and eating it is the reward for getting there. The high prices of the lobby restaurant will inhibit further snacking.

At longer timescales of weeks to months, the exercise of motivation may, like exercise of muscles, strengthen motivational resources that are then available for use in other activities (Schmeichel & Baumeister, 2004). Future research should investigate the time intervals and intensity of motivated activity that strengthen rather than deplete motivational resources. This raises the possibility of cross-training. High school athletic coaches, for instance, sometimes argue that students develop willpower through their daily 4 am hockey practice that will later carry over to their efforts in other domains. Maybe. In all forms of practice, whether physical, cognitive, or motivational, the most effective exercise is typically that which practices the desired skill.

Brain Mechanisms that Influence Creative Drive

The following section describes the three best-understood brain systems that influence creative motivation (Figure 2.3). The first, limbic midbrain inputs, carry the aminergic neurotransmitters dopamine, serotonin, and norepinephrine. The second is intercortical connections between the left and right hemispheres, and the third connects frontal and temporal lobes.

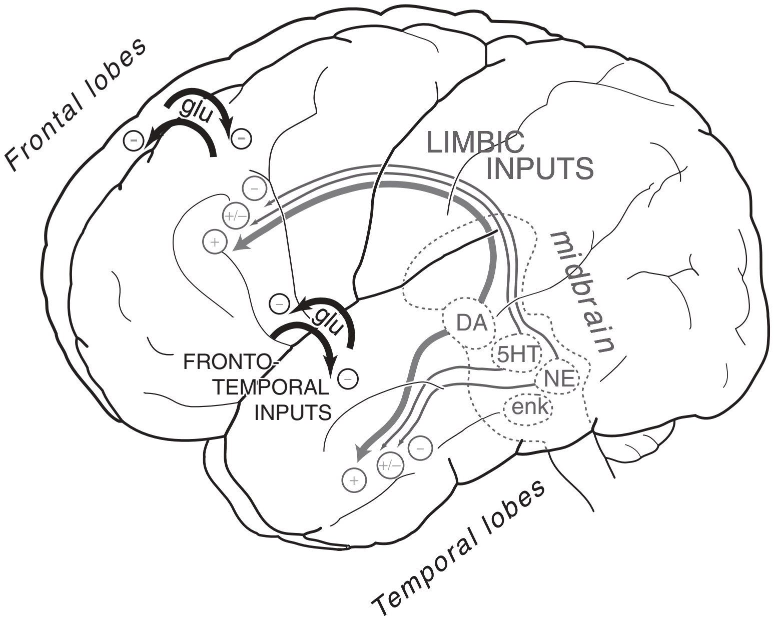

Figure 2.3 Simplified model of anatomical pathways involved in creative behavior.

Notes. Frontotemporal and interhemispheric inputs tend to inhibit each other. The valences assigned to the dopaminergic (DA), serotonergic (5HT), noradrenergic (NE), and opiate (enk) projections from the limbic midbrain indicate their proposed net effect on the creativity of typical research subjects (moderately aroused, moderately intelligent, moderately paid to do moderately interesting lab tests thought to moderately test creativity).

Neurochemistry

Subcortical neurotransmitter systems have powerful effects on drive regulation. Motivation is stimulated by subcortical aminergic neurons, which send dopamine, serotonin, and norepinephrine to the cortex. Satisfaction or relief, the decrease in drive when a motivation is achieved, is regulated in part by subcortical endorphins. Glutamate, the most common transmitter of cortical neurons, is important both for cognitive skill and for cortical response to motivational inputs. However, because glutamate is ubiquitous in the cortex, it is harder to study the effects of cortical glutamate than the effects of more transmitter-specific subcortical inputs.

Approach motivation arises from the incentive salience system that includes dopamine projections from the nucleus accumbens. The risk-avoidance system, regulated and suppressed by serotonin, includes the amygdala and the cingulate cortex. General arousal, necessary for both approach and avoidance behavior, depends in large part on norepinephrine projections from the locus ceruleus.

Reward and pain systems interact with arousal, approach, and avoidance mechanisms (Table 2.1). The reward system is endorphin-based and mediates liking or satisfaction, in distinction to the approach system, which mediates wanting (Berridge, Robinson, & Aldridge, 2009). Wanting and liking are not always the same: people can frantically seek goals that give them no pleasure when achieved. In the short term, rewards decrease motivation by producing contentment, although in the long term the memory of reward can drive future motivation.

Norepinephrine. At moderate levels, norepinephrine increases arousal and reactivity to both attractive and aversive stimuli. It encodes the degree of effort needed to attain a goal (Varazzani, San-Galli, Gilardeau, & Bouret, 2015). The effect on task performance of arousal from norepinephrine obeys the Yerkes–Dodson law: above an optimum level of norepinephrine activity, performance decreases. Because more complex cognitive tasks have lower optimal arousals, high arousal is counterproductive for creative work. In animal studies, high levels of norepinephrine and arousal decrease the ease of cognitive shifts and make responses faster and more stereotypic (Bouret & Sara, 2005). That makes sense evolutionarily. Reflexive behaviors can be protective in dangerous environments where it is safer, on average, to act quickly than to pause, reflect, and take a creative risk. This algorithm does not apply to extremely dangerous situations where the risk of failure or death from a reflexive action is certain. In that case, any chance of a creative solution is higher than the alternative stereotypic response.

Dopamine fosters approach motivation such as reward-based drives and curiosity. It currently appears to be the neurotransmitter with the strongest influence on creativity. Below I will discuss the brain conditions linked to creativity that boost activity in dopaminergic systems. Bilateral deep brain stimulation near the forebrain's dopamine-rich nucleus accumbens can increase mental actions, such as idea generation, as well as physical actions, and some patients with deep brain stimulators in that region have become more creative (Flaherty et al., 2005; Gabriels, Cosyns, Nuttin, Demeulemeester, & Gybels, 2003). In the cerebral cortex, dopaminergic inputs are densest in the frontal regions that regulate motivated action, and less dense in posterior regions that integrate sensory perceptions (Benavides-Piccione & DeFelipe, 2007). We can restate this medicalese in mentalese: dopamine drives us to act more than to consider the meaning and risk of our actions.

Creative work nonetheless requires perception as well as action, and dopamine alters perceptions in ways that seem to benefit creativity. Dopamine lowers perceptual latent inhibition – the likelihood that subjects will recognize, rather than screen out, novel phenomena – and low latent inhibition is associated with creativity in average subjects (Carson, Peterson, & Higgins, 2003). Dopamine regulates attentional flexibility in changing between widely diffuse and narrowly focused attention. Alleles of dopamine-related genes correlate with variations in novelty-seeking behavior and with creativity (Reuter, Roth, Holve, & Hennig, 2006). Dopamine improves working memory in average subjects, so it facilitates mental associations (McNab et al., 2009). These associations include the metaphors that often underlie creative art and scientific models. Dopamine enhances mental imagery in average subjects and, at high levels, can cause hallucinations. When metaphors become so vivid as to seem literally true, they can contribute to delusions (Rhodes & Jakes, 2004). For example, if Romeo believed that Juliet warmed him like the sun, his simile might be considered creative. If he believed that she was actually the sun, and concluded that staring at her too long could cause retinal damage, then he would be considered psychotic.

The previous paragraph so often repeats the hedging phrase "in average subjects" that readers should be feeling wary. Most subjects are not average. For instance, dopamine agonists improve working memory in people who at baseline have average working memories, but worsen the working memory in people with high baseline working memory (Kimberg, D'Esposito, & Farah, 1997). And not all of the relationships between dopamine and its behavioral effects have inverted-U shapes; some may be monotonic or sigmoidal (Floresco, 2013).

We like our neuroscience to be elegant because our brains are not big enough to grasp our brains' true complexity. It is easier to think of dopamine broadly as "the molecule of motivation." Yet that simplification is not ridiculous. First-order approximations are more useful than no estimate at all, and may support useful heuristics. As the next section will discuss, individuals who try to boost dopamine through drugs or physical exercise do change their overall task performance and creativity. Observing the effects on an individual may allow predictions that apply to that person, even if it does not easily generalize to others. New approaches to tailoring interventions, such as personalized medicine, can reveal new clues to allow particular individuals to tell how much of a variable is too much for them. For instance, a recent study suggests that eye blink rate may be a rapid index of a person's overall dopaminergic state (Chermahini & Hommel, 2010). Could people doing creative work use their own blink rate as a signal to tell them whether they are in a good zone – at least dopaminergically speaking – for creative work? Further research is needed to address this possibility.

Serotonin decreases withdrawal from frightening stimuli (Cools, Roberts, & Robbins, 2008), which can aid novelty-seeking. Clinically, raising brain serotonin activity decreases depression, calming patients rather than directly increasing their happiness. When serotonin decreases avoidance motivation, it sometimes decreases approach motivation as well, because brain serotonin systems can inhibit dopaminergic systems (Alex & Pehek, 2007). By boosting serotonin activity, selective serotonin reuptake inhibitors (SSRIs) such as fluoxetine can inhibit goal-directed behavior including sex, pleasurable exercise, and curiosity (Bolling & Kohlenberg, 2004). The effects of SSRIs on creativity are discussed later.

Other neurochemicals, too, have intriguing effects on creativity that need more study. Oxytocin, which promotes approach behavior, may increase novelty-seeking and creativity (De Dreu, Baas, & Boot, 2015). The endogenous cannabinoid system appears to help homeostatic control of dopamine, and thus influence attention and motivation (Georges & Melis, 2015). The endogenous opiate system plays an important role in motivation by acting as the reward for achieving a goal. Moments of insight can generate a rush that feels similar to the endorphin rush of runner's high (Gopnik, 1998). To the extent that dopamine mediates desire and endorphins mediate satisfaction, they can in the short term have opposite effects. Even though seeking an endorphin-based reward can be motivating, achieving the reward decreases motivation. Too low, too high, or inappropriately timed endorphin release may inhibit drive.

Neuroanatomy

The brain anatomy of neuronal interconnections is as important for creativity as brain chemistry is. The cortical networks that activate during different creative skills are complex, and vary with the creative task (Boccia, Piccardi, Palermo, Nori, & Palmiero, 2015; Gonen-Yaacovi et al., 2013). The anatomy of creative motivation is somewhat simpler than that of skill. Even so, the following section will touch only on its simplest aspects – its gross anatomy – and will not attempt to describe its microcircuitry.

There are, to a first approximation, two cortical axes that influence creative motivation: pathways connecting the left and right cortical hemispheres, and pathways running front to back, between the frontal and temporal lobes (Figure 2.4). Anatomically, they are roughly perpendicular to each other, and to the limbic midbrain inputs shown in Figure 2.4. Cortical networks coordinate the perceptions and actions that produce approach and avoidance behavior. At a macro level, these pathways are inhibitory. Each hemisphere's activity tends on average to inhibit the contralateral hemisphere, and frontal and temporal lobes also tend to inhibit each other.

Table 2.2 summarizes some effects of these interactions on creative behavior. These effects are not limited to motivational mechanisms of approach, avoidance, arousal, and satisfaction, but also include effects on the vividness of mental imagery, cognitive flexibility, novelty

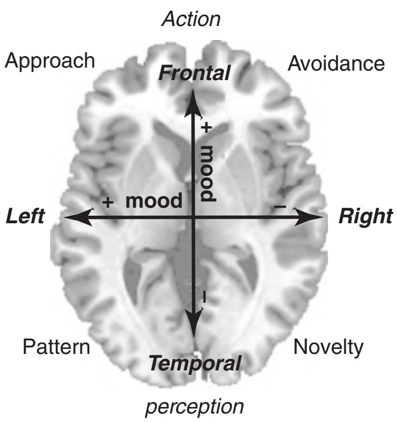

Figure 2.4 Simplified model of frontotemporal and hemispheric effects on creativity.

Notes. Frontal activity drives action to approach (L dominant frontal) or avoid (R nondominant frontal). Temporal activity drives perception of patterns on L, of novelty on R. Approaching novelty and then integrating it into a new pattern, as in creative behavior, requires bilateral coordination of all these functions. The L–R and frontotemporal axes also underlie mood gradients: more frontal and more L-dominant brain regions subserve more positive moods than do more temporal and R-nondominant regions. Thus, dominant frontal lesions are more likely to trigger depression, nondominant temporal lesions are more likely to trigger mania.

detection, and other features that are outside the scope of this paper. Table 2.2 also describes the subcortical neurotransmitter pathways discussed in the previous section. The right-most column of Table 2.2 proposes the direction of the creativity effect in average subjects in research settings – with the caveat that this monotonic relationship may not apply to highly creative people in real-world settings.

Hemispheric interactions. The right-brain creativity hypothesis proposed that the nondominant right hemisphere was specialized for artistic talent and the dominant left hemisphere was skilled at analytical and rule-based work. This belief still surfaces occasionally in the popular press. Current creativity research, however, supports the need for balanced activity between the two hemispheres (Aberg, Doell, & Schwartz, 2015). The dominant and nondominant cerebral hemispheres are specialized for approach and avoidance behavior, respectively. On average, dominant hemisphere activity promotes both pursuit actions and positive perceptions, while nondominant frontal activity promotes escape actions and negative perceptions (Maxwell & Davidson, 2007).

Table 2.2 *Some biological influences on creativity.*

Brain feature	Psychological mechanism	Average effect on creativity*
Dopamine	More approach drive	More
	More visual imagery	More
Serotonin	Less approach drive	Less
	More avoidance drive	More
Norepinephrine	Less flexible cognition	Less
	More arousal	More
Dominant L hemisphere	More approach drive	More
	Ignores novel stimuli	Less
	Notices familiar stimuli	~Less
Nondominant R hemisphere	More avoidance drive	Less
	Notices novel stimuli	More
	Ignores familiar stimuli	~More
Frontal lobes	Generates actions	More
	Suppresses perceptions	Less
Temporal lobes	Generates perceptions	More
	Suppresses actions	Less

Notes. *Column 3 may not apply to people working near the peak of their creative function.

Frontotemporal interactions. The frontal lobes specialize in driving action: physical movement in posterior frontal motor areas, and mental actions such as ideas and plans in anterior frontal areas. Temporal lobes have a greater role in sensory perception and judgments of motivational salience. This distinction between action and interpretation provides an anatomical substrate for the generation and editing stages that Goethe described as a systole and diastole of creative work. The dominant temporal lobe is more active during perception of familiar or patterned stimuli, whereas the nondominant temporal lobe is more active during novelty perception (Daselaar, Fleck, & Cabeza, 2006). Figure 2.4 summarizes these frontotemporal interactions.

The fact that the nondominant temporal lobe assists novelty detection and the nondominant frontal lobe assists avoidance behavior suggests that if the nondominant hemisphere were left to its own devices, it would recognize novelty but tend to withdraw from it (Figure 2.4). Conversely, the dominant hemisphere assists approach of recognized patterns. To generate a creative product such as a new scientific theory, creators must generate systematic patterns from novel stimuli, by combining nondominant hemisphere novelty recognition with dominant hemisphere approach behavior. Indeed, subjects with high creativity have greater bilateral activation than subjects with low creativity (Badzakova-Trajkov, Häberling, & Corballis, 2011; Carlsson, Wendt, & Risberg, 2000).

People differ in their tendency to perform approach and avoidance behavior, and in their ability to respond more quickly to rewards or punishments. This motivational bias correlates with a lateralization of dopamine innervation: reward-biased learning is stronger in subjects with greater dominant hemisphere dopamine, whereas punishment-biased learning is stronger in those with greater nondominant-hemisphere dopamine (Aberg, Doell, & Schwartz, 2016). The anatomical association of novelty detection and avoidance motivation makes evolutionary sense. In dangerous environments, novel stimuli are more likely to be harmful, and, on average, novelty-averse people will have greater fitness. Even in high-risk environments, though, a minority of people with novelty-seeking traits may persist because the few successful explorers and inventors who do spectacularly well offset the larger numbers who fail in trying. In safe, resource-rich environments, more novelty-seeking people survive long enough to do creative work.

A simple attribution of idea production to the frontal lobe and interpretation to the temporal lobe neglects many aspects of their complicated interactions. Ventral and medial frontal cortex, for instance, functions more like temporal lobe cortex than like dorsal and lateral frontal cortex. Thus, while dysfunction of dorsolateral prefrontal cortex can impair working memory and cause depressive symptoms, inferior medial frontal dysfunction can decrease hypersensitivity to risk and improve motivation in depressed patients (Mayberg, 2003). Such changes have opposing effects on creativity.

The interaction of frontotemporal and hemispheric connections provides evidence against the lay belief that suppressing "the uncreative left hemisphere" or "the judgmental frontal lobes" would help a subject's creativity. Some of the suppressive techniques recommended to the general public are harmless because they are ineffective. For example, one paper recommended plugging the right nostril to boost right hemisphere function because the airflow through the left nostril would stimulate right hemisphere activity (Werntz, Bickford, & Shannahoff-Khalsa, 1987). Other suppressive techniques can be dangerous, as when college students drink alcohol while writing, to suppress their "hypercritical frontal lobes." The connections described above predict that frontal lobe hypoactivity will typically hurt, not help, creativity. And nonselective large decreases in activity in any region impair creativity and cognition because they interrupt other systems needed for cognition or action. The next section will discuss creative interventions in more detail.

Other anatomical networks no doubt play important roles in creative motivation as well. The default mode network is worth special mention because it increases activity when people are not performing goal-directed actions or thought. It has effects on autobiographical memory, emotional processing, and self-referential activity. Although popular descriptions of the default mode associate it with daydreaming, this is unlikely to be its major function (Raichle, 2015). When creativity is measured by a divergent thinking task, the default mode network appears to be more strongly connected to certain parts of the frontal lobe in people of high creativity (Takeuchi et al., 2012). The default mode network also increases its activity during the judgment stage of creative problem-solving (Ellamil, Dobson, Beeman, & Christoff, 2012). The default mode plays no direct role in motivation, yet alternation between the default mode and the systems-regulated goal-directed attention may be another example of creative systole and diastole (Beaty, Benedek, Barry Kaufman, & Silvia, 2015).

Illness and Creative Drive

The Effect of Bodily Illness

Some observers have argued that any illness can stimulate creativity (Sandblom, 1997). In the nineteenth century, for instance, tubercular fevers were thought to produce a hectic creative state. If illness typically helped creativity, though, hospitals would be much more stimulating institutions than they are in fact. Illnesses, like all suffering, may in some cases raise arousal and motivate a search for inventive solutions, or at least distractions. In any disease state, though, the inverted-U relationship between illness and creativity has a peak far to the left of the graph. Serious illness is a classic example of how necessity can inhibit invention: patients create less when they are very ill (Richards, Kinney, Lunde, Benet, & Merzel, 1988). As the poet Sylvia Plath said, “When you are insane, you are busy being insane – all the time … When I was crazy, that’s all I was” (Wagner-Martin, 1987, p. 112).

The Effect of Brain Illnesses

Plath is nonetheless often cited as the index case of the eponymous Plath effect: the association of mental illness with creativity. Indeed, a few brain disorders appear to have a positive association with creativity, at least when the illness is mild (Table 2.3). Research on the subject has been hampered by the fact that mental illness has received far more attention than other brain disorders. It has also been hampered by publication bias – small negative studies are published less often than positive ones. The largest study done so far has shown that several diseases long thought to be associated with creativity probably have no direct creative benefit to people with the disease – although, in some cases, their first-degree relatives have a creativity benefit because of partially shared genes (Kyaga et al., 2011).

Many of the disease states associated with creativity also increase motivation in general. This parallels the effect of increased motivation in the general population, in which very high creative drive often correlates with other highly motivated behaviors, including hypersexuality and risk-taking. Conversely, when an illness

Table 2.3 *Medical disorders perceived as linked to creativity.*

More evidence	Less evidence
Hypomania	Depression
Schizotypy	Schizophrenia
Temporal lobe dysfunction	Frontal lobe dysfunction
Parkinson’s drugs	Parkinson’s disease
	Autism
	Attention deficit disorder

Notes. Research supports the link much more strongly for the conditions in the left-hand column than those in the right-hand column.

causes loss of creative drive, it is a marker for the loss of other important aspects of approach motivation, such as libido.

Of the genes so far found to correlate with increased creativity, all affect the brain. Study of twins reared apart show a modest but significant genetic effect on creativity (Velázquez, Segal, & Horwitz, 2015). Genes that increase sensitivity to the environment may be useful in safe environments but cause dysfunction in harsh environments. Several genes related to dopamine and serotonin metabolism have been tentatively linked to creativity, mood disorders, aggressive behavior, and substance use disorders (Carson, 2014; Reuter et al., 2006). The genes' effects are strongly influenced by the subjects' other genes. For instance, creativity is better predicted by interactions between several dopamine-related genes than by any of the genes individually (Zabelina, Colzato, Beeman, & Hommel, 2016). Most of the diseases that boost creativity arise from multiple genes, and healthy family members who have only some of the genes may be more creative than relatives with all of them.

Temporal lobe lesions are the anatomical injuries that are most likely to produce behaviors associated with creativity. They can also cause both mood disorders and psychosis. They can increase risky goal-directed behavior by disinhibiting frontal lobe action systems. If the lesion is small enough that it has little effect on the frontal lobes, and does not cause gross cognitive impairment, creative acts may accompany the general increase in motivated action (Mayseless, Aharon-Peretz, & Shamay-Tsoory, 2014). Even temporal lobe patients whose lesions are extensive enough to cause cognitive deficits such as aphasia may still show traits related to creativity, such as constant drawing and painting. They also typically show increased verbal fluency despite their aphasia. This increase in speech production may stem from their decreased verbal comprehension – they are less inhibited by consciousness of their mistakes.

Clinically, mood has both a left-to-right and a frontal-to-temporal gradient (Figure 2.4). The dominant left frontal lobe contributes most to positive moods, and the nondominant right temporal lobe activity contributes most to negative moods. Thus temporal lesions, especially nondominant temporal lesions, predispose patients to organic mania with pressured speech (Carran, Kohler, O'Connor, Bilker, & Sperling, 2003). Frontal lesions, by contrast, tend to produce depression, risk aversion, and decreased verbal fluency. Patients with frontal lobe lesions, and those with the frontal lobe hypoactivity of depression, have disinhibited temporal lobes that contribute to the dearth of their speech by making them painfully aware of, and inhibited by, their errors (Flaherty, 2005).

The mutual inhibition between frontal language production and temporal language reception has a parallel in the mutually inhibitory effects of idea generation and of assessing what one has produced. It helps explain why brainstorming, during which critical judgment is temporarily muted, generates more creative ideas. When musicians improvise, a process similar to verbal brainstorming, they deactivate their nondominant temporoparietal region (Berkowitz & Ansari, 2010). To produce lasting compositions, brainstorming alone is not enough for creativity. Frontal lobe production of ideas must alternate with temporal lobe contributions to the critical evaluation of the ideas.

Temporal lobe epilepsy. One-tenth of patients with temporal lobe epilepsy exhibit Geschwind syndrome, a personality cluster that includes hypergraphia, a pressured drive to write (Benson, 1991). The writing occurs between seizures, when the temporal lobe is typically hypoactive, rather than during seizures. Hypoactive temporal lobes disinhibit frontal lobe activity. Epileptic hypergraphia correlates with hypomanic traits and inversely correlates with depression (Hermann, Whitman, Wyler, Richey, & Dell, 1988). A number of prolific creative writers, such as Charles Dickens and Fyodor Dostoevsky, suffered from epilepsy.

Frontotemporal dementia (FTD). A subgroup of patients with neurodegeneration of frontal and temporal lobes develop *de novo* artistic output, and become suddenly and intensely motivated to paint or draw (Miller et al., 1998). Brain scans show that this subgroup has selective temporal lobe degeneration that relatively spares their frontal lobes. About one-third of FTD patients have organic hypomania, and depression is rare. In Alzheimer's dementia, where neurodegeneration affects the cortex more uniformly, artistic talent typically deteriorates (Rankin et al., 2007).

Hypomania, a mild expression of manic traits, can be a symptom not only of bipolar disorder, but also of other brain conditions such as temporal lobe epilepsy. Manic traits produce hyperassociativeness that can lead to insights, but the manic traits of ambition and motivation seem more closely linked to creativity than insight is (Ruiter & Johnson, 2015). The increased creativity associated with bipolar disorder stems most directly from hypomanic episodes, not manic ones (Kyaga et al., 2013; Richards et al., 1988), even though manic people perceive themselves to be as creative as hypomanic people do (McCraw, Parker, Fletcher, & Friend, 2013). Full-blown mania tends to disrupt creativity with its severity, with motivation that is so focused that it leads to self-injury, or hyperassociativeness that disrupts attention and sustained work.

Unipolar depression. Recent evidence does not support the long-standing popular belief that depression is associated with creativity. Depression narrows associative thought, producing stereotyped ruminations (Harel, Tennyson, Fava, & Bar, 2016). Because of depression's slowed motivation and rigid thinking, patients are rarely creative within a depressive episode itself. In mild bipolar disorder, hypomanic episodes often precede or follow depressive ones. Unipolar depression's reputation for boosting creativity may reflect the fact that many people with mild bipolar disorder have been misdiagnosed as having unipolar depression. The largest study of mental illness and creativity showed that neither unipolar depressives nor their first-degree relatives are more likely to have creative professions (Kyaga et al., 2011).

Psychotic traits are symptoms of schizophrenia and bipolar disorder, but also of drug ingestion and neurological conditions including dementia. Some observers have reported a correlation between psychotic traits and creativity. The correlation is stronger for mild schizotypal traits and for patients' close relatives (Kyaga et al., 2013). It may not be psychosis per se –the false beliefs and hallucinations – that predict creativity best, but other cognitive traits often associated with psychosis. These include low latent inhibition (a decreased tendency to screen out unexpected perceptions), openness to unusual ideas, as well as motivational traits such as impulsiveness (Acar & Sen, 2013; Carson et al., 2003; Nelson & Rawlings, 2010).

Parkinson's disease treatment. Parkinson's disease kills dopamine-producing neurons, and is associated with depression and apathy. For this reason, creativity decreases in untreated patients. Treatment of Parkinson's disease with dopamine agonists can produce highly focused goal-directed behavior such as hypersexuality and gambling. In some people with Parkinson's disease, the chief compulsive behavior is a *de novo* passionate artistic drive to write, compose music, or paint (Canesi, Rusconi, Isaias, & Pezzoli, 2012). High dopamine agonist doses can also produce vivid visual imagery, which may influence the content of the creative output independent of the motivation. Both compulsive art-making and hallucinations decrease when agonists are decreased (Lhommée et al., 2014).

Attention deficit hyperactivity disorder (ADHD)? Although many parents of children with ADHD argue that ADHD raises creativity, research does not support this claim (Healey & Rucklidge, 2005; Paek, Abdulla, & Cramond, 2016). Nor does scientific evidence confirm the equally common belief that drugs which treat ADHD lower creativity (Farah, Haimm, Sankoorikal, & Chatterjee, 2009; González-Carpio Hernández & Serrano Selva, 2016). ADHD attentional deficits disrupt goal-directed activity, and make it harder to transition between wide and narrow attention. People with ADHD have, on average, smaller working memory, which decreases idea association (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005). Although children with ADHD share several traits with creative children, such as risk-taking and low agreeableness, it is more often to a degree that makes the traits a hindrance rather than a boost to creativity (Healey, 2014).

Autistic savant syndrome? Popular opinion links autism with creativity, because of the existence of savant syndrome in some patients, and because of high-profile creative people with autistic traits, such as the physicist Albert Einstein and the inventor Temple Grandin. Yet most forms of imagination, including imaginative play and counterfactual thought, are decreased in autism spectrum disorders. Savants' talents are generally demonstrated in a behaviorally rigid way (Turner, 1999). Still, their decreased fluency on divergent thinking tasks may be counterbalanced by an increased numbers of unusual responses (Best, Arora, Porter, & Doherty, 2015). Subjects with autistic traits that are mild enough to allow behavioral flexibility may be able to use their focused skills creatively. On average, people with autism are underrepresented in the creative professions (Kyaga et al., 2013).

Autistic traits contribute to skill acquisitions in some domains, such as mathematics and playing music by ear, more than others. The autistic deficit in theory of mind – causation by human agency – can accompany increased ability in perceiving mechanical causation. Thus, creative people with autistic traits are more likely to be natural scientists or computer programmers than to produce art that requires them to perceive and communicate emotion. Savants, then, seem to gain their creativity from a talent that arises from nowhere, apparently independent of motivation and hard work. However, savants' skills arise in large part from the single-minded drive with which they practice their talent repetitively (Happe & Vital, 2009). Savants' motivation can be overlooked when their language deficits make it hard for them to report motivational states.

Medical Treatments and Creative Drive

All treatments that affect creativity do so through effects on the brain. Not all such treatments are marketed as psychoactive. Pills that treat hypertension or nausea, for instance, may have creativity effects of which their consumers are unaware. Drugs rarely boost creative skill except indirectly through aiding the motivation for constant practice. Most drugs that affect creativity do so by changing motivation and arousal. However, normal subjects have strong homeostatic regulation of motivation and arousal. The homeostatic mechanisms soon react to drug effects, causing drug tolerance, and rebound symptoms once the drug is stopped.

The existence of medication that affects creative motivation raises ethical and practical issues. Patients and their doctors must weigh any treatment's benefit to creativity against the risk of destabilizing the patient's health and social connections. Very ill patients, like subjects in dangerous environments, may need to at least temporarily give up creative pursuits in order to stay alive. Current studies and the practice patterns of experts in the field can point toward therapeutic approaches, although not yet to definitive ones. Table 2.4 summarizes current understanding of medications that may affect creativity. All other things being equal, treatments that increase approach motivation and arousal are typically more helpful than those that cause withdrawal or sedation (Baas et al., 2008). However, all other things are often not equal. When a creators' baseline arousal is high, stimulating medications may push them off the right

Table 2.4 *Drugs that may have effects on creativity.*

Condition	**Risky for creativity … on average**	**Less risky for creativity … on average**
ADHD	Atomoxetine	Dextroamphetamine, methylphenidate
Anxiety	Alcohol, alprazolam, paroxetine	Bupropion, low-dose venlafaxine
Depression	Aripiprazole, paroxetine, duloxetine	Bupropion, lamotrigine
Epilepsy	Topiramate, valproate, carbamazepine	Lamotrigine, oxcarbazepine
Fatigue	Daily caffeine	Modafinil, intermittent stimulants
Insomnia	Quetiapine, diazepam, trazodone	Ramelteon, zolpidem
Mania	Topiramate, antipsychotics	Valproate, lithium, oxcarbazepine
Nausea	Prochlorperazine, metoclopramide	Ondansetron
Pain	Opiates, duloxetine	NSAIDS, anticonvulsant pain meds
Parkinson’s	Trihexyphenidyl, benztropine	Pramipexole, rotigotine
Psychosis	Sedating typical neuroleptics	Stimulating atypical neuroleptics, antimanics
Stage fright	Benzodiazepines, alcohol	central beta-blockers, e.g., propranolol

Notes. Medication choice must also weigh the benefit to the patient’s health.

side of their Yerkes–Dodson curve into overstimulation, decreasing their creativity.

Dopaminergic Drugs

Dopamine receptor agonists – drugs that boost the effect of dopamine – can increase motivation in general, and thus creative motivation (Lhommée et al., 2014). The most sedating dopamine agonists, such as ropinirole (commonly used to treat restless leg syndrome), may boost motivation less. Dopamine agonists in small doses increase the vividness of mental imagery and night dreaming, both of which are associated with increased creativity. In larger doses, however, dopamine agonists cause hallucinations. Dopamine agonists can also trigger impulse control problems, gambling addiction, compulsive spending, and hypersexuality. The drugs are thus hard to use safely to selectively boost creativity.

Stimulants ranging from caffeine to dextroamphetamine are widely used for cognitive enhancement by people who do not have ADHD. One group found that dextroamphetamine boosted convergent creativity for those with low, but not high, baseline performance (Ilieva, Boland, & Farah, 2013). Most stimulants tend to increase norepinephrine as well as dopamine functions in the brain, so stimulants produce more arousal than do dopamine receptor agonists. Highly potent illegal stimulants such as cocaine are typically too arousing and addictive to achieve anything except decreased creativity.

The alertness agent modafinil mildly but very specifically boosts dopamine function, with little direct effect on norepinephrine. It thus increases alertness with less risk of overstimulation. It is also unusual in not causing tolerance or withdrawal symptoms. One small study showed that modafinil improved scores on the Remote Associates Test for less-creative people, but worsened scores for more creative people (Mohamed, 2016). Another study showed inconsistent effects (Müller et al., 2013).

Dopamine blockers include not only antipsychotics and antimanic drugs such as haloperidol and olanzapine, but also widely prescribed antinausea medicines such as metoclopramide and prochlorperazine. Treating nausea with dopamine blockers is almost never necessary, as other potent antinausea drugs such as ondansetron do not affect dopamine. Treating psychosis with dopamine blockers, however, is sometimes necessary. Doing so may even help their creativity by making them less delusional. Pimavanserin is the first member of a novel class of antipsychotics that does not directly affect dopamine. It raises hope for future antipsychotics with fewer side effects.

Sedatives

Benzodiazepines, alcohol, and many other classes of drugs are sedating. In theory, low doses of a benzodiazepine such as lorazepam might help the creativity of anxious, overaroused patients. However, because homeostatic mechanisms compensate for tranquilizers by increasing baseline arousal, users can develop drug tolerance and rebound hyperarousal when the tranquilizer wears off. That drives repeated use with diminishing benefits. The huge market for sedatives depends heavily on chronic users who are treating the withdrawal effect from their previous sedative dose. Non-benzodiazepine sleep aids such as zolpidem are not much better. The long-term use of non-benzodiazepine hypnotics such as zolpidem produce sleep benefits that, while statistically significant, are well below clinical significance. Benzodiazepines mildly hinder the encoding of new memories, even at low doses, and increase risk of Alzheimer disease (Beracochea, 2006; Gage et al., 2014). Despite alcohol's mild cardioprotective effect, its use can cause brain cell death even at moderate doses (Verbaten, 2009).

Alcohol impairs many aspects of cognition. One study did show increased scores on the Remote Associates Test (Jarosz, Colflesh, & Wiley, 2012). The relatively short presentation time of that test may make it more suitable for the decreased attentional focus of intoxicated subjects. In another study, it impaired lab tests of creativity in subjects with baseline higher creativity scores, but raised creativity in those with low scores (Lowe, 1994). A high number of creative people drink heavily, and believe that alcohol can suppress "frontal lobe inhibition" or creative block. This may reflect a placebo effect (Lapp, Collins, & Izzo, 1994). Alcohol can falsely elevate a person's judgment of how creative their work is (Lang, Verret, & Watt, 1984). Decreased self-criticism may be helpful to the creativity of highly self-critical subjects, but there are less neurotoxic ways than alcohol to achieve it.

Selective serotonin reuptake inhibitors (SSRIs). By decreasing depression, antidepressant medications can increase creative productivity. However, SSRIs not only lower aversive motivations such as fear and shame, they sometimes also lower appetitive motivations such as libido and curiosity. This can cause SSRI-induced apathy syndrome (Barnhart, Makela, & Latocha, 2004).

SSRIs' ability to lower avoidance motivation makes them useful treatments for interpersonal hypersensitivity and social fears. Indifference to others' opinions is associated with creativity (Feist, 1998). SSRIs might, by fostering this indifference, be helpful influences on creative output. For instance, SSRIs could make scientists worry less about the social and interpersonal consequences of abandoning their mentors' model of the world. However, reducing interpersonal sensitivity may be less helpful for novelists who need to stay exquisitely aware of social nuance.

Other antidepressants. Patients who develop decreased motivation or creativity while taking an SSRI have several medical alternatives. Bupropion, an antidepressant that boosts dopaminergic function, can preserve or even raise goal-directed drives, treat apathy, and aid motivation in tasks like cigarette cessation (Corcoran, Wong, & O'Keane, 2004; McCarthy et al., 2008). Adding bupropion to SSRI therapy can treat SSRI-induced apathy syndrome even if the SSRI is continued (Demyttenaere & Jaspers, 2008). Lamotrigine is another mood-elevating drug with no direct effect on dopamine or serotonin. Mirtazapine is an antidepressant that tends to preserve libido, but its sedative effects may not help motivation in general. The motivational and creativity effects of SNRIs such as venlafaxine, tricyclic antidepressants such as nortriptyline, and monoamine oxidase inhibitors are not well studied.

Mood-stabilizing drugs include lithium, neuroleptics (covered above), and some anticonvulsants. Lithium and anticonvulsants do not directly alter either serotonin or dopamine function. They may decrease creativity if they decrease hypomania, but increase it by decreasing full-blown mania. In bipolar disorder, lithium has been shown to aid creativity when it makes patients less ill so that they can function (Schou, 1979). Once extremes of mood are controlled, however, lithium may somewhat decrease associational productivity and idiosyncrasy (Shaw, Mann, Stokes, & Manevitz, 1986).

As with other psychoactive drugs, less-sedating mood stabilizers are probably better for creativity. Mood stabilizers that are also prescribed as seizures medications, such as valproate, do not suppress the hypergraphic writing of patients with temporal lobe epilepsy (Geschwind, 1983), suggesting that mood stabilizers may have a relatively benign effect on creative motivation. In one study, self-perceived creativity improved when patients were switched from lithium to valproate (Stoll, Locke, Vuckovic, & Mayer, 1996). However, manic delusions of grandeur can make patients perceive themselves as creative when they are not.

Recent evidence suggests that valproate may restore brain plasticity to adults, as measured by the ability to learn the new skill of recognizing absolute pitch (Gervain et al., 2013). Does increased plasticity lead to increased creativity? The changes in that study were not due to a general change in cognitive function, but rather a specific effect on a sensory skill normally acquired only during a critical period in early childhood development. And the plasticity that underlies skill learning is also an energetic drain that can destabilize other brain functions (Takesian & Hensch, 2013). Nonetheless, skills, not just motivation, are important for creativity.

Other Drugs

Beta-blockers. Beta-adrenergic antagonists treat hypertension and heart disease. Some, such as propranolol, also have brain effects. Propranolol may have modest creativity benefits after acute administration, by decreasing the central effects of norepinephrine and increasing cognitive flexibility, but a more recent study did not replicate this effect (Steenbergen, Sellaro, de Rover, Hommel, & Colzato, 2015).

Hallucinogens may affect the content of creative ideas rather than creative motivation. Users so often report having new thoughts or insights that most self-report questionnaires ask about feelings of enlightenment. These insights tend to be more novel than effective, though: studies of creativity show little benefit from hallucinogens (Baggott, 2015).

Cannabis. Like many other drug users, cannabis users advocate for their preferred drug's ability to increase creativity. Its acute effects include reduced inhibitory control (McDonald, Schleifer, Richards, & de Wit, 2003) and increased striatal dopamine release (Bossong et al., 2008), but its chronic effects include decreased baseline dopamine levels (Volkow et al., 2016). However, it also impairs divergent thinking (Bourassa & Vaugeois, 2001; Kowal et al., 2014). There is not yet systematic study of the different creativity effects of the two active components of cannabis, tetrahydrocannabinol, and cannabidiol.

Pain medications have as controversial effects on motivation as pain itself does. Although pain increases motivation, it typically drives stereotypic behaviors to rapidly escape pain, rather than more complex creative explorations. Medications that decrease pain thus might help energy and creativity, to a certain degree. Opiates such as morphine are probably the most controversial. Proponents of the benefit of opium typically cite the number of musicians addicted to opiates, but there are almost no experimental data in support of this link (Tolson & Cuyjet, 2007). Opiate users' high addiction rate reflects the fact that the brain homeostatically increases pain sensitivity in response to pain medication use. This blunts the effects of the pain drug and even of endogenous painkillers like endorphins. After pain medications are stopped, withdrawal effects can cause increased pain sensitivity even in people who had no pain before using the drug.

Nonsedating pain medications such as the anti-inflammatory drug ibuprofen are less likely to hurt creativity than are opiates or sedating pain medications such as nortriptyline, duloxetine, and pregabalin. Nondrug approaches to pain are typically safer for creativity, and sometimes more effective for pain. Neck pain, one of the most common causes of chronic pain, decreases more with home exercise programs than with painkillers (Bronfort et al., 2012).

Nondrug Interventions

Many creative people believe that even small environmental changes, such as leaving the office to work in a café, or words of praise from a mentor, can spur or inhibit their creativity. However, there have been few scientific studies of such environmental effects.

Sleep and exercise. Although these two activities are in some ways diametrically opposed, their alternation benefits creative work. Sleep, and REM sleep in particular, enhances creativity and stimulates associative networks (Walker, Liston, Hobson, & Stickgold, 2002). Sleep performs actions traditionally attributed to an incubation period (Cai, Mednick, Harrison, Kanady, & Mednick, 2009). Disrupted sleep itself may have fewer negative effects than daytime sleepiness does (Vartanian et al., 2014). Too much sleep may be counterproductive if it decreases the only time available for creative work. Too little sleep can, in some creative subjects, trigger hypomanic or manic episodes.

Regular exercise enhances creativity (Gondola & Tuckman, 1985), although effects vary across studies and the benefit is stronger in physically fit people (Colzato, Szapora Ozturk, Pannekoek, & Hommel, 2013). Acute vigorous exercise typically impedes divergent thinking, especially in nonathletes, possibly because it is competing for scarce mental and physical resources. Treadmill desks raise the possibility of creative work *during* exercise. Slow walking may boost creativity during some creative tasks (Oppezzo & Schwartz, 2014), possibly because undemanding tasks can improve mind wandering during incubation periods (Baird et al., 2012), or simply through mildly increased arousal.

The need for both sleep and exercise is evidence against the monotonic assumption that more is always better. When motivation on a creative project pins creators to their desks, neither sleeping nor exercising, the resulting stasis can be counterproductive. The laws of physics show that efficiency is best achieved by the theoretical Carnot engine – which approaches perfect efficiency by working constantly but very slowly. However, Carnot's theorem does not apply to messy biological systems. Feedback control loops are more stable with some degree of oscillations about a goal level than if they are fine-tuned to poise on a knife-edge of perfect functioning. People work best when they alternate between mental and physical activity, between divergent and convergent thinking, between idea generation and editing. The existence of this metaphorical systole and diastole in many different aspects of human performance reflects the underlying homeostatic negative feedback loops that keep us functioning.

Psychotherapy. Research on psychotherapy and creativity has focused on the benefit that creativity can bring to psychotherapy, rather than the reverse. Art therapy would seem most directly related to creativity. Art therapy's primary goal, though, is typically not creative works that are useful to others, but self-expressive works that help patients understand and vent their emotions. The psychoanalytic literature has addressed the subject of creativity more extensively than other branches of psychiatry, but at the level of case study and theory. In fields such as literature, psychotherapists may aid a writer's creative work through ways independent of their effect on the writer's neurosis or creative block. The writer can try out ideas on the therapist, using the therapist's response as if it were feedback in a writers' group.

Cognitive training and education. Traditional education has been the longest-used technique in imparting creative skill, although creative behavior has only recently become an explicit educational goal. Traditional education can also impart creative motivation, especially when it produces emotion-rich relationships with inspiring role models. Classmates, as well as teachers, can be models. When children see other children approach a task creatively and with pleasure, their emotions and behaviors are contagious (Amabile & Tighe, 1993). Behavioral interventions such as education seem safer, if slower, than drugs as creativity enhancers. Even education, though, is not free of unexpected side effects: every year, many students who went to college to become a writer graduate with the goal of becoming a stockbroker. And traditional education can impart traditional beliefs that cause anchoring errors which keep would-be creators too firmly tied to their field's standard model (Mumford, Blair, Dailey, Leritz, & Osburn, 2006).

Research on the effects of meditation on creativity has produced conflicting results (Lippelt, Hommel, & Colzato, 2014). That may in part reflect the fact that two major types of meditation, focused attention and open monitoring, affect thinking in contrasting ways. Focused attention meditation teaches practitioners to concentrate on a single stimulus, such as their breathing, whereas open monitoring meditation, such as mindfulness techniques, teaches practitioners to monitor their focus of awareness as it jumps from subject to subject. Focused awareness may improve convergent thinking, whereas mindfulness may improve divergent thinking (Colzato, Szapora, & Hommel, 2012). This raises the possibility that, on average, the best meditative practice would be to alternate between the two (Taylor et al., 2013). Of note, all major meditation practices decrease default mode network activity during meditation, but also increase connectivity between major regions of the default mode – possibly increasing its efficiency (Brewer et al., 2011).

Electrical brain stimulation techniques, dramatically more invasive than any of the others in this section, may provide anatomically targeted boosts to brain regions important for creativity and cognition (Luber & Lisanby, 2014). Deep brain stimulation (DBS) is delivered through implanted electrodes and is FDA-approved for several neurological and psychiatric conditions. Two case studies showed patients had improved artistic or intellectual creativity when DBS was delivered near the nucleus accumbens, an area important for goal-directed motivation (Flaherty, 2005; Gabriels et al., 2003). Transcranial magnetic stimulation (TMS) is delivered via an electromagnet placed on the scalp. TMS that inhibited the left anterior temporal lobe temporarily improved drawing, mathematical fluency, and insight solutions (Snyder, 2009). Direct current stimulation (DCS) uses a battery connected to scalp electrodes. It has excited popular interest because of its do-it-yourself potential: a 9V battery connected to saltwater-soaked sponges is enough to deliver DCS. DCS of the dorsolateral prefrontal cortex aided the Remote Associates Test and novel analogy finding (Cerruti & Schlaug, 2008; Green et al., 2016). Although these results are intriguing, they are not yet well studied. DBS requires invasive surgery, and the noninvasive stimulation effects of TMS and DCS typically last an hour or less.

Conclusion

Creativity depends on high, but not too high, motivation. The optimally creative level of goal-oriented drive – the peak of its inverted-U relation – is higher than that of fear-driven drive. On the right side of those peaks, the brain's homeostatic control of arousal and motivation helps limit the energetic drain and risky behavior of too-high motivation. However, homeostatic set-points that evolved to deal with dangerous environments may be too low for permissive ones, and vice versa. Normal drives homeostatically decrease when creative individuals achieve their goal. Traits that make people work as if their life or career is at stake in situations where they are not can promote creative behavior in safe environments, but cause harm in dangerous ones.

Homeostatic feedback control is typically more efficient when it allows a degree of oscillation between different states. This is true in creativity, which seems to require the alternation of idea generation and editing, divergent and convergent thinking, but also the alternation of physical states such as sleep and wakefulness, exercise and stillness. Brain conditions such as mood disorders can produce defective homeostatic feedback, with excessive oscillations between too-low and too-high motivation, or with tonic levels that are inappropriate for a given environment. Treatments of brain disorders may have complex effects on creativity. Response to treatment is itself shaped by the brain's homeostatic controls, leading to treatment tolerance and withdrawal effects. Because motivation varies so dramatically across individuals and contexts, creativity research looking for general relationships will often not apply to specific cases, especially those of high creativity. Future research should (1) uncover cues that let individuals judge whether, on a given task or day, they are above or below the optimal level of motivation and other variables, and (2) develop techniques by which individuals can rapidly change those levels.

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3 Laterality and Creativity: A False Trail?

Michael C. Corballis

Creativity poses a problem for science, because anything that is genuinely creative is utterly new, and therefore not predicted by scientific laws. Perhaps because of this, we are often led to invent explanations that are somehow in defiance of natural laws, even to the point of supposing that life on earth, or humanity itself, is the product of some all-knowing, all-powerful creator, whose powers lie beyond natural science. Creativity must therefore be in the hands of a creator. It is perhaps also for this reason that many have suggested that the source of human creativity resides in the right side of the brain – the hemisphere that seems to defy the rational, scientific logic of its more prosaic partner, the left hemisphere. Julian Jaynes, in his 1976 book *The Origin of Consciousness in the Breakdown of the Bicameral Mind*, proposed that, in ancient times at least, the gods spoke to us through the right hemisphere, until the left hemisphere eventually asserted dominance. So it is that humans became rational and less reliant on the hallucinatory voices of the gods.

The mere fact that the brain is a divided organ, with each half more or less the mirror-image of the other, seems to have been a powerful influence in the emergence of folklore, and this was no doubt heightened by the discovery that the two sides have rather different functions in spite of their close structural similarity (M.C. Corballis, 1980). I begin, then, with a brief history of ideas about the duality of the brain itself.

The Duality of the Brain

As long ago as 1844, in his book *The Duality of Mind*, the English physician Arthur C. Wigan surmised that the two sides of the brain operated as separate "minds," each with its own consciousness. In order to provide a balanced life, Wigan thought, the two sides had to be coordinated through "exercise and moral cultivation." He was more interested, though, in the breakdown of coordination, which might explain such experiences as *déjà vu*, or even cases of seemingly motiveless crime, where one side of the brain provides the hidden motive for a felony actioned in innocence by the other. Cases of double personality were a source of fascination in the late nineteenth and early twentieth centuries, exemplified in fiction by Robert Louis Stevenson's 1886 book *The Strange Case of Dr Jekyll and Mr Hyde*, and perhaps culminating in Morton Prince's 1906 book *The Dissociation of a Personality*, describing the case of a Miss Beauchamp who occasionally adopted the persona of an altogether different individual known as Sally B. The association with the two sides of the brain was somewhat weakened, though, by later claims of three-way (Thigpen & Cleckley (1957) and even five-way (Confer & Ables, 1983) splits of personality within single individuals.

Wigan believed one side of the brain, generally the left, to be dominant, but wrote before Broca's (1861, 1865) discoveries in the 1860s of the left-hemispheric representation of speech. This reinforced the idea of a generalized left-brained dominance, but also began a flurry of speculation as to how the two sides of the brain might differ systematically, perhaps even profoundly, in our mental and emotional lives. A common theme, developed mainly in France by authors such as the well-respected physician Gaetan Delaunay (1874), was that the left brain stood for humanity, reason, will, masculinity, and white superiority, while the right brain was associated with animality, instinct, emotion, femininity, native inferiority – and madness. The association of the right brain with madness, in particular, was elaborated by the neurologist Jean-Martin Charcot (1878) and the psychotherapist Pierre Janet (1899), who both remarked on the predominance of left-sided symptoms in hysteria, implying right-brain causation. This led to the extreme and often bizarre speculations of the later nineteenth century, including the idea that metal discs might be applied to the afflicted side of the body to influence brain dominance, or even that the two sides of the brain might be differentially hypnotized (see Harrington, 1985, 1987, for useful reviews).

Perhaps the link between the right brain and madness was the beginning of the idea that the right brain is dominant for creativity, because creativity itself has long been linked to insanity; as Theseus put it in Shakespeare's *A Midsummer Night's Dream*:

> The lunatic, the lover and the poet
> Are of imagination all compact.
>
> (Act 5. Scene 1)

The association goes back at least to Aristotle, and bipolar illness in particular has been associated with a number of creative individuals, among them Beethoven, Ernest Hemingway, van Gogh, Isaac Newton, and Virginia Woolf. Schizophrenia too is often associated with creativity, as in the celebrated economist John Nash, or Vaclav Nijinsky, the famous dancer and choreographer. There may even be a common genetic basis. In one study genetic markers for schizophrenia and bipolar disorders were also found to be associated with creativity, as characterized by individuals belonging to the national artistic societies of actors, dancers, musicians, visual artists, and writers (Power et al., 2015). In a careful, large-scale meta-analysis, Baas, Nijstad, Boot and De Deu (2016) concluded that risk of bipolar disorder is positively correlated with creativity, while depressive mood is negatively correlated with it, albeit weakly. Neither this study nor the titles of the articles cited include any reference to handedness or brain asymmetry.

In any event, the ideas about hemispheric differences that were prominent in the latter part of the nineteenth century, and buttressed to a large extent by the notion of the left hemisphere as epitomizing rational Western man [*sic*], soon faded, and would perhaps have been forgotten altogether were they not restored to the public domain by the historian Anne Harrington, cited above. And the association of creativity with the right hemisphere seemed not to be made explicit until the dual brain returned to favor in the latter part of the twentieth century.

The Revival

Almost exactly a century after Broca's discoveries, the dual brain made a remarkable comeback, but with somewhat different associations, through the pioneering work of Roger W. Sperry and Michael S. Gazzaniga on patients who had undergone section of the corpus callosum for the relief of intractable epilepsy (Gazzaniga, Bogen, & Sperry, 1962). Sperry belatedly received the Nobel Prize for this work in 1981. The "split brain" allowed researchers to assess the functions of each side of the brain with little or no interference from the other side. This work confirmed the dominance of the left hemisphere for speech, but also suggested a right-brained advantage for a number of nonverbal functions, including "reading faces, fitting designs into larger matrices, judging whole circle size from a small arc, discriminating and recalling nondescript shapes, making mental spatial transformations, discriminating musical chords, sorting block sizes and shapes into categories, perceiving wholes from a collection of parts, and the intuitive perception and apprehension of geometric principles" (Sperry, 1982, p. 1225).

Although these advantages tend to be relative rather than absolute, Sperry and Gazzaniga's research seemed to unleash interest in the dual brain, although with a somewhat different interpretation. In the nineteenth century the differences between left and right brains were seen largely in terms of the dominance of one side, usually the left, over the other. In the rather different culture that emerged in the 1960s, the differences were interpreted in terms of complementarity rather dominance – with suggestions that the right brain might even be mentally superior to the left. Joseph E. Bogen (1969), who with Philip J. Vogel undertook the split-brain surgery itself, described the functioning of the left brain as propositional and of the right brain as appositional, even suggesting that the right brain might be responsible for creative thinking. The dual brain was enthusiastically elaborated and popularized in Robert E. Ornstein's (1972) best-selling book *The Psychology of Consciousness*. The new duality may have owed less to the neurological evidence than to the prevailing conflicts of the late 1960s and 1970s – the Vietnam War, and the rise of the Feminist and Black Power movements. The left and right sides of the brain seemed to be associated with, respectively, the military–industrial establishment of the West versus the supposedly peaceful East, men versus women, Black versus White. In the catch-cry of the time, "Make love, not war," the left brain stood for war, the right brain for love.

The right brain in particular was idealized and romanticized, standing for creativity, the flower people, the exploited people of the world. The idea of the right brain as the more creative was well captured by Betty Edwards' 1979 book *Drawing on the Right Side of the Brain*, and many other authors urged release from the tyranny of the left brain in education, and even in business, so that the creativity of the right brain could find expression. Another popular book of the time was Carl Sagan's *The Dragons of Eden*, published in 1977, which depicted the right brain as intuitive, emotional, and creative but paranoid, often seeing patterns and conspiracies where they do not exist, and it was up to the left hemisphere to subject them to critical analysis.

Such analyses went well beyond the data; indeed, right-hemisphere function in the split brain proved difficult to assess, because the isolated right hemisphere is largely incapable of speech and has limited verbal understanding. There was, and is, little evidence from the split-brain studies that the right brain is more creative than the left. Even so, this idealization of the right brain has shown remarkable persistence. The online American Heritage Dictionary of the English language still defines "right-brained" as:

"1. Having the right brain dominant.
2. Of or relating to the thought processes involved in creativity and imagination, generally associated with the right brain.
3. Of or relating to a person whose behavior is dominated by emotion, creativity, intuition, nonverbal communication, and global reasoning rather than logic and analysis."

Betty Edwards' book continues to be a best seller, and appeared in a fourth edition in 2013. It may well be the case, of course, that her teaching methods are effective, even if any association with the right brain is dubious. A Google search for "right brain" yields around 13,700,000 hits, whereas "left brain" yields around 11,600,000 – yet until quite recently it was the left brain that was assumed, at least in neurology, to be dominant. "Right brain and creativity" produces just over three million hits, while "left brain and creativity" produces just over two million, most of them contrasting the prosaic left with the creative right. In his well-received book *The Master and his Emissary*, Iain McGilchrist (2009) examines Western history in the light of what he terms the "divided brain," and declares the right brain the master, the left the mere emissary. As though to reverse the trend envisaged by Julian Jaynes, he urges that the right brain be restored to its rightful prominence. "Certainly," he writes, "there is plenty of evidence that the right hemisphere is important for creativity, which given its ability to make more and wider-ranging connections between things, and to think more flexibly, is hardly surprising" (p. 42).

Although the left brain/right brain dichotomy remains prominent in contemporary folklore, it no longer features in modern science, although there is of course a well-documented pattern of relative differences in function between the two sides of the brain. As early as 1984, there was serious questioning of the idea of "hemisphericity," and the associated notion that individuals might differ in terms of which hemisphere controls their mode of cognitive processing (Beaumont, Young, & McManus, 1984). The authors review a number of studies which, they say, "point to a lack of any direct evidence to link creativity or imagery with the right hemisphere" (p. 195). In a review of the split-brain findings in 2000, Michael Gazzaniga does not mention creativity or even duality, and if anything restores a measure of dominance to the left hemisphere, characterizing it as the "interpreter" that "allows us to construct theories about the relationship between perceived events, actions, and feelings" (Gazzaniga, 2000, p. 1293). That may even suggest the left hemisphere to be the source of creativity, although it also smacks of personification, and some evidence even suggests an "interpreter" in the right hemisphere (e.g., P.M. Corballis, 2003a b).

Evidence from brain imaging casts further doubt on the idea of a dichotomy. A factor-analytic study of intrinsic activity while the brain is at rest indicated four networks, two lateralized to the left and two to the right hemisphere (Liu, Stufflebeam, Sepulcre, Hedden, & Buckner, 2009). One of the left-lateralized networks was the so-called default-mode network, which is active when the brain is at rest and has been linked to mind wandering (Buckner, Andrews-Hanna, & Schacter, 2008; M.C. Corballis, 2015); indeed, this network is now often considered the true basis of creativity (e.g., Zedelius & Schooler, 2016). Given that it is biased more toward the left hemisphere than the right, this might be taken as evidence for a *left*-hemisphere bias in creative thinking. The asymmetry of the networks revealed by Liu et al., though, suggests relative rather than absolute asymmetry, and it seems reasonable to suppose that both hemispheres contribute to creative thought, with perhaps the left hemisphere contributing more to verbal creativity and the right to spatial or musical creativity.

Handedness and Creativity

One manifestation of the right-brain theory is the common belief that left-handers are more creative than right-handers. The most celebrated example is Leonardo da Vinci, who was indeed left-handed and arguably the most creative individual of all time. So strong is the idea that left-handers are more creative, though, that creative individuals are often asserted to be left-handed when in fact they are not. McManus (2002) gives several examples, including Albert Einstein, Picasso, and Bob Dylan – and when Pulitzer Prize-winner James Michener was named one of the "Southpaws of the Year" by Southpaws International, he wrote back to say that the only thing he did with his left hand was scratch his right elbow. As Grimshaw and Wilson (2013) point out in a large-scale study of personality differences between left- and right-handers, "the important point is not the accuracy of the belief, but its existence" (p. 147).

The idea that left-handedness signals right-brain dominance is itself flawed. Contrary to the widespread belief that "only lefties are in their right minds," often emblazoned on T-shirts, left-handers typically do not show right-hemisphere dominance for cognitive processes. Some 70% of left-handers have language represented predominantly in the left hemisphere (e.g., Pujol, Deus, Losilla, & Capdevila, 1999; Rasmussen & Milner, 1977; Warrington & Pratt, 1973), and although spatial attention shows an overall right-hemisphere advantage, this appears to be uncorrelated with handedness (Badzakova-Trajkov, Häberling, Roberts, & Corballis, 2010; Bryden, Hécaen, & DeAgostini, 1983). Large-scale studies of handedness suggest that left-handers belong to a subgroup characterized by the absence of any systematic tendency to be left- or right-handed, so that handedness in this group is effectively a matter of chance (Annett, 2002; McManus, 2002).

This has raised the possibility, though, that creativity might be related to ambidexterity rather than left-handedness, perhaps on the assumption that ambidexterity might signal better access to both hemispheres rather than reliance on one or the other. In one study, Shobe, Ross, and Fleck (2009) do indeed report higher scores on all five components of a creativity test among mixed-handers compared with "strong"-handers – although this group included only one left-hander. They also report that a task requiring bilateral eye movements enhanced creativity in the "strong"-handedness group but not in the mixed-handed group, suggesting that the operative mechanism was not handedness *per se* but rather bilateral activation of the brain. This may apply to left-handers as well as to mixed-handers, given that left-handers appear to lack consistent cerebral asymmetries. Reviewing the evidence, Shobe et al. write as follows:

> the RH does not appear to operate independently of the LH in the creative process, whereby any argument for the RH as the seat of creativity is likely to be false. Indeed, a growing body of evidence suggests that the neurological contributions to the creative process are better qualified as a collaborative effort or interaction between the two hemispheres. (p. 205)

The data, though, remain equivocal as to actual hemispheric involvement. Our own data do show a correlation between absolute hand preferences and magical ideation (confirming an earlier finding by Barnett &Corballis, 2002) and creativity, indicating higher scores on average on both measures for mixed than for both left- and right-handers – although left-handers also scored higher than right-handers, suggesting that they too had more mixed cerebral asymmetry (Badzakova-Trajkov, Häberling, & Corballis, 2011). However, handedness scores based on performance (finger-tapping) rather than preference showed no such effects, a finding also reported by Grimshaw, Yelle, Schoger, and Bright (2008). More critically, neither magical ideation nor creativity showed any relation to measures of cerebral asymmetry based on functional magnetic imaging of activity induced by word generation, spatial judgments, or face recognition, even though these measures were correlated with each other. Perhaps people's reports of their own handedness are shaped by self-perceptions rather than actual performance or neuropsychological dispositions.

Conclusions

Brain imaging now suggests that creativity depends on widespread circuits of the brain, including the default-mode network. Of course, there are likely to be differential, though graded, contributions from each hemisphere, simply because there are functional differences between them, but these appear not to constitute the simple polarity so widely assumed. Beaty et al. (2014) compared activity in individuals who scored highly on a test of creativity with those with low scores, and found that high creativity was associated with higher connectivity between the left inferior frontal gyrus and the default mode network. However, the right inferior gyrus also played a role, with greater connectivity to the bilateral inferior parietal cortex and the left dorsolateral prefrontal cortex.

The picture that is beginning to emerge, then, is not so much a matter of left versus right hemisphere, but rather a complex and perhaps variable set of interconnections between as well as within hemispheres and a critical role of the prefrontal cortex rather than one or other hemisphere – more a question of front versus back, perhaps, than left versus right. In another recent study, Ellamil, Dobson, Beeman, and Christoff (2012) had design students make designs for a magazine cover while actually in the scanner, and found the default-mode network to be active throughout, but the medial temporal lobe contributed more to the generative component of creativity, while the evaluative component activated frontal executive areas. Although there were small hemispheric differences within the networks activated, the activation was predominantly bilateral. This study also reminds us that creativity itself is not a simple process, and involves generation as well as evaluation.

The psychologist and epistemologist Donald T. Campbell (1960) once defined creativity as "blind variation and selective retention" (p. 1), and it is the element of blind variation, or sheer chance, that provides the creative component. This seems to solve the problem of the disembodied creator. Albert Einstein once remarked that "God doesn't play dice with the world" (Hermanns & Einstein, 1983, p. 58), but perhaps it's more a question of the dice playing God. The best model of creativity is evolution itself, depending on chance variations and natural selection, establishing the vast diversity of life forms on earth, without the need to postulate a creative deity. The brain itself seems to be a natural source of random variation, mediated largely through the default-mode network, and perhaps most evident in our dreams – although our nightly dreams are mostly forgotten and therefore only weakly available for selective retention. However, mind wandering occupies nearly 50% of our waking hours (Killingsworth & Gilbert, 2010), and is perhaps the most available source of creative ideas. In his recent book *Seven Brief Lessons on Physics*, the Italian physicist Carlo Rovelli describes the mind wandering that led Albert Einstein to the theory of relativity, and remarks that "You don't get anywhere by not 'wasting' time" (2014, p. 3).

Yet the idea of left brain/right brain duality, and the notion that the right brain is responsible for creativity, remain strongly with us, although if history is our guide such ideas may well decline by the 2020s, just as they did by the 1920s. We should be wary, though, of a revival in the 2060s.

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4 The Neural Basis and Evolution of Divergent and Convergent Thought

Liane Gabora

It is standard to define convergent thinking problems as those with only one correct solution and divergent thinking problems as open-ended problems with multiple solutions (Guilford, 1950; Runco, 2010), and to essentially equate creativity with the capacity for convergent and divergent thinking (e.g., Onarheim & Friis-Olivarius, 2013), with divergent thinking the more important of the two for creativity. However, this conception of divergent and convergent thinking does not align with what people think of as creative.

First, not all tasks with multiple solutions require creative thinking, such as the task of responding to the question "what is something red?" Indeed, some problems with just one correct solution, such as the Remote Associates Test (RAT), require more creativity than coming up with things that are red. Second, it is often said that creative problem-solving tasks "require both convergent and divergent thinking" (e.g., Biggs, Fitzgerald, & Atkinson, 1971; Riddell et al., 2007). However, given the conventional view of convergent/divergent thinking problems this makes no sense, for a problem either has one solution or it has multiple solutions; it cannot have both. Third, and perhaps most importantly, does it really make sense to define creative thought in terms of the number of correct solutions, as opposed to the process by which those solutions are generated?

In this chapter I hope to convince you that by looking to the neural level mechanisms underlying creative thought, and how these mechanisms evolved, we are led to a new conception of convergent and divergent thought. Specifically, I will argue that convergent thought is characterized not by the generation of a single correct solution, but by conceiving of concepts in their conventional contexts. Likewise, it will be argued that divergent thought is characterized not by the generation of multiple solutions, but by playing with "halo of potentiality" surrounding concepts – new affordances yielded by new contexts – to hone as few as a single idea.

The chapter begins by summarizing a neural-level explanation for creative insight that arose from studies of the architecture of associative memory. It then outlines problems with conventional conceptions of divergent and convergent thought. Finally, it proposes a new conception of divergent and convergent thought that is consistent with the architecture of associative memory, evolutionary considerations, and empirical studies of divergent and convergent processing.

Conventional Conceptions of Divergent and Convergent Thought

Psychological theories of creativity typically involve two modes of thought. As mentioned in the introduction, *divergent thought* is defined and measured in terms of the generation of multiple discrete, often unconventional possibilities, possibly due to defocused attention and facitilitatation of free-association by reduced latent inhibition (Carson, Peterson, & Higgins, 2003). It is characterized as intuitive and reflective, and thought to predominate during idea generation (for a review see Runco, 2010; for comparison between divergent/convergent processes in creativity and dual process models of cognition, see Sowden, Pringle, & Gabora, 2015).

Divergent thought is contrasted with *convergent thought*, which as mentioned above is defined and measured in terms of the capacity to perform on tasks where there is a single correct solution. Convergent thought – as involving selection or tweaking of the most promising possibilities – is characterized as critical and evaluative, and is believed to predominate during the refinement, implementation, and testing of an idea.

Note the difference between how divergent and convergent are *defined and measured*, in terms of number of generated and/or acceptable solutions, versus how they are commonly *conceived*, in terms of cognitive processes. If one were to schematically illustrate divergent thought as it is defined and measured, one might draw a set of multiple blobs with well-defined edges to represent the multiple final outcomes generated, whereas if one were to schematically illustrate divergent thought as it is commonly conceived, one might draw a single blob with blurry edges, as is consistent with the literal meaning of divergent as “spreading out” (as in a divergence of a beam of light).[1] Indeed, there are several incompatibilities between how we define and measure divergent thought and how we informally conceive of it. The generation of multiple solutions may or may not involve defocused attention and associative memory. Moreover, in divergent thought as it is generally construed, the associative horizons simply widen generically instead of in a way that is tailored to the situation or context, as illustrated in Figure 4.1. (For these reasons, the term *associative thought* has sometimes been used to refer to creative thinking that involves defocused attention and context-sensitive associative processes, and the term *analytic thought* has sometimes been used to refer to creative thinking that involves focused attention and executive processes.) In short, the way we define and measure divergent and convergent thought is not consistent with how we appear to think about them.

Brief Summary of Research on the Neural Mechanisms of Creative Thinking

We now review some well-established features of associative memory, and how they are believed to come together in creative thinking (Gabora, 2001, 2010; Gabora & Ranjan, 2013). First, memory is *sparse*: the total number of neurons in the brain is smaller than the total number of stimuli in the world that could potentially be encoded in memory. Therefore, there exist stimuli that no neuron is tuned to respond to. However, as illustrated in Figure 4.2, the brain is nevertheless able to encode (and respond to) these stimuli because their representation is *distributed* – or spread out across a cell assembly containing many neurons – and likewise each neuron participates in encoding many items. Neurons exhibit *coarse coding*: although each neuron responds maximally to a particular feature, dimension, or property, it responds to a lesser degree to similar properties. As illustrated in Figure 4.3, memory is also *content addressable*; there is a systematic relationship between the content of a stimulus and the cell assemblies that encode it, such that memory items are evoked by stimuli that are similar or “resonant” (Hebb, 1949).

The fact that representations are distributed across cell assemblies of content-addressable neurons that are sensitive to particular high-level or low-level properties ensures the feasibility of forging associations among items that are related, perhaps in a surprising but useful or appealing way. This enables reinterpretation of higher-order relations between perceptual stimuli through synchronization of prefrontal neural populations (Penn, Holyoak, & Povinelli, 2008).

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[1] For more on how light can be used as a metaphor for cognition, see Gabora (2014, 2015).

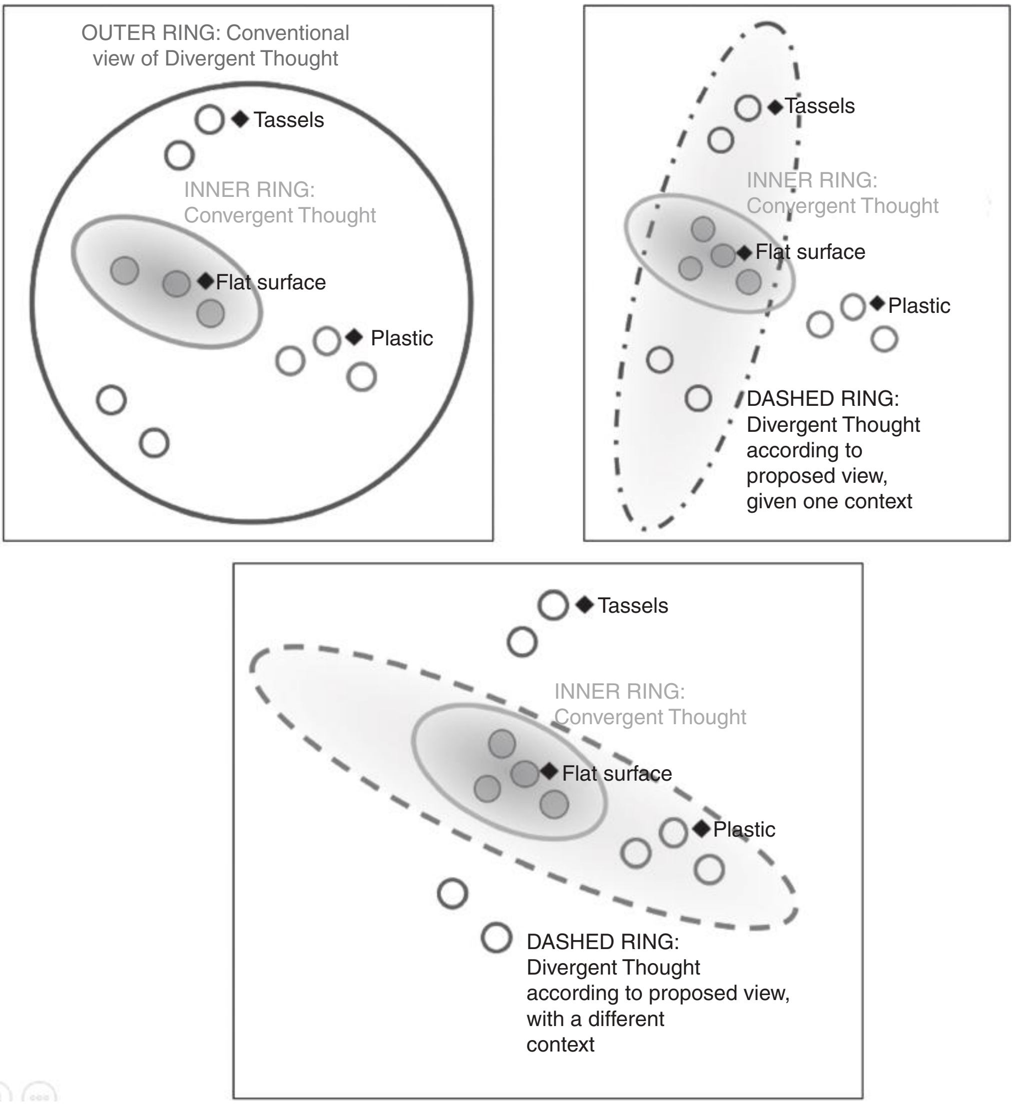

Figure 4.1 Neural-level illustration of context-dependency of creative thought. Small closed circles represent neural cell assemblies activated when thinking of CHAIR (regardless of which mode of thought). Small open circles represent neurons activated only in divergent thought referred to as "neurds." The top left figure illustrates divergent thought as it is conventionally construed. The figures on the top right and bottom illustrate the new conception of divergent thought. Notice that the subset of neurons that act as neurds in one context is not the same as the subset of neurons that act as neurds in a different context. Thus, given the context *living room*, the property "tassels" might be activated (middle figure), but not in the context *outdoors*; in that context "plastic" might be activated (bottom figure). For a color version of this figure, see the color plate section.

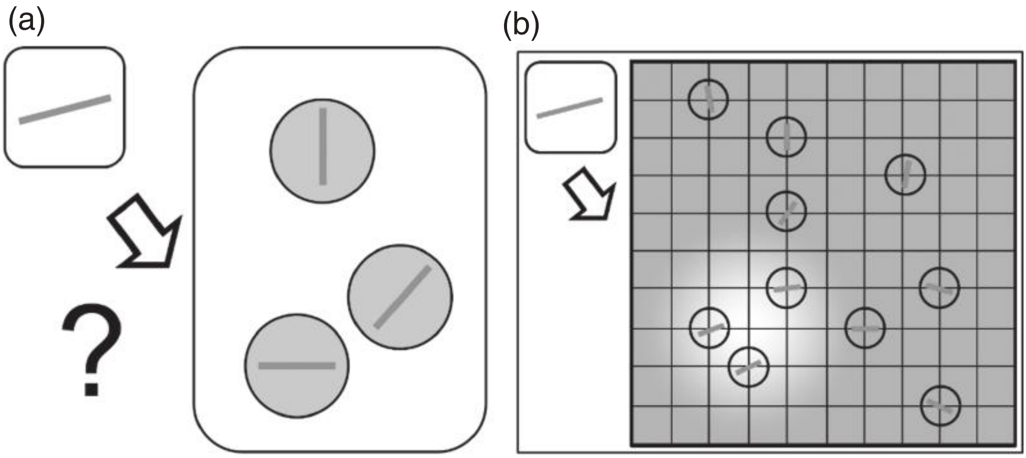

Figure 4.2 (a) In this schematic illustration of a portion of memory, the circles represent neurons, and the orange bars represent properties responded to by particular neurons – in this case, lines of a particular orientation. Because the total number of neurons in the brain is smaller than the total number of stimuli in the world that could potentially be encoded in memory, there exist stimuli that no neuron is tuned to respond to – such as, in this illustration, the line oriented at 15° to the left. For simplicity it contains only three neurons; in a real brain, it would contain many more. Therefore, the question arises how the brain is nevertheless able to encode (and respond to) so many stimuli. (b) In this more detailed schematic representation of this portion of memory, each vertex represents a *possible* property, and each black ring represents a property that actually elicits maximal response from an existing neuron. (Thus, the fact that the number of neurons is smaller than the number of potential stimuli is represented by the fact that not all vertices have black circles.) The reason the 15° line can be encoded in memory is because its representation is *distributed*, or spread out across a cell assembly containing many neurons. The diffuse white circle indicates the region activated by the 15° line. For a color version of this figure, see the color plate section.

Figure 4.4 provides a simplified illustrative example of how this works. Let us consider the task of inventing a casual chair that would appeal to the free-spirited mindset of the 1960s.[2] We imagine that the designer had recently thrown beanbags with a toddler, and consider what was going on at the neural level during the invention of the beanbag chair. The context of wanting to invent a comfortable chair could have elicited context-driven expansion of the concept CHAIR such that not just neurons that respond to typical chair properties – such as “flat surface to sit on” – were activated, but also neurons that respond to context-relevant properties such as “conforms to shape.” Activation of the neuron that responds to “conforms to shape” causes associative retrieval of previously encountered items with this property, such as beanbags. The designer recognizes that while a little beanbag conforms to the hand, a giant one might conform to the body. The overlap in the distributed representations of ‘CHAIR in the context “*comfortable*” and “BEANBAG” means that there is a route by which the first could elicit associative retrieval of the second, culminating in the invention of BEANBAG CHAIR.

Note that an associative memory that encodes items in less detail might not contain a neuron that responds to objects with the property “conforms to shape.” In this case, the context “comfortable” could not elicit associative retrieval of

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[2] The earliest artifact that could be called a beanbag chair, referred to as a *sacco*, was introduced in 1968 by three Italian designers: Piero Gatti, Cesare Paolini, and Franco Teodoro as part of the Italian Modernism movement.

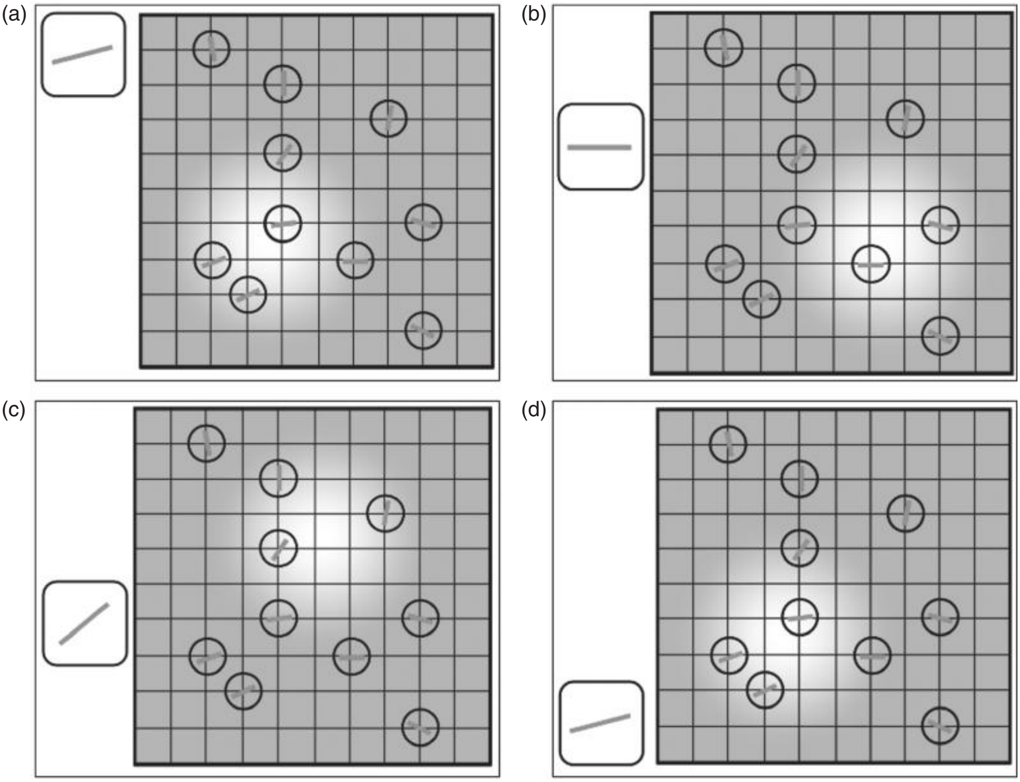

Figure 4.3 As in Figure 4.2, in this schematic illustration of a portion of memory, the circles represent neurons, and the orange bars represent properties responded to by particular neurons – in this case, lines of a particular orientation. Each of the four panels depicts a line of a particular orientation, and the corresponding region of memory activated by that stimulus. The fact that memory is content-addressable is illustrated by the fact that there is a systematic relationship between the stimulus *content* and *where* it gets encoded. Specifically, (b) depicts a stimulus that is similar to that in (a), and a nearby region of memory is activated, whereas (c) depicts a stimulus that is quite different to that in (a), and the region activated is further away. The stimulus in (d) is so similar to that in (a) that it activates the same region of memory. For a color version of this figure, see the color plate section.

BEANBAG and bring about the invention of BEANBAG CHAIR.

Thus, the sparse, distributed, content-addressable nature of memory is critical for creativity. The fact that associations come to mind spontaneously as a result of representational overlap due to sharing of features encoded by content-addressable neurons means there is no need for memory to be searched or randomly sampled for creative associations to be made (Gabora, 2001, 2010). The more detail with which stimuli and experiences are encoded in memory, the greater the degree to which their distributed representations overlap, and the more potential routes by which they can act as contexts for one another and combine. They may have been encoded at different times, under different circumstances, and the relationship between them never explicitly noticed, but some situation could come along and make their relationship apparent.

There is empirical evidence for oscillations in convergent and divergent thinking, and a relationship between divergent thinking and chaos (Guastello, 1998). The capacity to shift between different modes of thought has been referred to

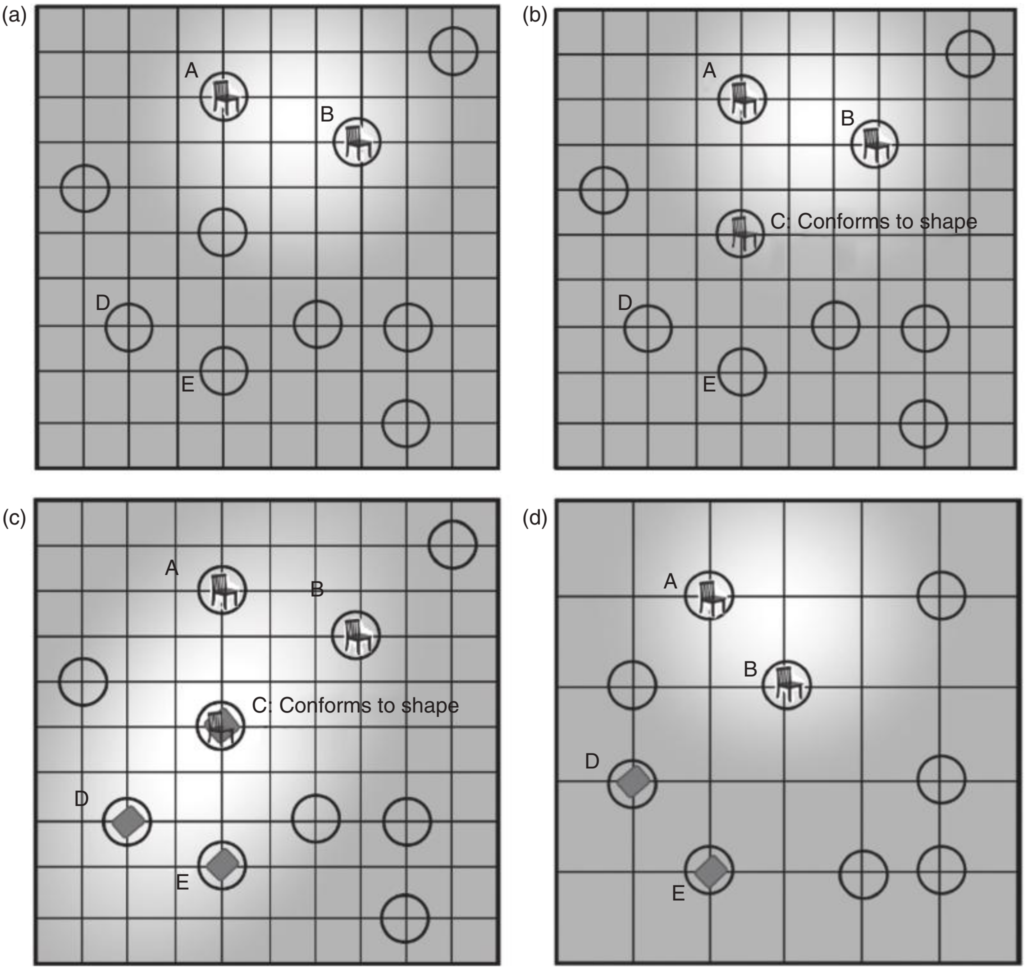

Figure 4.4 These panels provide a schematic illustration of a portion of memory in the process of inventing a beanbag chair. The circles represent neurons that respond to properties of objects such as chairs and beanbags. (a) The first panel depicts activation of the concept CHAIR in the absence of the goal of inventing a comfortable chair. Neurons that respond to only the most typical properties of CHAIR – such as that it has a flat surface and legs – are activated, and these are represented for simplicity as neurons A and B. (b) In the context of wanting to invent a *comfortable* chair, a fine-grained associative memory can expand its conception of CHAIR to additionally activate neurons that respond to context-relevant properties such as comfort. This is depicted as activation of neuron C that responds to "conforms to shape." (c) The concept BEANBAG is encoded in neurons C, D, and E, where C still responds to "conforms to shape," and D and E respond to other typical beanbag properties such as that it is small and square. The overlap in the distributed representations of "CHAIR in the context *comfortable*" and "BEANBAG" means that there is a route by which the first can elicit associative retrieval of the second, culminating in the invention of BEANBAG CHAIR. (d) The bottom right panel depicts an associative memory that encodes items in less detail. It does not contain a neuron that responds to objects with the property "conforms to shape." With CHAIR now activating only neurons A and B, and BEANBAG activating only neurons D and E, the context "comfortable" cannot elicit associative retrieval of BEANBAG. Thus, this degree of detail is insufficient to bring about the invention of BEANBAG CHAIR. For a color version of this figure, see the color plate section.

as *contextual focus* (CF) (Gabora, 2003). While some dual processing theories (e.g., Evans, 2003) make the split between automatic and deliberate processes, CF makes the split between an associative mode conducive to detecting relationships of correlation, and an analytic mode conducive to detecting relationships of causation. Defocusing attention facilitates associative thought by diffusely activating a broad region of memory, enabling obscure (although potentially relevant) aspects of a situation to come into play. Focusing attention facilitates analytic thought by constraining activation such that items are considered in a compact form that is amenable to complex mental operations.

A plausible neural mechanism for CF has been proposed (Gabora, 2010; Gabora & Ranjan, 2013). In a state of defocused attention more aspects of a situation are processed, the set of activated properties is larger, and thus the set of possible associations is larger. Activation flows from specific instances to the abstractions they instantiate to other seemingly unrelated instances of those abstractions. Cell assemblies that would not be activated in analytic thought but that would be in associative thought are referred to as *neurds* (see also Ellamil, Dobson, Beeman, & Christoff, 2012; Yoruk & Runco, 2014). Neurds respond to properties that are of marginal relevance to the current thought. They do not reside in any particular region of memory; the subset of cell assemblies that count as neurds shifts depending on the situation. For each different perspective one takes on an idea, a different group of neurds participates.

Neurds may generally be excluded from activated cell assemblies, becoming active only when there is a need to break out of a rut. In associative thought, diffuse activation causes more cell assemblies to be recruited, including neurds, enabling one thought to stray far from the preceding one while retaining a thread of continuity. Thus, the associative network is not just penetrated deeply, but traversed quickly. There is greater potential for overlapping representations to be experienced as wholes, resulting in the uniting of previously disparate ideas or concepts. While the preparation phase of the creative process likely involves long-term change to how ideas are encoded in the neocortex, the merging of thoughts culminating in insight may involve recurrent connections in the hippocampus, particularly when the insight involves generalization and inference triggered by a particular recent experience (Kumaran & McClelland, 2012). Research on the neuroscience of insight suggests that alpha band activity in the right occipital cortex causes neural inhibition of sensory inputs, which enhances the relative influence of internally derived ("non-sensory") inputs, and thus the forging of new connections (Kounios & Beeman, 2009, 2014). Following insight, the shift to an analytic mode of thought could be accomplished through decruitment of neurds. Findings that the right hemisphere tends to engage in coarser semantic coding and have wider neuronal input fields than the left (Jung-Beeman, 2005; Kounios & Beeman, 2014) suggest that the right hemisphere may predominate during associative thought while the left predominates during analytic thought. In short, the architecture of associative memory is conducive to self-supervised learning and achievement of a more coherent network of understandings, with creative output as an external manifestation of this process.

A New Conception of Divergent and Convergent Thought

Having examined how creative connections are forged in associative memory, we are led to the suggestion that instead of characterizing convergent thought in terms of the generation of a single correct solution, it be characterized in terms of sticking to conventional contexts, such as the context *car* when thinking of the concept TIRE. Similarly, it is proposed that divergent thought be characterized not by the generation of multiple solutions, but by capitalizing on the capacity to re-view an idea from new, context-relevant perspectives, using shared properties of concepts as bridges, to hone as few as a single idea. This is consistent with the RAT having only one solution yet requiring a more creative kind of thought than answering the question "what is red?" which has many possible solutions. Answering the question "what is red?" does not require thinking of concepts in unconventional contexts. In contrast, the RAT does require thinking of concepts in unconventional contexts. For example, consider the RAT question: what is the common associate of TANK, HILL, and secret? The correct answer is top. To arrive at the correct answer, it is necessary to conceive of the concept TOP in very different ways.

For an everyday example of how this might work outside of creative thinking tests, consider how the concept TIRE might be brought to mind in a divergent mode of thought, as illustrated schematically in Figure 4.5. In its conventional context *car*, the concept TIRE collapses on tire-relevant properties such as "goes on wheel" and "filled with air." However, in the unconventional context *playground equipment*, the concept TIRE might collapse on the properties that you could hang it and sit on it, which are essential for conceiving of it as a possible swing. In an even less conventional context, *pet needs*, the concept

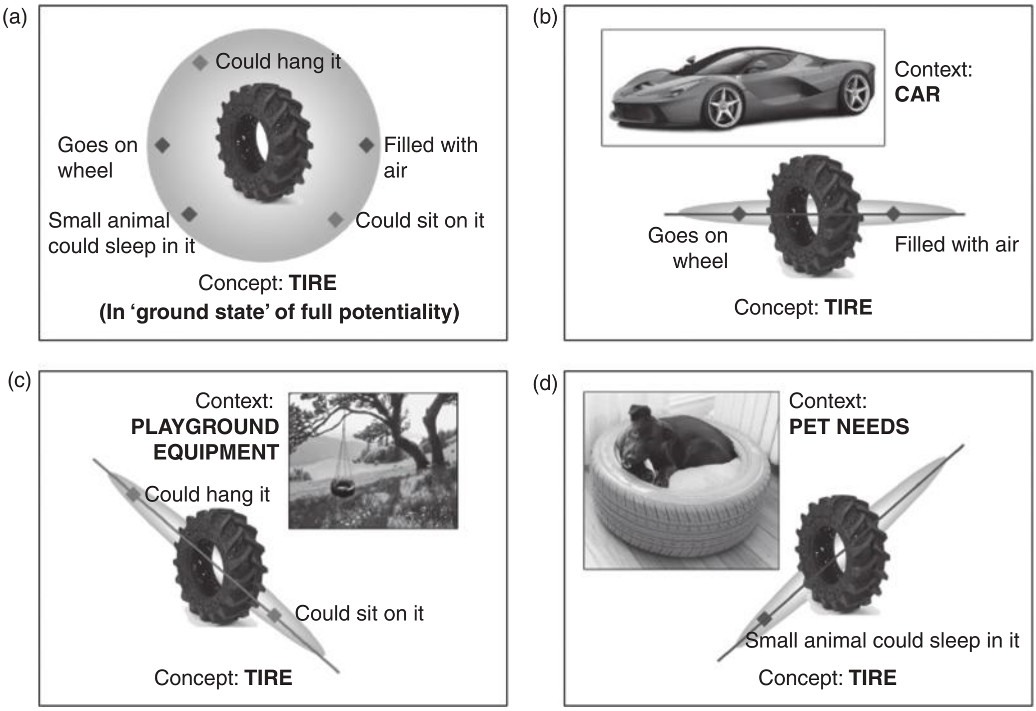

Figure 4.5 (a) A schematic depiction of the concept TIRE in its state of full potentiality, with many potential properties or affordances. (b) Depiction of how, in its conventional context *car*, the concept TIRE collapses on tire-relevant properties, such as "goes on wheel" and "filled with air." (c) Depiction of how, in the unconventional context *playground equipment*, the concept TIRE collapses on the properties that you could hang it and sit on it, which are essential for conceiving of it as a possible swing. (d) Depiction of how, in an even more unconventional context for this concept, *pet needs*, it collapses on the property "small animal could sleep in it," which is essential for conceiving of it as a dog bed. For a color version of this figure, see the color plate section.

TIRE might collapse on the property “small animal could sleep in it,” which might enable it to be conceived of as a bed for a dog.

This view of convergent and divergent thought arose as part of the honing theory of creativity (Gabora, 2017), according to which creativity is a byproduct of the self-organizing, self-mending nature of a mind, and its proclivity to minimize what Hirsh, Mar, and Peterson (2012) refer to as psychological entropy: arousal-generating uncertainty. Honing theory grew out of a mathematical theory of concepts and their combinations, referred to as the State COntext Property theory (SCOP) (e.g., Aerts, Gabora, & Sozzo, 2013; Gabora & Aerts, 2002). As such, it takes seriously the need to formally model and study the chameleon-like way concepts change in response to new contexts, as well as the ill-formed, intermediate, or “half-baked” states an idea can be in as it is being mulled over (e.g., Gabora & Carbert, 2015). Using data from a study in which participants rated the typicality of exemplars of a concept for different contexts, SCOP was able to model how the typicality of different contexts changes during a shift from a convergent (analytic) to a divergent (associative) mode of thought, such that seemingly atypical exemplars of the concept (e.g., PILON as an exemplar of the concept HAT) can emerge (Veloz, Gabora, Eyjolfson, & Aerts, 2011).

This conception of convergent and divergent thought is consistent with the widely held view that divergent thought is conducive to insight, abduction, viewing situations from new perspectives, escaping fixation, and insight, while convergent thought is conducive to logic and the refinement of ideas. On the face of it, it is not obvious that fluency, or the capacity to generate many solutions, should equate with the kind of deep, prolonged, complex thought necessary for many creative accomplishments. However, if divergent thought is conceived of in terms of the capacity to conceive of the state of the problem or task in a new context, which yields a new state of the problem, and so on recursively until psychological entropy reaches an acceptable level, it becomes natural to equate divergent thinking with the kind of deep, prolonged, complex thought necessary for even big-C creativity.

The Evolution of Convergent and Divergent Thought

Let us now examine how evolutionary considerations bear on the question of how divergent and convergent thinking problems are most fruitfully conceived. Does there exist a mechanism by which the brain could have evolved the capacity to engage in two kinds of thought processes, one for problems for which there is only one solution, and the other for problems that afford multiple solutions, as conventional views of convergent and divergent thinking would suggest? The answer must be no, for how could a brain even know, when the problem is first encountered, how many solution paths there are? Indeed, as strikingly demonstrated by the Indian mathematician Srinivasa Ramanujan, problems that are initially thought to have only one solution may later be revealed to be solvable by other means.

Now let us consider: Does there exist a mechanism by which the brain would evolve the capacity to vary the extent to which context-specific aspects of a situation cause activation of the atypical yet potentially relevant properties that drive creative associations, as suggested by the view of convergent and divergent thinking proposed here? The answer is yes.

More specifically, a multifaceted program of research has been exploring the hypothesis that open-ended cultural evolution came about through two temporally distinct cognitive transitions (Gabora, 2001, 2013; Gabora & Aerts, 2009; Gabora & Kaufman, 2010; Gabora & Kitto, 2013; Gabora & Steel, in press). First, the emergence of *Homo*-specific culture approximately two million years ago, characterized most notably by the onset of primitive tool use, resulted from localized clustering of concepts, enabling the redescription and chaining of thoughts and actions, and the capacity for a stream of thought. This enabled a limited form of divergent thinking involving close associates but not remote ones.

Second, fully cognitive modernity and what Mithen (1998) refers to as the birth of art, science, and religion, following the appearance of anatomical modernity after 200,000 years ago during the Middle–Upper Paleolithic resulted from the onset of contextual focus (CF): the ability to shift along the spectrum from an extremely convergent mode on the one hand to an extremely divergent mode on the other, involving remote associates as well as close ones. Thereafter, the fruits of divergent thought could now be used as ingredients for convergent thought, and vice versa. This paved the way for cognitive integration, which enabled the ongoing assimilation of new experiences and accommodation of the network of previous experiences.

It has been proposed that the onset of CF was made possible by a mutation of the FOXP2 gene known to have occurred in the Paleolithic period (Chrusch & Gabora, 2014). Although FOXP2 was initially called the “language gene,” further research revealed that it is not uniquely associated with language. This suggests that the modified form of FOXP2 may have enabled the fine-tuning of the neurological mechanisms underlying the more general capacity to tailor their mode of thought to the situation at hand.

The proposal that the cultural transition of the Middle/Upper Paleolithic was due to the onset of contextual focus is consistent with Mithen’s (1998) hypothesis that it was due to the onset of cognitive fluidity – the capacity to explore, map, and transform conceptual spaces across different knowledge systems – for contextual focus would enable one to engage in cognitive fluidity when it was appropriate, and then shift back to a more convergent mode of thought when unnecessary associations would be a distraction.

This two-transition theory is supported by simulations of chaining and CF carried out using an agent-based model of cultural evolution in which agents invent ideas for actions and imitate the fittest of their neighbors’ actions (Gabora, Chia, & Firouzi, 2013). The mean fitness and diversity of actions across the model society increased with chaining, and even more so with CF, consistent with the hypothesis that these simulations broadly capture at an algorithmic level the mechanisms underlying the two cultural transitions. CF was particularly effective when the environment changed, which supports its hypothesized role in escaping fixation. CF has also been implemented in computational models of creativity, resulting in complex and fascinating works of music (Bell & Gabora, 2016) and art (DiPaola, & Gabora, 2009; McCaig, DiPaola, & Gabora, 2016).

Summary, Conclusions, and Practical Implications

By looking at the neural basis and evolution of creative thinking, it becomes apparent that creative thinking might diverge, not in the sense that it (necessarily) results in the generation of multiple ideas, but in the sense of construing each concept in a manner that blurs distinctions between it and other concepts, thereby inviting associations. It is interesting that this is analogous to the way that “divergent” is used with respect to light; divergent light does not consist of multiple small, focused beams, but rather a diffuse beam.

The proposed conception of divergent and convergent thinking suggests that conventional creativity tests as they are commonly used in educational and vocational settings may not be ideal. Both conventional tests of divergent thinking (such as the alternate uses test, which involves questions such as “How many uses can you think of for a brick?”) and of convergent thinking (such as the RAT discussed previously) may be assessing only a minor aspect of what the creative process entails. Creativity may be largely about tuning one's mode of thought in a context-specific manner such that each concept's halo of potential associations matches the specifics of the task and how far along one is in it. To tap into this, it may be necessary to use a new breed of creativity tests that investigate how individuals shift between divergent and convergent modes of thought over the course of a creative task. Such tests are just beginning to be developed (e.g., Armen, 2015; Pringle, 2011; Pringle & Sowden, 2016; Sowden, Pringle, & Gabora, 2015).

Acknowledgments

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Part II

Pharmacology and Psychopathology

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5 Stress, Pharmacology, and Creativity

David Q. Beversdorf

In the discussion of the neural mechanisms involved in creativity, it is important to gain an understanding of the conditions that impact optimal performance on creativity tasks. Stress is an important factor, long known to impair performance on tasks requiring creativity in healthy individuals (Martindale & Greenough, 1973). The effects of stress are mediated by pharmacological systems, and as such, discussion of stress and pharmacological effects are intertwined. Stress is known to increase activity of the noradrenergic system (Kvetnansky,Pacak, Sabban, Kpoin, & Goldstein, 1998; Ward et al., 1983), as well as the hypothalamic–pituitary–adrenal (HPA) axis. Drugs that block the noradrenergic system in the brain, specifically via action on β-adrenergic receptors, have long been used to mitigate stress-induced impairment in performance on tasks including public speaking or test-taking in anxiety-prone individuals (Faigel, 1991; Lader, 1988; Laverdue & Boulenger, 1991). Exploration of these mechanisms will allow a greater understanding of the processing of information involved in creativity. Additionally, as discussed below, understanding the links between stress, pharmacology, and creativity may also allow a greater opportunity for clinical interventions. Most research has focused on the catecholaminergic systems – the dopaminergic system and the noradrenergic system – but evidence is beginning to be explored for other systems as well. A greater volume of literature exists for the pharmacological effects on other executive functions highly interrelated with creativity, such as set-shifting and working memory. However, some evidence suggests that the distinctions between creativity and these other executive functions may also be quite critical, as will be discussed.

Stress and the Noradrenergic System

While stress is well known to increase activity of the noradrenergic system (Kvetnansky et al., 1998; Ward et al., 1983), it is the effects of performance and test anxiety that have led to the understanding of the role of the noradrenergic system in creativity. Propranolol, a centrally acting β-adrenergic antagonist, has long been used for stress-induced impairment in performance on tasks including public speaking in anxiety-prone individuals (Lader, 1988; Laverdue & Boulenger, 1991). Furthermore, research involving healthy adolescents with a history of stress-induced cognitive impairment during exams has demonstrated that treatment with the beta-adrenergic antagonist propranolol significantly improved scores on the Scholastic Aptitude Test (SAT) (Faigel, 1991). However, the effects of stress and the noradrenergic system on cognition are not limited to patients with known stress-induced cognitive impairment. Stress has long been known to impair performance on tasks requiring creativity in healthy individuals (Martindale & Greenough, 1973). More recently, administration of a well-characterized social evaluative stressor involving public speaking and mental arithmetic, the Trier Social Stress Test (Kirschbaum,Pirke, & Hellhammer, 1993), resulted in impaired performance on creative verbal problem-solving requiring flexibility of access to lexical, semantic, and associative networks in individuals without any history of anxiety-related disorders (Alexander et al., 2007). This impairment was reversed by the administration of propranolol (Alexander et al., 2007). This effect on individuals without any history of an anxiety-related disorder suggests that the effects of stress and the noradrenergic system represent a fundamental aspect regulating cognitive performance, not a phenomenon limited to specific patient populations. However, it should be noted that the effect of propranolol in this study does not exclusively implicate the noradrenergic system, because propranolol has also been shown to block the corticosterone-induced impairment of working memory (Roozendaal, McReynolds, & McGaugh, 2004), the potential implications of which will be discussed later.

The locus coeruleus contains the majority of neurons in the central nervous system, sending efferents throughout the brain (Barnes & Pompeiano, 1991) (Figure 5.1), thus supporting an effect on such a distributed function such as creativity. Effects of the noradrenergic system outside the setting of stress, though, are more dependent on the situation. For example, performance on an anagram task is better after administration of the centrally and peripherally acting beta-adrenergic antagonist propranolol than after the noradrenergic agonist ephedrine (Beversdorf, Hughes, Steinberg, Lewis, & Heilman, 1999; Heilman, Nadeau, & Beversdorf, 2003). Performance on the anagram task is also better after administration of propranolol than after the peripheral-only beta-adrenergic antagonist nadolol (Beversdorf, White, Cheever, Hughes, & Bornstein, 2002), suggesting that this effect of propranolol is mediated centrally rather than as a result of peripheral feedback. Central mechanisms are consistent with the effect of norepinephrine on the signal-to-noise ratio of neuronal activity within the cerebral cortex (Hasselmo, Linster, Patil, Ma, & Cecik, 1997) as well as the correlation between the electronic coupling of noradrenergic neurons in the monkey cortex and proportions of goal-directed versus exploratory behavior (Usher, Cohen, Servan-Schreiber, Rajkowski, & Aston-Jones, 1999). However, in each of the anagram studies, performance on propranolol was better than on ephedrine or nadolol, but it did not significantly differ from placebo (Beversdorf et al., 1999, 2002). Subsequent research examined how task difficulty might relate to the drug's effect (Campbell, Tivarus, Hillier, & Beversdorf, 2008). A drug proposed to benefit a broad search of a network might be expected to yield a greater benefit when problems are more challenging, requiring greater access to the "noise" in the signal-to-noise ratio in order to solve the problem, as is discussed further below. In this exploration, propranolol was found to be beneficial for a range of verbal problem-solving tasks requiring network flexibility when the subject was struggling, and did not confer benefit, and in some cases impaired performance, when the subject was solving problems with ease (Campbell et al., 2008). The benefit was seen both for the subjects who had the greatest difficulty solving the problems, and for the most difficult problems across all subjects (Campbell et al., 2008). Also, potentially consistent with this, performance on creativity tasks has been found to be better in the setting of "leaky sensory gating" as indicated by the P50 ERP (Zabelina, O'Leary, Pornpattananangkul, Nusslock, & Beeman, 2015). Propranolol can benefit performance on verbal problem-solving for the easiest problems in situations where there is upregulated activity of the noradrenergic system due to cocaine withdrawal (Kelley, Yeager, Pepper, & Beversdorf, 2005, Kelley, Yeager, Pepper, Bornstein, & Beversdorf, 2007) and psychosocial stress (Alexander et al., 2007), or where there is anatomic rigidity of the language network due to conditions such as autism spectrum disorder (ASD) (language network: Beversdorf, Narayan, Hillier, & Hughes, 2007a; convergent task effects: Beversdorf,

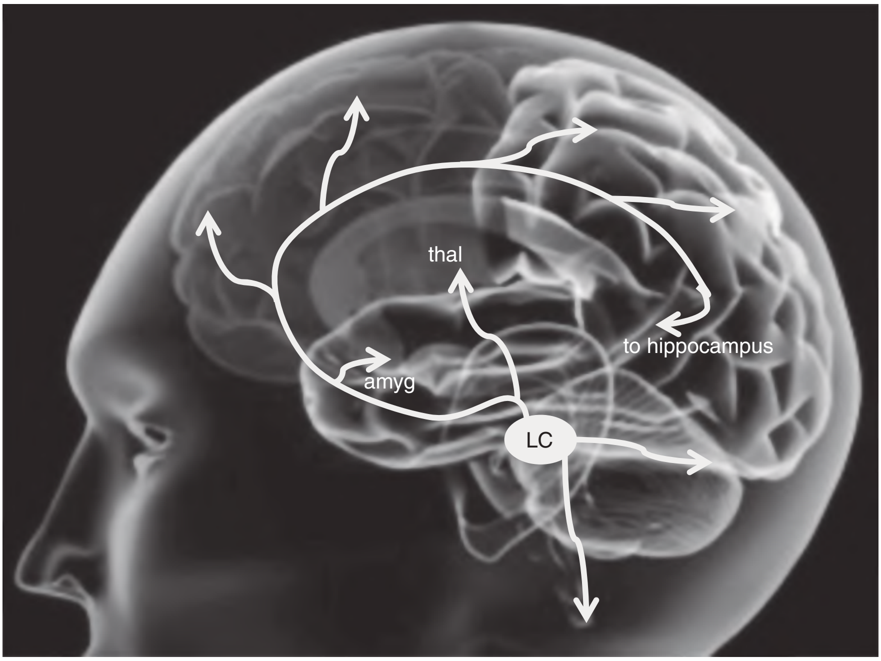

Figure 5.1 Noradrenergic pathways. The locus coeruleus (LC) projects posteriorly to the cerebellum and up to the thalamus (thal) and amygdala (amyg), as well as throughout the neocortex along a pericingular tract, also terminating posteriorly at the hippocampus (Heimer, 1995). The descending fibers to the spinal cord are also shown. Not shown is the lateral tegmental noradrenergic system, which also projects to the amygdala and down to the spinal cord. For a color version of this figure, see the color plate section.

Carpenter, Miller, Cios, & Hillier, 2008; Zamzow et al., 2017; divergent task effects: Beversdorf et al., 2011) and benefits are also seen for naming in Broca's aphasia due to stroke (Beversdorf et al., 2007b). More recently, these benefits in ASD with propranolol have also been observed in the social domain (Zamzow et al., 2014, 2016).

The variation in the effect of noradrenergic drugs between patient groups, as observed in cocaine withdrawal, ASD, and aphasia, may also be important in the use of adrenergic drugs in attention deficit disorder. Early theories proposed that arousal and optimal performance might be related on an inverted U-shaped curve (Yerkes & Dodson, 1908), suggesting such a relationship for the noradrenergic system. While markedly increased arousal or noradrenergic tone might result in hyperarousal and inability to perform a task in most individuals, a person with attention deficit disorder might be at baseline at a suboptimal point on the inverted U-shaped curve and require stimulants to perform optimally. Animal data suggest that there is an optimal point of tonic activity of the locus ceruleus which tends to support the emergence of phasic activity, associated with focused or selective attention (Aston-Jones & Cohen, 2005; Aston-Jones, Rajkowski, & Cohen, 1999). Noradrenergic transmission is known to be genetically weaker in some patients with attention deficit disorder (Arnsten, 2007). The effects of drugs on creativity in this population warrant further study. Preliminary evidence suggests that the effect of stimulants on creativity is limited (Farah, Haimm, Sankoorikal, Smith, & Chatterjee, 2009).

The relationship between noradrenergic tone and performance on creative verbal problem-solving tasks can also be observed in the performance impacts of alterations in noradrenergic tone induced by changes in posture (Lipnicki & Byrne, 2005), sleep phase (Stickgold, Hobson, Fosse, & Fosse, 2001), and vagal nerve stimulation (Ghacibeh, Shenker, Shenal, Uthman, & Heilman, 2006). Rapid eye movement (REM) sleep, a state associated with decreased noradrenergic activity, enhances integration of unassociated information for creative problem-solving (Cai, Mednick, Harrison, Kanady, & Mednick, 2009; Stickgold et al., 2001). These effects appear to be specific to the noradrenergic system and not due to general anti-anxiety effects, because such cognitive effects do not appear to occur with non-adrenergic anxiolytics (Silver, Hughes, Bornstien, & Beversdorf, 2004).

Evidence from models derived from activity in brain slice preparations support an effect of norepinephrine on the signal-to-noise ratio of neuronal activity within the cerebral cortex (Hasselmo et al., 1997). Presumably, propranolol increases access to “noise,” which in this case would be represented by increased associational input that might be adaptive for solving more difficult problems where the most immediate response is not optimal (Alexander et al., 2007). In one population characterized by decreased flexibility of network access (Beversdorf et al., 2007a), a potential imaging marker is observed. Decreased functional connectivity on fMRI, or a decrease in the synchrony of activation between activated brain regions, is observed for long distance cortico-cortical connections during language and executive function tasks in ASD (Just, Cherkassky, Keller, & Minshew, 2004; Just, Cherkassky, Keller, Kana, & Minshew, 2007), as well as in other conditions believed to be related to the underconnectivity between distant cortical regions in ASD (Belmonte et al., 2004). Recent evidence suggests that propranolol increases functional connectivity on fMRI in ASD, lending some support to the proposed mechanism of action of propranolol on network access (Narayanan et al., 2010). It is not clear whether the noradrenergic system is dysregulated in ASD (Martchek, Thevarkunnel, Bauman, Blatt, & Kemper, 2006; Minderaa, Anderson, Volkmar, Akkerhuis, & Cohen, 1994). However, others have proposed that the behavioral effects of fever in ASD (Curran et al., 2007) may be related to normalization of a developmentally dysregulated noradrenergic system in ASD (Mehler & Purpura, 2009). Regardless of the ambient activity of the noradrenergic system in ASD, network rigidity in ASD (Beversdorf et al., 2007a) and the suggested effect of propranolol on network access (Campbell et al., 2008) support a potential for benefit from noradrenergic agents in ASD. Furthermore, case series study has suggested a benefit in both social and language domains in ASD with beta-adrenergic antagonists (Ratey et al., 1987), in addition to the benefits observed with this single-dose psychopharmacological challenge studies described above. The effect of propranolol on task performance has not yet been incorporated in imaging studies, as the previous imaging study assessed functional connectivity with fMRI (fcMRI) during a task where all subjects perform at ceiling (Narayanan et al., 2010).

The noradrenergic system, of course, has a range of other behavioral effects. The noradrenergic system is critical in arousal (Coull, Frith, Dolan, Frackowiak, & Grasby, 1997, Coull, Jones, Egan, Frith, & Maze, 2004; Smith & Nutt, 1996). The prefrontal cortex, important in a range of types of cognitive flexibility (Duncan, Burgess, & Emslie, 1995; Eslinger & Grattan, 1993; Karnath & Wallesch, 1992; Robbins, 2007; Vikki, 1992), has afferent projections to the locus coeruleus in primates (Arnsten & Goldman-Rakic, 1984), which contains the majority of noradrenergic neurons that project throughout the central nervous system (Barnes & Pompeiano, 1991). The cognitive flexibility as assessed by verbal problem-solving tasks, such as anagrams and the compound remote associates task (Bowden & Jung-Beeman, 2003), involves a search through a wide network in order to identify a solution (“unconstrained flexibility”), and generally improves with decreased noradrenergic activity. Other cognitive flexibility tasks such as the Wisconsin Cart Sort Test (Heaton, 1981) involve set-shifting between a limited range of options ("constrained flexibility"), and may not be modulated by the noradrenergic system in the same manner, even potentially benefitting from increased noradrenergic activity (Aston-Jones & Cohen, 2005; Usher et al., 1999). Decreased noradrenergic activity appears to benefit tasks such as anagrams when subjects are struggling or challenged by stressors (Alexander et al., 2007, Campbell et al., 2008), whereas increased set-switching on a two-alternative forced-choice task is associated with increased noradrenergic tone in primate studies (Aston-Jones & Cohen, 2005; Usher et al., 1999). "Constrained" flexibility can be further subdivided into intradimensional and extradimensional set-shifting (Robbins, 2007). Intradimensional shifts require shifting to responses to novel sets of stimuli from within the same sensory domain (such as shifting from choosing between two odors to responding to two novel odors), and extradimensional shifts require shifting to stimuli from a different sensory domain (such as shifting from choosing between two odors to responding to two textures). The dopaminergic system appears to affect intradimensional set-shifting (Robbins, 2007), while the noradrenergic system, specifically by action on the alpha-1 receptor, appears to modulate performance on extradimensional set-shifting (Lapiz & Morilak, 2006; Robbins, 2007). The beta adrenergic receptors in the noradrenergic system, though, appear to modulate "unconstrained" flexibility (Alexander et al., 2007; Beversdorf et al., 1999, 2002). A systematic exploration contrasting the effects of the noradrenergic system on intradimensional and extradimensional set-shifting as well as creative problem-solving is warranted. Exploration of such comparisons has been initiated in an animal model, revealing no effects of beta-adrenergic antagonists on reversal learning, intradimensional set-shifting, or extradimensional set-shifting, but significant benefit on the requirement for the rodent to shift to a novel solution in order to obtain reward (Hecht, Will, Schachtman, Welby, & Beversdorf, 2014). Furthermore, while previous work has explored the effects of propranolol on convergent tasks among "unconstrained cognitive flexibility" tasks, involving problem-solving, where one solution is the product of the cognitive process, such as finding the single correct response on the compound remote associates task or the correct word that solves an anagram (Alexander et al., 2007, Campbell et al., 2008), effects are not known on divergent tasks among the "unconstrained cognitive flexibility" tasks, where subjects are required to produce multiple alternative responses. Noradrenergic agents are also known to have a range of other cognitive effects, including effects on motor learning (Foster, Good, Fowlkes, & Sawaki, 2006), response inhibition (Chamberlain, Muller, Blackwell, Robbins, & Sahakian, 2006b), working memory, and emotional memory (Chamberlain et al., 2006a).

Furthermore, stress is well known to affect the HPA axis as well as the noradrenergic system, and the effects are difficult to disentangle, as propranolol can also block downstream HPA activation (Roozendaal et al., 2004). Administration of cortisol is associated with a number of effects, including impaired memory (de Quervain, Roozendaal, Nitsch, McGaugh, & Hock, 2000; Het, Ramlow, & Wolf, 2005), and enhanced response inhibition (Shields, Bonner, & Moons, 2015). Therefore, future work must systematically disentangle the roles of the adrenergic system and the HPA axis in the effect of stress on cognitive processes associated with creativity.

The noradrenergic effect on emotional memory deserves particular comment, due to a potentially important clinical role. Centrally acting beta-adrenergic receptor antagonists are known to reduce the enhancement of memory resulting from emotional arousal (Cahill, Prins, Weber, & McGaugh, 1994; van Stegeren, Everaerd, Cahill, McGaugh, & Gooren, 1998). This may contribute to the development of intrusive memories in clinical conditions such as posttraumatic stress disorder (Ehlers et al., 2002, Ehlers, Hackmann, & Michael, 2004; Smith & Beversdorf, 2008). Research has explored the role of propranolol in the development of posttraumatic stress disorder, by interfering with reconsolidation (Pitman et al., 2002; Vaiva et al., 2003). Alpha-1 antagonists have similarly revealed benefit in patients with posttraumatic stress disorder (Arnsten, 2007). More recently, propranolol has been used to block the return of fear when combined with exposure therapy in phobias (Kroes et al., 2015). The relationship between creativity and the emotional effects of the noradrenergic system are in need of further exploration.

In the periphery, alpha-2 adrenergic agonists inhibit release of norepinephrine presynaptically, which suggests that they would have a similar effect as the postsynaptic beta-adrenergic antagonists. In fact, both are used clinically for the control of elevated blood pressure. However, alpha-2 agonists have distinct cognitive effects. High-dose clonidine, an alpha-2 agonist, has been shown to improve immediate spatial memory in aged monkeys (Arnsten, Cai, & Goldman-Rakic, 1988, Arnsten & Leslie,1991), an effect also found in younger monkeys (Franowicz & Arnsten, 1999), and believed to be mediated by action at the prefrontal cortex (Li, Mao, Wang, & Mei, 1999). Lower doses of clonidine, those that are typically utilized clinically in humans, demonstrate varying results at varying doses, including impaired visual working memory, impulsive responses on planning tasks, and varying effects on spatial working memory (Coull, Middleton, Robbins, & Sahakian, 1995; Jäkälä et al., 1999). Pharmacological stimulation of the postsynaptic alpha-2A subtype of adrenoreceptors decreases noise and results in beneficial effects for attention deficit disorder patients (Brennan & Arnsten, 2008). However, alpha-2 agonists do not appear to have the effect on creative verbal problem-solving that beta-adrenergic antagonists have (Choi, Novak, Hillier, Votolato, & Beversdorf, 2006).

Less is known about the specific cognitive effects of beta-1 and beta-2 adrenergic receptors. However, in one animal study, endogenous beta-1 selective activation impaired working memory (Ramos et al., 2005). A subsequent study demonstrated that beta-2 selective agonists enhance working memory in aging animals (Ramos, Colgan, Nou, & Arnsten, 2008), suggesting opposing effects between beta-1 and beta-2 receptors on working memory, and explaining the lack of effect of the nonspecific beta-antagonist propranolol on working memory in previous research (Arnsten & Goldman-Rakic, 1985; Li & Mei, 1994). Further research will be necessary to better understand the specific cognitive effects due to action at selective subtypes of beta (beta-1 and beta-2) receptors.

Dopaminergic System

A suggestion as to the potential role of the dopaminergic system in creativity came from the effects on the semantic network as observed in priming studies, since the ability to search within the semantic network is a critical component of both semantic priming and verbal creativity tasks. In 1996, Kischka et al. demonstrated in a priming experiment in healthy individuals that word recognition occurs more rapidly when presented 700 ms after exposure to another directly related or indirectly related word. However, after administration of L-dopa, the precursor for dopamine, only words presented after directly related words are recognized quickly. A role of the dopaminergic system in restriction of the semantic network in priming was proposed. Spreading activation of either a directly or indirectly related word facilitated word recognition without L-dopa, but only the directly related word facilitated word recognition with L-dopa. This effect appears to be sensitive to the time between the initial and target stimuli, likely a reflection of the effects of the timing of spreading activation. Subsequent research by Angwin et al. (2004) demonstrated that L-dopa affected both direct and indirect priming with an interstimulus interval of 500 ms, but had no affect at 250 ms. This finding would seem consistent with what might be expected with an effect on a widely distributed network (Alexander et al., 2007, Campbell et al., 2008). However, because L-dopa is a dopamine precursor, it remained unclear as to which specific dopamine receptors might be responsible for the priming effect. Studies in healthy volunteers (Roesch-Ely et al., 2006), in addition to studies in patients with Parkinson's disease (Pederzolli et al., 2008), suggest that the priming effect is mediated by action on the D1 receptor.

In order to begin to examine how dopaminergic agents might affect semantic networks, the effect of L-dopa on functional connectivity during fMRI was examined using a non-priming language task: a word categorization task. An isolated increase in connectivity was observed with L-dopa between the left fusiform gyrus and the receptive language areas, with no other region pairs affected (Tivarus, Hillier, Schmalbrock, & Beversdorf, 2008). Because the left fusiform gyrus is considered the visual word form receptive area (Beversdorf, Ratcliffe, Rhodes, & Reeves, 1997), this would appear to fit with the effects on priming, as the interaction between this fusiform area (critical for visual word form recognition) and Wernicke's area (critical for processing word meaning) would be essential for priming effects. However, because the predominant target among cortical areas for dopaminergic projecting fibers is the frontal lobe (Hall, Sedvall, Magnusson, Kopp, Halldin, & Farde, 1994; Lidow, Goldman-Rakic, Gallager, & Rakic, 1991) (Figure 5.2), such an effect of L-dopa on these posterior regions seems unexpected. Subsequent evidence using independent component analysis of fMRI data during language tasks suggests that the posterior effects of L-dopa may be mediated indirectly by the frontothalamic connections from the areas containing the frontal projections of the dopaminergic fibers (Kim, Goel, Tivarus, Hillier, & Beversdorf, 2010). Subsequent fMRI studies examining the effect of L-dopa during priming revealed changes in region-of-interest (ROI) activation with drug in the dorsal prefrontal cortex, anterior cingulate, left rolandic operculum, and left middle temporal gyrus (Copland, McMahon, Silburn, & de Zubicaray, 2009), which also may suggest an indirect frontal–posterior interaction.

However, in consideration of the research based on administration of L-dopa, it must be noted that L-dopa is also a precursor to norepinephrine. Further study has been initiated in hopes of disentangling the potential effects of the dopaminergic and noradrenergic systems on priming and creativity in problem-solving, both of which are known to be sensitive to the action of catecholaminergic agents (dopamine and norepinephrine) on semantic networks (Campbell et al., 2008; Kischka et al., 1996). Dopaminergic agonists were found to have no effect on creativity in verbal problem-solving (Smyth & Beversdorf, 2007), and noradrenergic agents did not appear to affect priming in the manner observed with dopaminergic agents (Cios, Miller, Hillier, Tivarus, & Beversdorf, 2009). This appears to suggest a role for the dopaminergic system (but not the noradrenergic system) on automatic searches of the semantic network as with word recognition (Cios et al., 2009; Kischka et al., 1996), and a role for the noradrenergic system (but not the dopaminergic system) on controlled searches of the semantic network as with verbal problem-solving (Campbell et al., 2008; Smyth & Beversdorf, 2007).

Despite these findings, other recent research has suggested a more direct relationship between the dopaminergic system and creativity. Studies examining rate of eyeblink, proposed as a marker of dopaminergic activity (Groman et al., 2014), demonstrated an inverted U-shaped relationship between eyeblink rate and creativity as assessed by an alternate uses task (AUT) and the remote associates task (RAT) (Chermahini & Hommel, 2010). Genetic studies demonstrate

Figure 5.2 Dopaminergic pathways. Projections from the substantia nigra (SN) to the striatum are demonstrated, as are projections from the ventral tegmental area (VTA) to the amygdala (amyg), ventral striatum, and frontal cortex (Heimer, 1995). Not shown are the tuberoinfundibular and posterior hypothalamic dopaminergic systems. For a color version of this figure, see the color plate section.

a relationship between D2 receptor polymorphisms and a composite creativity score as well as performance on verbal creativity, as assessed by object use fluency and sentence fluency from three words (Reuter, Roth, Holve, & Hennig, 2006). Catechol-*O*-methyltransferase (*COMT*) gene polymorphisms, critical for the metabolism of both norepinephrine and dopamine, have been shown to affect performance on insight-based problem-solving tasks (Jiang, Shang, & Su, 2015). A positive association has been found in the relationship between gray matter volume in dopaminergic subcortical regions as well as the right dorsolateral prefrontal cortex and divergent thinking (fluency for unusual uses and unimaginable things) with voxel-based morphometry on MRI (Takeuchi et al., 2010), and a negative association in the relationship between thalamic D2 receptor densities and performance on verbal, figural, and numerical fluency tasks with receptor binding studies using positron emission tomography (de Manzano, Cervenka, Karabanov, Farde, & Ullén, 2010). A case study describing changes in artistic behavior with dopaminergic agonists in Parkinson's disease has also been proposed as evidence for a relationship between the dopaminergic system and creativity (Kulisevsky, Pagpnabarraga, & Martinez-Corral, 2009), but the effects on interest in (as well as obsession with) artistic output and effects on style in such cases are hard to disentangle from other aspects of creativity (Chatterjee, Hamilton, & Amorapanth, 2006). Enhanced performance on several creativity-associated tasks, though, has recently been reported under dopaminergic therapy in Parkinson disease (Faust-Socher, Kennet, Cohen, Hassin-Baer, & Inzelberg, 2014). While this array of indirect supportive data for a role for the dopaminergic system in creativity is of interest, the distinction between the roles of the noradrenergic and dopaminergic systems in creativity is in need of further study.

The dopaminergic system has a range of other cognitive effects, including aspects of executive function closely related to creativity, in addition to its well-known effects on the motor system. Research in animal models has demonstrated varying effects of dopaminergic agents on set-shifting tasks, differing according to which receptor subtype each agent impacts (Floresco, Magyar, Ghods-Sharifi, Vexelman, & Magyar, 2005). Among set-shifting tasks, this effect appears to be specific to intradimensional set-shifting (Robbins, 2007). Whereas agonists for both D1 and D2 receptors did not affect set-shifting, D2 antagonists impaired set shifting in rodents (Floresco, Magyar, Ghods-Sharifi, Vexelman, & Tse, 2006; Stefani & Moghaddam, 2005), an effect also observed in humans (Mehta, Manes, Magnolfi, Sahakian, & Robbins, 2004). In further support of a role of the dopaminergic system in executive function, ability to maintain and flexibly alter cognitive representations in response to environmental demands is known to be impaired in Parkinson's disease (Cools, 2006). Computational models propose that phasic stimulation of D2 receptors in the striatum drives flexible adaptation of cognitive representations which are maintained by the prefrontal cortex (Cohen, Braver, & Brown, 2002), which contrasts with the effect on priming which appears to be mediated by D1 receptors (Pederzolli et al., 2008; Roesch-Ely et al., 2006). Receptor specificity of effects on creativity is not known. It should be noted that the interaction between dopaminergic agonists and Parkinson's disease and their effect on cognition is complex for set-shifting as well as working memory. Early in Parkinson's disease, greater dopaminergic depletion in the dorsal striatum leads to impaired adaptation in responses and updating in working memory, which is improved by L-dopa, while working memory itself benefits less from the administration of L-dopa. However, L-dopa also can excessively enhance reward biases due to effects on the relatively intact ventral striatum (Cools, 2006). These other cognitive effects of the dopaminergic system are discussed further below.

Regarding effects on other related executive functions, in healthy subjects those with lower working memory capacity tend to benefit from increased prefrontal function with dopaminergic stimulation (Gibbs & D'Esposito, 2005; Kimberg, D'Esposito, & Farah, 1997). This is likely related to the fact that dopamine synthesis capacity in the striatum is related to working memory capacity, such that those with the least working memory capacity also have less dopamine, and therefore benefit from dopaminegic stimulation (Cools, Gibbs, Miyakawa, Jagust, & D'Esposito, 2008a), suggesting an inverted U-shaped relationship between performance and dopaminergic function. In animal models this effect on working memory appears to be mediated by action at the D1 receptor (Arnsten, Cai, Murphy, & Goldman-Rakic, 1994; Sawaguchi & Goldman-Rakic, 1991; Williams & Goldman-Rakic, 1995). Dopamine also appears to be critical for a range of other aspects of cognition involving frontal–subcortical circuits, including the temporal coupling of deliberation and execution during decision-making, as dopamine replacement reverses the delay specific to decision-related hesitations, independent of motor slowing, in situations requiring decision-making in uncertainty in patients with Parkinson's disease (Pessiglione et al., 2005).

Another critical role of dopamine has recently become apparent with the development of pathological gambling in the setting of treatment with dopaminergic agonists (Dodd et al., 2005; Gallagher, O'Sullivan, Evans, Lees, & Schrag, 2007). This has contributed to a greater understanding of the roles of dopamine in decision-making, revealing that dopamine neurons encode the difference between expected and received rewards, and interact with other neurotransmitter systems to regulate such decision making (Nakamura, Matsumoto, & Hikosaka, 2008). The relationship between this effect of dopamine and creativity is also in need of further exploration.

Other Systems

Neurons in the nucleus basalis, medial septal nucleus, and the diagonal band of Broca in the basal forebrain are the main sources of cholinergic projection throughout the neocortex and hippocampus (Selden, Gitelman, Salamon-Murayama, Parrish, & Mesulam, 1998). The cholinergic system is another neurotransmitter system involved in modulating the signal-to-noise ratio within the cortex by suppressing background intrinsic cortical activity (Hasselmo & Bower, 1992), thus modulating efficiency of cortical processing of sensory or associational information (Sarter & Bruno, 1997). Acetylcholine is particularly important for attentional performance (Sarter & Bruno, 2001). Studies in rodents demonstrate that acetylcholine is critical for both top-down and bottom-up processing of stimuli, mediated by action on the prefrontal cortex (Gill, Sarter, & Givens, 2000; Newman & McGaughy, 2008). Cholinergic dysfunction has been used as a model for Alzheimer's disease (Whitehouse et al., 1982), due to the significant degeneration of the cholinergic neurons in these patients. Among the two main subtypes of acetylcholine receptors, muscarinic receptors have been clearly demonstrated to interfere with encoding of new information with less of an effect on previously stored information (Hasselmo & Wyble, 1997). Blockade of nicotinic receptors has also revealed significant effects on memory in an age-dependent manner (Newhouse, Potter, Corwin, & Lenox, 1992, 1994). However, despite clear effects on signal-to-noise ratio in the cortex as well as memory effects, neither muscarinic nor nicotinic blockade resulted in effects on the type of unconstrained cognitive flexibility modulated by the noradrenergic system (Smyth & Beversdorf, submitted).

Our understanding of the role of individual neurotransmitter systems in cognition has progressed significantly in recent years. However, these systems do not act in isolation. Complex interactions occur between them, which are only beginning to be understood. For example, action at D2 dopaminergic receptors and at NMDA receptors appear to interact in their effects on set-shifting (Floresco et al., 2005, 2006; Stefani & Moghaddam, 2005). Also, as described above, the dopaminergic system appears to affect intradimensional set-shifting (Robbins, 2007), while the noradrenergic system, specifically by action on the alpha-1 adrenergic receptor, appears to modulate performance on extradimensional set-shifting (Lapiz & Morilak, 2006; Robbins, 2007). Noradrenergic innervation of dopaminergic neurons, by action on alpha-1 adrenergic receptors, is known to directly inhibit the activity of the dopaminergic neurons (Paladini & Williams, 2004). In addition, the effects of drugs on cognition also depend on location of action when isolated brain regions are studied (Cools & Robbins, 2004). Finally, the mechanism by which the regulatory neurotransmitters act is beginning to be more fully understood, with potential treatment options targeting these second messenger systems (Arnsten, 2007, 2009). These factors will all need to be accounted for in future studies of creativity.

The serotonergic system, with neurons in the dorsal raphe nucleus projecting throughout the forebrain and neocortex, has long been known for its effects on mood and other psychiatric issues, and is also responsive to stress (Malyszko, Urano, Takada, & Takada, 1994). However, recent research is revealing that the serotonergic system and its interaction with other neurotransmitter systems serve important cognitive roles as well. Recent evidence suggests that the balance between the serotonergic and dopaminergic systems appears to be critical for processing of reward and punishment (Krantz, Kasper, & Lanzenberger, 2010). The firing of midbrain dopamine neurons shows a firing pattern that reflects the magnitude and probability of rewards (Roesch, Calu, & Schoenbaum, 2007; Schultz, 2007). While tryptophan depletion enhances punishment prediction but does not affect reward prediction (Cools, Robonson, & Sahakain, 2008b), serotonergic neurons appear to signal reward value (Nakamura et al., 2008). Furthermore, prefrontal serotonin depletion affects reversal learning, but not set-shifting (Clarke et al., 2005). A potential role in creativity is also suggested for the serotonergic system. Performance on figural and numeric creativity tasks has been associated with polymorphisms of the tryptophan hydroxylase gene *TPH1* (Reuter et al., 2006), and both the number solved and the prevalence of use of insight on the compound remote associates task was positively associated with high positive mood (Subramaniam, Kounios, Parrish, & Jung-Beeman, 2008), also suggesting a role of the serotonergic system.

Conclusion

As our understanding of neurotransmitter interactions, localized effects, and other types of neurotransmitters and neuropeptides grows, it will also need to be put into context with our advances in understanding of second messenger systems and epigenetic regulatory factors to fully understand how cognitive processes such as creativity are carried out in the brain. Furthermore, the recently reported effects of transcranial direct-current stimulation on creativity task performance (Colombo, Bartesaghi, Simonelli, & Antonietti, 2015; Green et al., 2017; Milano et al., 2016) may relate to critical underlying regional neuropharmacological mechanisms.

In addition to the patient populations described above where certain aspects of creative performance may be affected, recent evidence has demonstrated relationships between genetic markers for schizophrenia, bipolar disorder, and professional affiliations associated with creativity in a large population study (Power et al., 2015). Better understanding of modulatory effects on performance on creativity tasks may result in clinical benefits for patients with a wide variety of clinical syndromes. This understanding may also allow for the possibility of optimization of performance in stressful situations where creativity may be impaired. Finally, nonpharmacological approaches that are likely related to pharmacological systems will have increasing importance, as several studies have shown positive effects of meditation on performance on creativity tasks (Ding, Tang, Tang, & Posner, 2014).

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6 Functional Neuroimaging of Psychedelic Experience: An Overview of Psychological and Neural Effects and their Relevance to Research on Creativity, Daydreaming, and Dreaming

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Introduction: A Very Brief History of Psychedelic Substances and Science

Humans have employed an incredible variety of plant-derived substances over the millennia in order to alter consciousness and perception (Schultes, Hofmann, & Rätsch, 2001). Among the innumerable narcotics, analgesics, "ordeal" drugs, and other psychoactive substances discovered and used in ritualistic contexts by cultures around the world, one class in particular stands out not only for its radical psychological effects, but also for the highly charged political and legal atmosphere that has surrounded it since its widespread adoption about 50 years ago: so-called psychedelic substances.

In the 1950s and 1960s, psychedelic substances that had been used for thousands of years in indigenous communities, particularly in Mesoamerica and the Amazon basin, were rediscovered by adventurous foreigners and introduced into Western societies that had been largely ignorant of the use of such substances for centuries, if not millennia (McKenna, Towers, & Abbott, 1984; Schultes, 1957; Wasson, 1958; Wasson, Hofmann, Ruck, & Smith, 2008). These substances soon spilled beyond the boundaries of traditional use (Tupper, 2008) and were rapidly adopted by the countercultural movement of the time (J. Stevens, 1987). Around the same time as this Western adoption of natural psychedelic substances, synthetic and semi-synthetic psychedelics were being discovered or rediscovered in research laboratories, most notably lysergic acid diethylamide (LSD) in 1943 (Hofmann, 1980) and ketamine in 1962 (C. L. Stevens, 1966).

Interest in these substances was not limited to the counterculture movement: scientists, psychiatrists, and others saw potential for psychological research (Lilly, 1972), enhancement of creative thinking (Harman, McKim, Mogar, Fadiman, & Stolaroff, 1966) and artistic appreciation (Huxley, 1954), and clinical value in psychotherapy (Pahnke, Kurland, Unger, Savage, & Grof, 1970) and the treatment of addiction (Krebs & Johansen, 2012). Military and espionage applications were also envisioned, leading to a now well-documented series of nonconsensual (and illegal) misadventures in psychedelic "research" by the Central Intelligence Agency in the USA (Lee & Shlain, 1992) and MI6 in the UK (Streatfeild, 2008).

Essentially all such substances were criminalized on an international scale in the wake of the United Nations' Single Convention on Narcotic Drugs (1961) and Convention on Psychotropic Substances (1971) (McAllister, 2000). With criminalization and its concomitant social stigma, research on psychedelics in humans effectively ceased for several decades. Given that many promising avenues of research were revealed by the early investigations of the 1950s and 1960s, this hiatus very likely hindered progress in the fields of neuroscience, psychology, and psychiatry (Nutt, 2014; Nutt, King, & Nichols, 2013).

Even as psychedelic research stalled, the neuroscientific tools available for understanding human brain function were advancing by leaps and bounds. Rapid technological developments led to remarkable improvements in the ability to image the metabolism and functioning of the human brain noninvasively and at high spatial and temporal resolutions, in particular with positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) (Huettel, Song, & McCarthy, 2004; Raichle, 2009; Savoy, 2001). These functional neuroimaging modalities were rapidly applied in the investigation of the neural bases of many uniquely (or at least largely) human cognitive capacities that were difficult or impossible to study in animal models, including language processing (McCarthy, Blamire, Rothman, Gruetter, & Shulman, 1993; Petersen, Fox, Posner, Mintun, & Raichle, 1988), visual imagery (Kosslyn, Thompson, & Alpert, 1997), creativity (Bekhtereva et al., 2000), dreaming (Maquet et al., 1996), meditation (Lazar et al., 2000; Lou et al., 1999), empathy (Farrow et al., 2001), and mentalizing (Fletcher et al., 1995) – all of which have since developed into burgeoning subfields with dedicated journals, conferences, and research groups, and hundreds, if not thousands, of investigations of their neural correlates. The first PET study of psychedelic experience was similarly reported early on (Vollenweider, Leenders, Scharfetter, Antonini, et al., 1997), but in contrast, relatively little functional neuroimaging research has followed over the subsequent two decades (see Table 6.1 for a list of functional neuroimaging studies of psychedelic experience).

Despite various practical, political, and legal hurdles, however, recent years have seen an acceleration of the timid renaissance in human psychedelic research (Kupferschmidt, 2014; Langlitz, 2007; Sessa, 2012b), paralleled by growing evidence that psychedelics are among the least harmful and least addictive pharmacological substances regularly used by humans (Nichols, 2004; Nutt, King, & Phillips, 2010; Nutt, King, Saulsbury, & Blakemore, 2007). The last few years have witnessed an increasing number of functional neuroimaging investigations of "classic" psychedelic substances such as psilocybin (Carhart-Harris, Erritzoe, et al., 2012; Carhart-Harris et al., 2013; Carhart-Harris, Leech, et al., 2012; Lebedev et al., 2015; Roseman, Leech, Feilding, Nutt, & Carhart-Harris, 2014; Vollenweider, Leenders, Scharfetter, Maguire, et al., 1997) and ayahuasca (Bouso et al., 2015; de Araujo et al., 2012; Palhano-Fontes et al., 2015; Riba et al., 2006), as well as substances with related effects, such as ketamine (Grimm et al., 2015; Pollak et al., 2015; Vollenweider, Leenders, Scharfetter, Antonini, et al., 1997). Additionally, a recent study has finally offered the first investigation of the neural correlates of the LSD state (Carhart-Harris et al., 2016). We summarize this research in Table 6.1, including the general stage(s) of the psychedelic experience each study investigated (note that we primarily include studies that investigated neural correlates of the psychedelic experience *per se*, but omit studies that investigated tasks performed under the influence of psychedelic substances).

This burgeoning functional neuroimaging research is beginning to provide long-sought answers to questions about the neural correlates of psychedelic experiences. The purpose of this chapter is to review this small but growing body of functional neuroimaging research, and address two key questions. The first is whether

Table 6.1 *Neuroimaging investigations of psychedelic experience.*

Study	**Modality**	**Substance**	**Stage(s) investigated**[a]
Vollenweider et al. (1997a,b)	PET	Psilocybin	Peak
Holcomb et al. (2001)	PET	Ketamine	Onset, core, peak, resolution
Långsjö et al. (2003)	PET	Ketamine	Core
Aalto et al. (2005)	PET	Ketamine	Core
Deakin et al. (2008)	fMRI	Ketamine	Onset
Carhart-Harris et al. (2012a)	fMRI	Psilocybin	Onset, core
Carhart-Harris et al. (2012b)	fMRI	Psilocybin	Onset, core
De Araujo et al. (2012)	fMRI	Ayahuasca	Core, peak
Scheidegger et al. (2012)	fMRI	Ketamine	Core, assimilation
Carhart-Harris et al. (2013)	fMRI	Psilocybin	Onset, Core
De Simoni et al. (2013)	fMRI	Ketamine	Onset
Driesen et al. (2013)	fMRI	Ketamine	Onset, core
Roseman et al. (2014)	fMRI	Psilocybin	Onset, core
Bouso et al. (2015)	Morphometric MRI	Ayahuasca	Sequelae
Grimm et al. (2015)	fMRI	Ketamine	Core
Joules et al. (2015)	fMRI	Ketamine	Onset, core
Khalili-Mahani et al. (2015)	fMRI	Ketamine	Core, peak, resolution
Lebedev et al. (2015)	fMRI	Psilocybin	Onset, core
Palhano-Fontes et al. (2015)	fMRI	Ayahuasca	Core
Pollak et al. (2015)	ASL (MRI)	Ketamine	Onset
Carhart-Harris et al. (2016)	ASL, fMRI, MEG	LSD	Onset, core, peak

Notes. [a] Refer to our classification scheme in Table 6.3.

ASL, arterial spin labeling; fMRI, functional magnetic resonance imaging; MEG, magnetoencephalography; MRI, magnetic resonance imaging; PET, positron emission tomography.

differential neural correlates accompany the various stages of psychedelic experience: for instance, are there specific neural correlates accompanying the initial transition from baseline; the core psychedelic experience; and so-called "peak" experiences? Second, although the psychedelic state has most often been compared with the psychological extremes of psychosis (Gonzalez-Maeso & Sealfon, 2009) or profound religious experience (Pahnke, 1969), we believe that much can be gained from a comparison with kindred but naturally occurring altered states of consciousness, specifically dreaming, daydreaming, and creative thinking – all of which bear similarities to the psychedelic experience in terms of their general tendency toward internally focused attention, their potential for insightful or novel patterns of thinking, and the greater or lesser prevalence of immersive, imagined sensory experience (Dittrich, 1998).

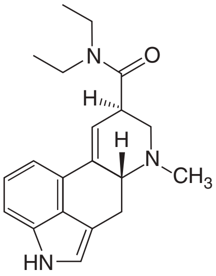
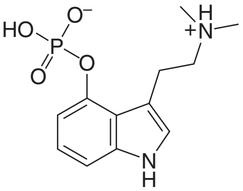
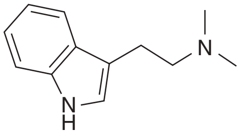
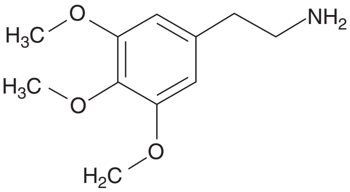
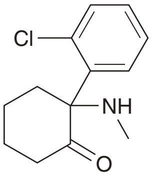
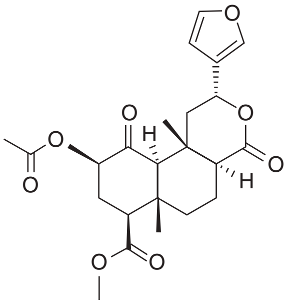
Overview of the Major Psychedelic Substances

There are about a half-dozen major psychedelic substances in widespread use (Table 6.2), but dozens, if not hundreds, of others have been identified in nature (Schultes et al., 2001) or synthesized in laboratories (Shulgin & Shulgin, 1997). The neurochemical mechanisms at the level of the synapse (i.e., pharmacokinetics and pharmacodynamics) are understood in broad outline for the widely used substances (Table 6.2), but the precise details are highly complex, poorly understood, and based almost exclusively on animal models (Nichols, 2004). The most salient finding to date is that many "classic" psychedelics appear to act primarily via the serotonin system, as agonists of the 5-HT_{2A} receptor in particular (Glennon, Titeler, & McKenney, 1984; Nichols, 2004). The structural simplicity of these substances at the molecular level (small in size and largely planar; Table 6.2) belies the profound influence they have on perception, memory, emotion, and sense of self, even at extremely low doses (in the microgram range in some cases).

Ketamine is not generally considered a classic psychedelic substance, but is instead typically classified as a "dissociative anesthetic," and has a distinct molecular mechanism of action (Table 6.2). Nonetheless, it can induce many experiences similar to those associated with "classic" psychedelics (Studerus, Gamma, & Vollenweider, 2010; Vollenweider & Kometer, 2010), and moreover (to anticipate our results somewhat) the large-scale neural activity engendered by ketamine appears to be appreciably similar to that elicited by serotonin agonists such as psilocybin. Ketamine is also the best-studied psychedelic substance in terms of the number and variety of functional neuroimaging studies conducted to date. We therefore include ketamine in our discussions here.

The Psychedelic Experience and its Relationship to Creativity, Daydreaming, and Dreaming

The psychedelic experience is by its very nature highly creative, often involving the generation of a high volume of novel ideas and insights; profuse visual, auditory, and somaesthetic hallucinations; and intense, widely valenced emotional experiences (Dittrich, 1998). These profound alterations in consciousness have most often been compared with either psychosis on the negative end of the spectrum (Vollenweider & Kometer, 2010) or transcendent religious and mystical experiences on the positive end of the spectrum (Pahnke, 1967, 1969). Less-sensational comparisons, however, can be made with the psychological experiences and neural correlates of more mundane "altered" states, including daydreaming, nighttime dreaming, and creative thinking. The main features of overlap are immersive visionary/hallucinated experiences (as in dreaming and, to a lesser extent, ble 6.2 *Overview of the major psychedelic substances.*

bstance ommon name)	**Main active constituent**	**Neurochemical mechanisms of action (main receptor affinity)**	**Chemical structure**	**Key references**
D/acid	Lysergic acid diethylamide	Serotonin agonist (esp. 5-HT$_{2A}$) Dopamine (all subtypes) Adrenoceptors (all subtypes)		Marona-Lewicka, Thisted, & Nichols, 2005; Nichols, 2004
agic mushrooms	Psilocybin	Serotonin (esp. 5-HT$_{2A}$; also 5-HT$_{1A}$, 5-HT$_{1D}$, 5-HT$_{2C}$)		Passie, Seifert, Schneider, & Emrich, 2002
ahuasca/DMT	*N*,*N*-dimethyltryptamine	Serotonin agonist (esp. 5-HT$_{2A}$; also 5-HT$_{1A}$, 5-HT$_{1B}$, 5-HT$_{1D}$, 5-HT$_{2B}$, 5-HT$_{2C}$)		Deliganis, Pierce, & Peroutka, 1991; Keiser et al., 2009; Ray, 2010
yote/mescaline	3,4,5-Trimethoxyphenethylamine	Serotonin agonist (esp. 5-HT$_{2A}$ and 5-HT$_{2C}$)		Monte et al., 1997; Nichols, 2004
ecial K	Ketamine	NMDA antagonist Opioid agonist		Brockmeyer & Kendig, 1995; Editorial, 1996; Jansen & Sferios, 2001; Kohrs & Durieux, 1998; Salt, Wilson, & Prasad, 1988
Salvia divinorum	Salvinorin A	κ-Opioid agonist		Roth et al., 2002

daydreaming); the loss of a sense of self (in peak experiences of creative thinking and inspiration, and to a lesser extent in dreaming as well); and in the need (in conscientious users, at least) to assess and evaluate the altered state experience in later periods of assimilation (as is common in creative idea generation, and in dreaming).

Relationship to Artistic, Scientific, and Philosophical Creation

Artists and other creative individuals have often reported using psychedelic substances in an effort to enhance creative output or novelty (Sessa, 2008), and some early experimental work suggested positive effects along these lines (Harman et al., 1966; Krippner, 1972). There are even reports (albeit anecdotal) of psychedelic experiences being centrally involved in major scientific breakthroughs, such as Kary Mullis' Nobel prize-winning discovery of the polymerase chain reaction (Mullis, 2010).

Although descriptions of the creative process tend to be more muted today, historically, many artists and poets have described entering an altered state of consciousness reminiscent of psychedelic experience (Kivy, 2001; McMahon, 2013; Murray, 1989). Indeed, Plato's theory of creative inspiration directly credited the possession of the artist by the Muse or other gods; the artist lost their own mind or self and entered a poetic "fury" or "frenzy" during which a higher force created *through* them (McMahon, 2013; Murray, 1996; Pieper, 1964). Plato even went so far as to directly compare the frenzy of artistic creation with the cultic rites of Dionysus, where participants were similarly filled with (probably substance-induced) ecstasy and enthusiasm (Murray, 1996). William Blake provides an excellent (if more modern) example: Blake's poetry and painting are all but unimaginable absent the visionary altered states that inspired them (Bloom, 1963). The loss of the sense of self in visionary states is in many ways reminiscent of core and peak psychedelic experiences, discussed in more detail below.

Similarly, although philosophy today brings to mind dry academic discussions and impenetrable texts, the search for philosophical truth in Ancient times strongly endorsed altered states of consciousness as a valid source of knowledge and understanding. The timeless mystical vision of Plato's Allegory of the Cave (Plato, Grube, & Plochmann, 1974) is probably the most well-known example, but many other Classical philosophers made visionary, mystical experience the foundation upon which they later built elaborate philosophical systems of their own creation, including Plotinus (Plotinus & Katz, 1950; Plotinus & MacKenna, 1969) and likely also Pythagoras (Burkert, 1972). Mystical experience has similarly played a fundamental role in the rich history of Eastern philosophy and spirituality, as especially apparent in Buddhist, Hindu, and Jain traditions (Sarma, 2011). In the fine arts, the sciences, and even philosophy, then, the notion that visionary and ego-dissolving altered states are a legitimate (perhaps even necessary) ground upon which to base creative output has a long history.

Another important parallel is that many theories of creativity propose a "two-stage" model, whereby initially generated ideas must then be subsequently evaluated for novelty and utility (Basadur, Graen, & Green, 1982; Beaty, Benedek, Silvia, & Schacter, 2016; Ellamil, Dobson, Beeman, & Christoff, 2012). We suggest that, similarly, an "ideal" psychedelic experience is not simply accepted uncritically, no matter how profound its insights might be, but is later evaluated and assimilated into prior knowledge structures, even as it may expand the boundaries or alter the form of these very structures (we call this the *assimilation* stage; see Figure 6.1 and Table 6.3). Another important similarity, then, is the need to subsequently evaluate the highly novel and creative experiences generated in the psychedelic state. The same principle is applied by those who pay close attention to dream experience: dreams are typically analyzed, interpreted, and assessed for significance and insights after the fact.

Table 6.3 *Phases and stages of psychedelic experience.*

Phase	Stage	Overview
Acute (0.5–12 hours)	Onset	Initial transition into the psychedelic state following ingestion of a substance
	Core	Sustained effects of the core psychedelic experience, often strongly visual in nature
	Peak	“Peak” experiences of ego-dissolution, mystical union
	Resolution	Denouement and “come-down”; the cessation of acute effects
Subacute (hours–days)	Assimilation	Lingering effects and insights immediately following the experience; evaluation and contemplation of acute experience
Long term (days–years)	Sequelae	Long-term effects on brain structure and function, personality, worldview, and other cognitive-affective variables

Notes. Various putative phases and stages of a typical psychedelic experience. The gray shading of the “peak” stage indicates that this stage may be much more rare and vary enormously in intensity as compared to the other stages.

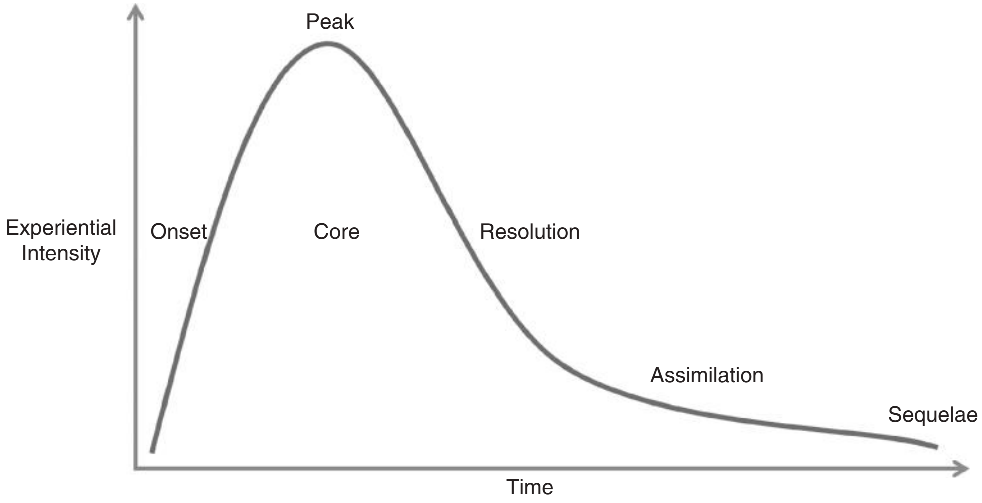


Figure 6.1 An idealized representation of the phases and stages of psychedelic experience. For a color version of this figure, see the color plate section.

Relationship to Daydreaming and Dreaming

Although the vividness and content of daydreaming are not widely appreciated, detailed experience sampling has revealed that mild-to-moderate visual imagery and fantasy are ubiquitous throughout our everyday lives (Fox, Nijeboer, Solomonova, Domhoff, & Christoff, 2013; Klinger, 2008; Klinger & Cox, 1987; Stawarczyk, Majerus, Maj, Van der Linden, & D’Argembeau, 2011). Dreaming is a more familiar example of a bizarre and visionary experience that each of us participates in every night; there are many parallels with intense psychedelic experience, including immersive visual imagery, highly novel and unusual patterns of thinking, intensive emotional experience, and a disrupted sense of self (Fox et al., 2013; Windt, 2010, 2015). Specific examples of parallel brain recruitment and subjective experience will be discussed as they arise throughout the remainder of this chapter.

Stages of Psychedelic Experience: Phenomenology and Neural Correlates

Users of psychedelic substances have long reported that a typical psychedelic experience is by no means uniform, but rather follows a general trajectory (Figure 6.1). It is tempting to simply map this experiential trajectory onto the putative concentrations of active substance in the blood and brain, but such a view fails on several counts. Research *does* suggest that various dimensions of psychedelic experiential intensity indeed increase in a dose-dependent fashion (Bowdle et al., 1998; Studerus, Kometer, Hasler, & Vollenweider, 2011; Vollenweider & Kometer, 2010), and so substance concentration may well follow a broadly similar trajectory in many cases. Nonetheless, a monotonic relationship between substance concentration and experiential intensity cannot explain the enormous influence of set (i.e., psychological expectations and cognitive-affective state of the individual) and setting (i.e., factors including physical environment, social milieu, and so on) (Nichols, 2004; Nour & Krzanowski, 2015; Sessa, 2012a). Moreover, it is increasingly well-documented that only some features of experiential intensity parallel substance concentration (Studerus et al., 2011): psychological and neural changes persist long after the acute phase of the psychedelic experience (Bouso et al., 2015; Griffiths et al., 2011; Griffiths, Richards, McCann, & Jesse, 2006; Studerus et al., 2011), and long after substance concentrations in the blood and brain are negligible or zero. On the psychological side, subsequent reflection upon, and evaluation of, the acute psychedelic experience, as well as alterations in mood and personality, may persist indefinitely, perhaps becoming less marked over time, but never diminishing entirely – i.e., diminishing asymptotically (Figure 6.1).

Our model of psychedelic phases and stages (Figure 6.1; Table 6.3) is meant merely as a crude preliminary scheme for beginning to parse and understand the growing body of functional neuroimaging evidence. Aside from the huge variability to be expected at the individual level, we hasten to underline the fact that our smooth curve of experiential intensity is merely an abstraction or idealization that does not take into account the complexity of a typical psychedelic experience, which can unfold unpredictably and with varying intensity. We therefore intend the model not as a hypothesis to be tested, but merely as a helpful classification scheme.

Onset

The *onset* stage corresponds to the initial transitional period following drug intake, during which subjective effects first start to take hold. Depending on a variety of factors, including the particular substance ingested and route of administration used, this stage can vary anywhere from as little as 30 seconds to over 60 minutes. Phenomenologically, this stage involves the initial changes in perception, cognition, internal thought, and sense of self. General physiological arousal often rises, resulting in some level of anxiety, increased heart-rate, and sometimes visual hallucinatory effects, in the case of classic psychedelics such as psilocybin and LSD (Hollister, 1984). With ketamine, on the other hand, the initial transition stage tends to be accompanied by impaired thought and a sense of dissociation from the body (Jansen & Sferios, 2001).

So far, only work with ketamine has directly investigated the neural correlates of this early stage of the psychedelic experience. In one study, Deakin and colleagues (2008) intravenously administered ketamine to 12 participants and observed minute-to-minute brain activity changes over a time course from 8 minutes pre- to 8 minutes post-infusion using fMRI.

The authors observed rapid onset, with peak subjective effects at 4–5 minutes following infusion (Deakin et al., 2008). The first significant neural effects observed were deactivations in medial orbitofrontal cortex and the temporal pole two minutes post-infusion (T2). Deactivation then spread to the subgenual anterior cingulate and frontopolar cortex at 3 minutes post-infusion (T3).

The T2 deactivations in the medial prefrontal cortex and the temporal pole were highly correlated with self-reported scores on “derealization” and “depersonalization” (Deakin et al., 2008). Additionally, medial orbitofrontal cortex deactivation was uniquely correlated with self-reported “thought disorder” and “hallucinations” (Deakin et al., 2008). These results are intriguing, because medial prefrontal cortex and temporopolar cortex are both key regions supporting a sense of self and internal streams of thought, such as mind-wandering, daydreaming, and other kinds of self-referential thinking (Andrews-Hanna, Smallwood, & Spreng, 2014; Ellamil et al., 2016; Fox, Spreng, Ellamil, Andrews-Hanna, & Christoff, 2015).

Overall, in line with the subjectively reported dissociative effects of ketamine, fMRI investigations suggest a deactivation of key midline brain areas involved in sustaining a coherent stream of thought and sense of self during the onset of ketamine-induced experiences. Intriguingly, these results parallel findings of more serious disruptions of the default network being associated with full-blown ego-dissolution in peak experiences (see below). The interested reader should consult another study investigating ketamine onset by Driesen and colleagues (2013).

Core Experience

The *core* stage of our model pertains to the bulk of a psychedelic experience, and can last anywhere from 10 minutes to upwards of 8 hours. The core stage has been explored in considerably more research, including independent work on psilocybin (Carhart-Harris, Erritzoe, et al., 2012), ayahuasca/DMT (Palhano-Fontes et al., 2015), ketamine (Långsjö et al., 2003), and most recently, LSD (Carhart-Harris et al., 2016) (refer to Table 6.1 for a full list of studies investigating the core stage). Although the core psychedelic experience can, of course, involve a nearly infinite range of effects, one of the most prevalent and predictable experiences, especially at high doses, is prominent visual imagery, illusions, and hallucinations. We therefore focus our discussion of the core experience on this ubiquitous feature of the psychedelic state.

One recent study investigated core experiences following intravenous injection of LSD using numerous noninvasive neuroimaging modalities (Carhart-Harris et al., 2016). A central result was increased cerebral blood flow and resting-state functional connectivity in visual cortex areas during the core LSD experience, and the finding that self-reported visual illusions and hallucinations correlated significantly with this altered activation in visual areas (Carhart-Harris et al., 2016). These results are intriguing because medial visual cortex areas are consistently activated during waking mind-wandering (Fox et al., 2015), which involves ubiquitous visual imagery (Fox et al., 2013; Klinger & Cox, 1987; Stawarczyk et al., 2011), as well as during REM sleep and dreaming – likewise characterized by vivid visual imagery and hallucinations (Domhoff & Fox, 2015; Fox et al., 2013; Schredl, 2010). Indeed, the cluster of increased visual cortex activation observed during the LSD experience overlaps strikingly with the clusters found in meta-analyses we conducted of the neural correlates of waking daydreaming (Fox et al., 2015) and nighttime dreaming (Fox et al., 2013) – presumably because this area is subserving the same function in each case (compare figure 1 in Carhart-Harris et al., 2016, with figure 2c in Fox et al., 2015 and figure 1i in Domhoff & Fox, 2015). Note that with LSD this visual cortex activation was observed compared to a resting placebo-controlled baseline, during which (presumably) there was a large degree of spontaneously generated thought and imagery. These results suggest that the same visual area apparently involved in normal waking visual imagery is more highly activated when visual illusions and hallucinations become more vivid and frequent, as during a typical psychedelic experience. The studies reporting this medial visual activation in REM sleep (Fox et al., 2013) likewise compared brain activity to a resting, waking baseline, leading us to a similar interpretation: the increased vividness and hallucinatory quality of dreams appears to more strongly recruit the same visual areas active in waking rest – just as does visionary psychedelic experience.

Another recent study explored the visionary effects of the brew ayahuasca (de Araujo et al., 2012), whose central active ingredient is dimethyltryptamine, another serotonin receptor agonist (see Table 6.2). Similar to the LSD results above, the authors observed widespread activation of visual cortex areas during an eyes-closed imagery task after ayahuasca consumption (de Araujo et al., 2012), including regions such as the lingual gyrus (BA 17) that are activated during daydreaming (Fox et al., 2015) and nighttime dreaming (Domhoff & Fox, 2015; Fox et al., 2013).

Of course, many other subjective experiences and neurophysiological findings have been reported during core experiences for various substances and under various conditions. We limit our discussion here for the sake of brevity, but refer the reader to Table 6.1 for further studies of core psychedelic experience.

Peak Experience: Ego-dissolution and Mystical Unity

The *peak* stage of a psychedelic experience is the period in which subjective effects reach their maximum intensity (Figure 6.1). Although some peak of intensity is presupposed by the rise and fall of effects over the course of the psychedelic experience (Figure 6.1), peak experiences can vary enormously in intensity and duration, from a mere amplification of core effects to qualitatively distinct "dissolution" and "breakthrough" experiences.

When a psychedelic substance is ingested in a positive and supportive environment by a mentally sound individual (i.e., with positive set and setting), peak experiences can often be characterized by feelings of "undifferentiated unity" or "ego dissolution" (Lebedev et al., 2015; Pahnke & Richards, 1966). Ego-dissolution has been specifically defined as "a feeling that one's 'self,' 'ego,' or 'I' is disintegrating or that the border between one's self and the external world is dissolving" (Lebedev et al., 2015, p. 3137). Similar to mystical religious experiences (James, 1985), but in contrast to pathological experiences of depersonalization, these experiences are often perceived as being of a sacred, profound, and highly positive character (Griffiths et al., 2006; Pahnke & Richards, 1966), and have also been documented to result in lasting positive behavioral (Griffiths, Richards, Johnson, McCann, & Jesse, 2008) and personality (MacLean, Johnson, & Griffiths, 2011) changes (see below). The lasting value of peak experiences was also recognized in early psychedelic psychotherapy studies, which specifically sought to induce such mystical experiences through high-dose sessions in order to maximize long-term therapeutic value (Grof, 2008; Pahnke et al., 1970; Sherwood, Stolaroff, & Harman, 1962).

In a recent study, Lebedev and colleagues (2015) used fMRI to determine the neural activity that subserves the ego-dissolution state, as induced by psilocybin. Subjects were intravenously administered psilocybin prior to scanning, and following their emergence from the scanner they filled out a 24-item visual analogue scale (Lebedev et al., 2015). From these ratings, the researchers derived a principal component that specifically relates to ego-dissolution and used this in subsequent analyses.

The researchers found that ego-dissolution was associated with a decoupling of the medial temporal lobe from various brain networks

(Lebedev et al., 2015). More specifically, ego-dissolution was correlated with reduced functional connectivity between the hippocampal formation and the sensorimotor network, frontoparietal control network, and salience network (Lebedev et al., 2015). Moreover, ego-dissolution was also highly correlated with a disruption of salience network integrity, and reduced interhemispheric communication (Lebedev et al., 2015). These results suggest that disruption of large-scale brain networks, and their connections in the psychedelic state, underlies the subjective experience of ego-dissolution.

A recent study of LSD also examined neural correlates of ego-dissolution (Carhart-Harris et al., 2016), with similar results. The authors first used seed-based analysis to examine resting-state functional connectivity between the parahippocampal cortex bilaterally and the rest of the brain. They found that decreased resting-state functional connectivity between the parahippocampal cortex and the retrosplenial cortex, two major hubs of the default mode network, predicted self-reported experiences of ego-dissolution (Carhart-Harris et al., 2016). They then examined global measures of network integration, finding that decreased default network integrity also significantly predicted self-reported ego-dissolution (Carhart-Harris et al., 2016). Collectively, these results suggest that compromised activity or connectivity within the default network, known to be critically involved in the sense of self (Northoff et al., 2006), correlates with the experience of the dissolution of self.

There are intriguing parallels here to dreaming and creative inspiration. As discussed above, historically speaking, true creativity and inspiration were often seen as a cooption and overshadowing of the individual self by divine or other "higher" forces (McMahon, 2013). Although we know of no empirical research that has addressed this phenomenon in artists or other creative people, the intriguing combination of visionary experiences, ego-dissolution, and mystical union in artistic inspiration is reminiscent of peak psychedelic experiences and warrants further consideration and study.

Dreaming provides another interesting parallel. Aside from the parallel immersive visionary experience, dreaming is characterized by a particular disruption of the sense of self: access to autobiographical memory seems to be singularly abolished in most cases, leading to the loss of a coherent sense of who one is and a failure to recognize the incongruence and bizarreness of the dream experience. At the same time, however, a sense of self as an agent, moving through and acting in a world, remains intact. That is, even as the sense of self as an *agent* is maintained, the sense of an *autobiographical* self is lost. Whereas default network integrity is compromised during peak ego-dissolution experiences in psychedelic states (Carhart-Harris et al., 2016), and the default network appears to generally be deactivated during psychedelic experiences (Carhart-Harris, Erritzoe, et al., 2012; Deakin et al., 2008; Muthukumaraswamy et al., 2013), activation in numerous default network regions remains high during REM sleep and dreaming (Domhoff, 2011; Domhoff & Fox, 2015; Fox et al., 2013), potentially helping to explain the differential alterations in the sense of self. These contrasts across dream and psychedelic experience hint at the possibility that the "self" might actually be decomposable into multiple components supported by different brain regions and networks (e.g. *agentive* vs. *autobiographical* senses of self) (Christoff, Cosmelli, Legrand, & Thompson, 2011).

Resolution: Coming Down

As the acute psychedelic experience comes to an end, the user can feel generally sober and back in control, yet at the same time lingering effects can endure for prolonged periods (sometimes up to several hours or more). Cognition and perception may still be altered in subtle yet significant ways, and feelings of bliss, well-being, and gratitude or awe at the antecedent psychedelic experiences can be pervasive.

To our knowledge, no study has yet investigated the resolution stage of the psychedelic experience. Investigation of this stage faces some unique challenges. For instance, the uncertainty of the timing of its occurrence, as well as the difficulty in defining when the experience is really "starting" to end, given that experiential intensity tends to rise and fall in waves (Figure 6.1), are both problematic for empirical study. Nonetheless, the neural correlates of the resolution stage are of great interest because of the singular mix of lingering psychedelic effects combined with relative cognitive clarity and meta-awareness. We hope that future work can address this stage.

Assimilation: Evaluating and Integrating Psychedelic Experience

As with the resolution stage, we know of no neuroimaging work that has directly addressed the stage we call "assimilation," i.e., evaluating and integrating the content of the preceding psychedelic experience. One study investigating ketamine found that acute decreases in default network connectivity persisted at a 24-hour follow-up fMRI scan, but no subjective reports were collected, precluding any speculation about the meaning of this effect for assimilation of the preceding ketamine experience (Scheidegger et al., 2012).

Some minimal questionnaire data have addressed subjective experiences 24 hours after psychedelic substance administration and found that users reported a variety of lingering side effects, such as fatigue or a feeling of dreaminess, which were generally very mild (Studerus et al., 2011), but very little other data exist beyond anecdotal reports. One possibility is that evaluating the psychedelic experience may be akin to the subsequent evaluation of creatively generated ideas (Ellamil et al., 2012), or interpreting and evaluating one's dreams the following morning – i.e., we expect executive resources would be recruited to evaluate the content and utility of experiences generated and perceived in altered states of consciousness. These possibilities remain to be studied in the future.

Sequelae: Long-term Effects on Brain, Behavior, and Beliefs

Long-term effects on the brain. Several long-term neurobiological effects have been reported following chronic exposure to psychedelic substances. Investigations in rats, for instance, have shown that chronic exposure to ketamine (Garcia et al., 2008) results in elevated levels of brain-derived neurotrophic factor (BDNF). These results are intriguing because BDNF plays a crucial role in facilitating neurogenesis, synaptogenesis, and neuron survival (Binder & Scharfman, 2004) – whereas low levels of BDNF are associated with numerous psychiatric and neurodegenerative disorders, such as depression (Brunoni, Lopes, & Fregni, 2008) and Alzheimer's disease (Phillips et al., 1991). Another study found no effect on BDNF levels, but did observe that chronic ketamine administration reversed the adrenal gland hypertrophy and elevated levels of stress hormones evoked in rats by a chronic mild stress paradigm (Garcia et al., 2009). These animal results at least present some intriguing possible neurophysiological correlates of the persisting psychological effects reported by human users (see below).

Most relevant to our discussion is a study that used morphometric neuroimaging to examine cortical thickness in chronic ayahuasca users (Bouso et al., 2015). The rationale of the study was that, because psychedelic substances appear to stimulate neurotrophic and transcription factors associated with synaptic plasticity (such as BDNF), large-scale changes might be visible in chronic users as investigated with morphometric neuroimaging. Compared to controls, Bouso and colleagues (2015) found that chronic ayahuasca users exhibited significant cortical thinning in the posterior cingulate cortex (among other regions) – a major hub of the default mode network strongly implicated in self-referential thinking (Andrews-Hanna et al., 2014; Buckner, Andrews-Hanna, & Schacter, 2008; Fox et al., 2015). Moreover, the extent of the thinning in posterior cingulate cortex was correlated with the duration and intensity of ayahuasca use, as well as self-reported feelings of self-transcendence (Bouso et al., 2015). Recall that, consistent with these results, deactivation and disintegration of the default network has repeatedly been found during psychedelic experience, especially in relation to depersonalization and ego-dissolution (Carhart-Harris, Erritzoe, et al., 2012; Deakin et al., 2008; Muthukumaraswamy et al., 2013).

An equivocal pattern of results was observed in executive brain areas, with significantly increased cortical thickness in the dorsal anterior cingulate cortex, but significant thinning in the dorsolateral prefrontal cortex (Bouso et al., 2015). Although this somewhat ambiguous pattern of results precludes any facile interpretation, it does provide preliminary evidence that morphometric neuroimaging might be useful in the study of long-term brain structure changes in chronic psychedelic users. In summary, although long-term neurobiological effects are supported by only very preliminary data, they nonetheless offer some tantalizing clues to the mechanisms that might account for the numerous long-term psychological effects observable after even a single high-dose session.

Long-term psychological effects. In contrast to the relative paucity of neurobiological data on the long-term sequelae of psychedelic experience, there are now several rigorous behavioral and questionnaire studies addressing its long-term psychological effects. The general conclusion of these investigations has been that even one or a few high-dose psychedelic experiences can have lasting and generally positive effects on attitudes, patterns of other drug use, and overall sense of well-being.

Early work had already suggested upon long-term (e.g., 6-month or 10-year) follow-up that LSD experiences had a number of lasting beneficial effects, such as decreased egocentricity; greater aesthetic appreciation of art, music, and nature; and more self-understanding (McGlothlin & Arnold, 1971; McGlothlin, Cohen, & McGlothlin, 1967). Recent work has corroborated and expanded upon these earlier studies.

For instance, a pioneering study by Griffiths and colleagues (2006) administered various doses of psilocybin to psychedelic-naïve participants and followed-up two months later with questionnaires about persisting behavior/attitude changes, as well as reports from community observers on changes in the users. Importantly, this study employed a double-blind design with an active control of methylphenidate, and control subjects also completed long-term follow-up questionnaires and were observed by community members. The authors found that at two-months' follow-up, as compared to methylphenidate, psilocybin was associated with significantly greater positive attitudes about life and/or oneself; positive mood changes; altruistic/positive social effects; positive behavior changes; and well-being and life satisfaction (Griffiths et al., 2006). Moreover, community observer ratings agreed with self-reports, in that significantly greater positive change was observed in the psilocybin vs. methylphenidate group (Griffiths et al., 2006). A subsequent follow-up at 14 months reported similarly positive results more than one year after the psychedelic experience (Griffiths et al., 2008). Recently, the same research group essentially replicated these findings with one- and 14-month follow-up in a separate sample (Griffiths et al., 2011).

Another recent study conducted long-term (8–16 months) follow-up with participants following 1–4 psilocybin sessions (Studerus et al., 2011). Whereas negative changes in beliefs and attitudes were hardly ever reported (between 1% and 7% of participants), many users (between

18% and 38%) reported positive changes in worldview, values, awareness of personal problems, relationship to one's body and other people, and relationship to the environment. Moreover, in a retrospective questionnaire, the original psychedelic experience was overwhelmingly described as "enriching" and "positive" (Studerus et al., 2011).

In summary, although more research clearly needs to be conducted with larger samples and with a wider variety of psychedelic substances, well-controlled and rigorous research currently suggests that psychedelic experience is associated with persistent and overwhelmingly positive changes in behaviors, attitudes, and sense of well-being. Conversely, there is negligible evidence that psychedelic substance use encourages increased consumption of other substances or leads to psychosis. A major task ahead will be developing an understanding of how these persistent psychological changes are mediated at the level of the brain.

Conclusions and Future Directions

The neural correlates of the psychedelic experience are increasingly being investigated with noninvasive functional neuroimaging methods. This research has now provided a preliminary understanding of the neural substrates of various stages and contents of psychedelic experience, elucidating how various stages differ from one another, and also relate to kindred "altered" states of consciousness such as dreaming and creative thinking.

Several conclusions can be gleaned from the preceding review. First, psychedelic experiences involving strong visual hallucinatory components activate the same brain areas as "natural" altered states involving high rates of visual imagery, most notably daydreaming and nighttime dreaming. Second, *peak* psychedelic experiences involving loss of the sense of the self or "ego-dissolution" involve deactivation or disintegration of brain networks, most notably the default mode network, that are widely thought to maintain and subserve an internal stream of thoughts and a coherent sense of self. Third, the effects of psychedelic experiences can be sustained long after the acute effects have worn off and substance concentration has reached zero. Potent psychedelic experiences appear to have long-term (potentially even lifelong) effects on brain, behavior, and beliefs. This drawn-out period of *assimilation* and *sequelae*, as we have termed them here, has parallels in dreaming and creative thinking. A compelling dream or a great creative discovery can be pondered and assimilated for months or years afterward, and can affect the life of the individual and others in profound ways.

These meager conclusions can represent only a first step on a long road leading toward understanding of the neural correlates of various stages of psychedelic experience and their relation to other altered states. Difficult but fascinating challenges lie ahead. From a theoretical point of view, a much more nuanced framework is required than the preliminary model proffered here – one that explicitly maps different stages of the psychedelic experience onto various stages of the creative process, as opposed to simply pointing toward intriguing similarities. From an empirical point of view, more work is needed to understand the neural correlates of the LSD experience, to follow up on a recent seminal study (Carhart-Harris et al., 2016). Similarly, neuroimaging of as-yet-uninvestigated psychedelic substances, such as mescaline and *Salvia divinorum* (see Table 6.2), would be a welcome addition to the small but growing literature of the neural correlates of other major psychedelics. Other as-yet-unanswered empirical questions are broader: for instance, do psychedelics interact with and potentially facilitate the creative process through cognitive mechanisms (such as a broadening of attentional scope); via affective-motivational aspects, such as perseveration on a creative project; or some combination of these and other mechanisms? Finally, a major challenge for researchers will be to investigate these substances in a more natural fashion. Virtually every study to date has used intravenous injection of concentrated and pure forms of a given psychedelic substance (for a notable exception, however, see de Araujo and colleagues (2012), who used a natural ayahuasca brew). While this method provides obvious advantages to researchers and participants alike (e.g., allowing for precise dosage and rapid onset), intravenous injection is almost never the preferred route of administration for any psychedelic drug in either recreational or traditional settings. Although this method of delivery is of course a sensible alternative in these early days of renewed research, in order to increase ecological validity researchers will eventually need to tackle the challenges of investigating psychedelic experiences arising from orally ingested, insufflated, or inhaled substances in their standard or natural (e.g., whole plant) forms.

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7

A Heated Debate: Time to Address the Underpinnings of the Association between Creativity and Psychopathology?

Simon Kyaga

Introduction

The association between creativity and mental illness does not only constitute one of the fieriest debates in creativity research, the association also has fundamental clinical implications that can be expected to rise in importance given novel treatment aims in psychiatry. This chapter reviews the current state of empirical knowledge on the association between creativity and mental illness, including some of the landmark studies published in the late 1980s as well as more recent studies, such as our own attempts to address this question in large-scale epidemiological investigations (Figure 7.1).

There is now reasonable support for an association between bipolar disorder, subsyndromal psychotic features, schizophrenia, and different aspects of creativity. These associations may be explained using some of the contemporary ideas in creativity research including growing data on the biology of creativity, genetics, neurophysiology, and neuroimaging. Although for historical and methodological reasons there is reason for restraint in embracing the general idea of an association between creativity and psychopathology, I argue that the critique toward this idea put forward today does not accurately reflect the development of research in this field. Specifically, given that the association between creativity and mental illness has important clinical implications, and the realization that creativity and related themes such as inventions and innovations have such an important impact on modern society, it is surprising that recent findings on the link between creativity and mental illness have yet to inform aspects of clinical care and societal structures.

The Association between Creativity and Psychopathology

History

Aristotle (384–322 BC) questioned in *Problemata XXX*, written by his pupil Theophrast (371–287 BC), "Why is it that all those who have become eminent in philosophy, politics, poetry, or the arts are clearly melancholics and some of them to such an extent as to be affected by diseases caused by the black bile?" Aristotle (1984) is often quoted as a starting point for the recurring observation of the mad genius link. This quote was later modified by Seneca the Younger (4 BC–AD 65) citing Aristotle to have said, "No great genius has existed without a strain of madness" (Motto & Clark, 1992).

Aristotle's original reference to eminence and melancholia was founded in the then prevailing humoral theory, closely associated with Hippocrates (Becker, 2014). This theory saw disease as the consequence of an imbalance in the four basic fluids (i.e., humors): blood, black bile, yellow bile, and phlegm (Adams, 2010). Each of these humors contained certain qualities, such as heat, cold, dryness, and moistness. Disease was the result of an excess in any of these humors triggered by external or internal influences. It

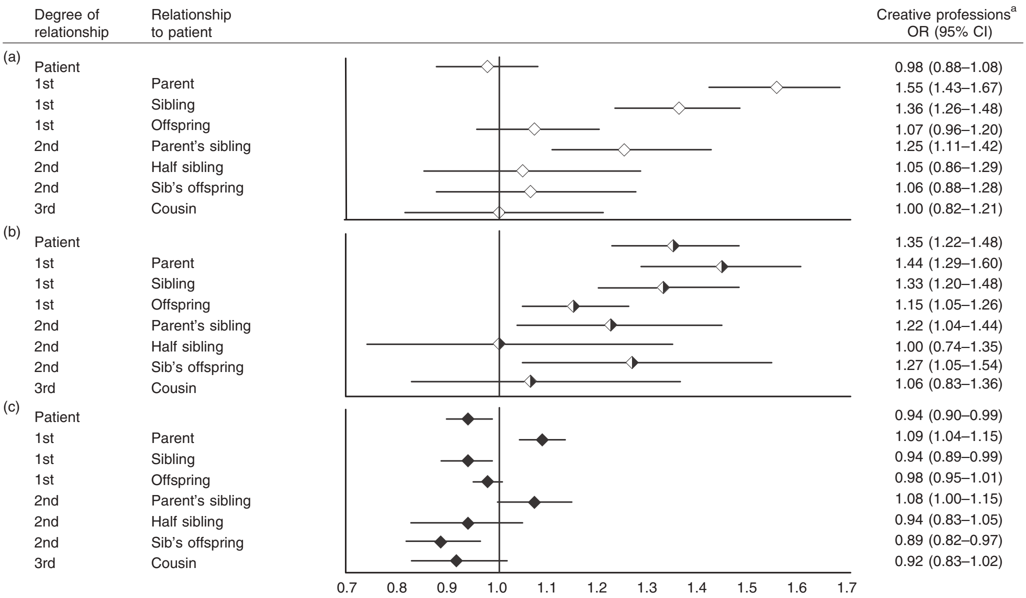

Figure 7.1 Associations between case group psychiatric morbidity and creative professions.

Notes. Study on ~300,000 patients demonstrating an increased occurrence of creative professions in patients with bipolar disorder (A) and relatives of patients with schizophrenia (B) and bipolar disorder compared to healthy controls. No association was found for patients with unipolar depression (C) or their relatives. An odds ratio (OR) higher than 1 implies an increased occurrence, whereas an OR lower than 1 implies a decreased occurrence. Creative professions were defined as artistic and scientific occupations. *Source*: Kyaga et al. (2011). For a color version of this figure, see the color plate section.

was also postulated that certain human temperaments were linked to the composition of these humors. Thus, a dominance of blood resulted in a sanguine personality, phlegm in a phlegmatic personality, yellow bile in a choleric personality, and lastly black bile in a melancholic personality.

Aristotle's original quote therefore cannot be taken as a general proclamation that psychiatric disorder is associated with achievement, but rather that the melancholic temperament is the reason for this association. Depending on the balance between the different humors, an individual with melancholic traits would become either sane or psychiatrically affected (Wittkower & Wittkower, 2007). This view is consistent with recent theory in psychiatric phenomenology, considering a bipolar spectrum of traits seen on a scale ranging from severe bipolar disorder through less severe and on to affective temperaments, with the more severe cases increasingly established through genetic loading (Akiskal & Akiskal, 2007), also reflected in the recent attempts to integrate a dimensional perspective on psychiatric diagnosis in the latest edition of the *Diagnostic and Statistical Manual of Mental Disorders* (DSM-5) (Jablensky, 2016).

The advance of the psychiatric field in the middle of the nineteenth century introduced a medical approach to the question of genius and madness. Soon, many psychiatrists and other scholars had published studies of geniuses (Galton, 1869; Lange-Eichbaum & Paul, 1931; Lombroso, 1891; Maudsley, 1908), and within a century there was a considerable literature on genius and in particular the association between genius and madness. Many argued for the genius as pathological, an opinion especially held by the growing psychiatric field. In turn, those questioning the mad genius link were more often psychologists, emphasizing physical and emotional stability rather than illness as emblematic of genius (Becker, 1978).

George Becker, a prominent scholar on the history of the mad genius literature, maintains that the great interest in the mad genius declined during the mid-twentieth century in parallel with an opposition to eugenics following the Second World War (Becker, 2014). Environmental factors were gradually more stressed in the formation of genius. This change from a biological to a sociological position was revealed in an alteration of language; studies on *genius* were now replaced with studies on *creativity*, intelligence, and motivation (Becker, 1978; Lehman, 1947).

Becker is accurate in pointing out the change from a biological to a sociological perspective during the first half of the twentieth century; however, it is not the case that studies on genetics and creativity or for that matter on creativity and mental illness waned. There has been a stable growth in studies on creativity and genetics during the last century (Kyaga, 2014), with a similar increase in the field of creativity and psychopathology (Thys, Sabbe, & De Hert, 2014b), the latter having increased in the amount of studies published from two studies in the 1950s to 41 studies in the last decade (Thys et al., 2014b), in parallel with a growing consensus of an association between creative abilities and specific psychiatric disorders (Becker, 2014).

Systematic Literature Review

In order to approach the question of creativity and mental illness, we and others have tried to systematically review the current literature rather than provide sporadic references to studies in the field (Kyaga, 2014; Lauronen et al., 2004; Thys, Sabbe, & De Hert, 2014a, 2014b).

For the purpose of this chapter, a previous review based on the following criteria was updated: all articles, letters, meeting abstracts or book chapters published in English attained through the MESH-terms "creativity" AND "mental disorder" in the databases MEDLINE and Web of Science. The initial search yielded a total of 98 original studies included until December 2013 (Kyaga, 2014). These were complemented with studies published in January 2014–December 2015 using the same search terms in MEDLINE and Web of Science resulting in another 46 and 40 hits, respectively, which after examining the titles and abstracts were pruned to include exclusively original studies (n = 22) (Ando, Claridge, & Clark, 2014; Batukhtina, Nevidimova, Vetlugina, Kokorina, & Bokhan, 2014; Damian & Simonton, 2015; Drake, Gumenyuk, Roth, & Howard, 2014; Hezel & Hooley, 2014; Higier et al., 2014; Johnson et al., 2015; Johnson, Tharp, & Holmes, 2015; Jones, Dodd, & Gruber, 2014; Kasirer & Mashal, 2014; LeBoutillier, Barry, & Westley, 2014; Leung et al., 2014; Minor et al., 2014; Mourgues, Preiss, & Grigorenko, 2014; Power et al., 2015; Rominger, Papousek, Fink, & Weiss, 2014; Ruiter & Johnson, 2015; Son et al., 2015; Takeuchi et al., 2015; Taylor, Fletcher, & Lobban, 2015; Wu et al., 2015; Zabelina, Condon, & Beeman, 2014). In total, 120 original studies published until December 2015 were thus included in the review below.

Schizophrenia and Schizotypy

Most studies reviewed have investigated psychotic disorders, such as schizophrenia and bipolar disorder, and subsyndromal psychotic symptoms (e.g., schizotypy) in relation to creativity. Schizotypal traits can be generalized into three aspects: positive schizotypy (e.g., unusual cognitive and perceptual experiences, tendency to magical ideation, and paranoid thoughts), negative schizotypy (e.g., social isolation and reduced emotional expression), and cognitive disorganization (e.g., poor attention and concentration as well as poor decision-making) (Claridge et al., 1996; Mason & Claridge, 2006). Studies reporting an association for schizotypy with creativity generally affirm this for *positive* schizotypy (Baas, Nijstad, Boot, & De Dreu, 2016).

Patients with Schizophrenia. Many of the early studies on creativity and mental illness investigated schizophrenia. On the whole, these studies failed to demonstrate increased creative abilities in patients with schizophrenia. For example, Herbert described a group of 60 patients, including those with schizophrenia, admitted from 1928 to 1955 (1959). There was no increased occurrence of artistic occupations in this group. Dykes and McGhie (1976) concluded that schizophrenic patients' widening of attention was unintentional and detrimental to creative performance. Patients with schizophrenia have also been demonstrated to perform worse on the Remote Associate Test, and other creative tests compared to healthy controls (Abraham, Windmann, McKenna, & Gunturkun, 2007; Folley & Park, 2005; Higier et al., 2014; Son et al., 2015). We investigated patients with schizophrenia in two nation-wide studies including 65,589 patients and found no support for a higher incidence of overall creative professions compared to healthy controls (Figure 7.1); however, there was a significant increase in people with artistic occupations (Kyaga et al., 2011; Kyaga et al., 2013). Studies exploring prominent personalities have rarely found a greater proportion of schizophrenia among them (Andreasen, 1987).

Psychoticism and Schizotypy. While few studies have suggested increased creative abilities in patients with schizophrenia, several have found a link between subsyndromal psychotic symptoms (psychoticism or schizotypy) with creativity. Schuldberg and colleagues. demonstrated a correlation between positive schizotypy and creativity as measured by the Barron Welsh Art Scale (BWAS) and How Do You Think (Schuldberg, French, Stone, & Heberle, 1988), with similar findings being made by Kinney et al. (2000) using the Lifetime Creativity Scales, and Weinstein & Graves (2002) using the Remote Associate Test and a written fluency test. Folley & Park (2005) found heightened divergent thinking (see below) in schizotypal subjects compared to both healthy controls and patients with schizophrenia. By using near-infrared optical spectroscopy, these authors proposed that the increased ability in divergent thinking was concurrent with activation of the right prefrontal cortex, while a more recent study suggested that impulsiveness and sensation-seeking were mediating the association to creative achievements and divergent thinking (Zabelina et al., 2014).

Relatives to Patients with Schizophrenia. Authors have also explored subsyndromal features by investigating nondiagnosed relatives of patients with schizophrenia. This is congruent with the so-called "inverted-U" relationship between creativity and psychopathology, which suggests that lesser symptoms displayed in relatives of patients may be more beneficial for creativity than those more clearly manifested in patients (Richards, Kinney, Lunde, Benet, & Merzel, 1988). Karlsson demonstrated that relatives (n = 486) of patients with schizophrenia were more often found in *Who's Who*, a lexicon including noteworthy people, compared to the general population (Karlsson, 1970). The author concluded that findings were possibly due to shared genetics. Our two nation-wide studies affirmed an increase in not only artistic occupations, but also overall creative professions (Figure 7.1; artistic and scientific occupations), in first-degree relatives of patients with schizophrenia (Kyaga et al., 2011, 2013).

Bipolar Disorder and Thymotypy

Patients with Bipolar Disorder. Although few studies have supported an association between schizophrenia disorder and creativity, the reverse can be said about bipolar disorder. One of the most well-known studies was completed by Andreasen investigating 30 creative writers in the Iowa writers' workshop, as well as these writers' first--degree relatives (Andreasen, 1987). The Iowa workshop is a widely recognized creative writing program in the USA. Eighty per cent of the writers, compared to 30% of controls, had been suffering an affective disorder sometime in their lives, with a high proportion of them suffering bipolar disorder (writers: 43% vs. controls: 10%). Jamison found similar results in 47 British writers and artists (Jamison, 1989). Ludwig demonstrated an increased rate of manic episodes in a group of roughly thousand individuals based on their biographies having been published in the *New York Times* Book Review from 1960 to 1990 (Ludwig, 1992, 1995). These findings were further emphasized when only those active within classical creative professions were investigated (~3% vs. ~10%). Interestingly, these findings have later been extended in an African American sample, which showed reduced prevalence of mental illness compared to Ludwig's original sample, but nevertheless increased compared to people in non-creative domains (Damian & Simonton, 2015). Another recent study proposed that the increase in creativity in patients with bipolar disorder may be due to greater ambition in this group (Johnson et al., 2015).

Richards and colleagues examined patients with bipolar disorder, cyclothymes, and relatives of patients using the Lifetime creativity scales (Richards et al., 1988). Subjects were considered cyclothymes if they had received another form of affective diagnosis than manic-depressive illness (bipolar disorder). The hypothesis was that this would represent less-severe cases on the bipolar spectrum. Results did not show an increase of creativity in only patients vs. controls, but there was an increase in the combined group of patients and relatives vs. controls. Simeonova and co-workers studied 40 adults with bipolar disorder, 20 bipolar offspring with bipolar disorder, 20 bipolar offspring with ADHD, and 18 healthy control parents and their 18 healthy control children using the BWAS (Simeonova, Chang, Strong, & Ketter, 2005). Results showed that adults with bipolar disorder compared to controls scored (120%) higher on the BWAS Dislike subscale. Mean BWAS Dislike subscale scores were also greater in offspring with bipolar disorder (107% higher) and offspring with ADHD (91% higher) than in healthy control children. Santosa et al. showed that patients with bipolar disorder and creative controls, but not patients with major depressive disorder, scored significantly higher on BWAS compared to normal controls (Santosa et al., 2007). We showed that bipolar patients receiving psychiatric inpatient treatment had an increased occurrence of overall creative professions (Figure 7.1), but not patients with major depressive disorder (Kyaga et al., 2011). These results were later confirmed in a follow-up study, where outpatient treated patients were also included (Kyaga et al., 2013).

The Affective Temperament. Some studies have investigated the affective temperament in relation to creative behavior. For example, Strong and colleagues established that cyclothymia and dysthymia assessed by the Temperament evaluation of the Memphis, Pisa, Paris, and San Diego autoquestionnaire (TEMPS-A) was correlated to BWAS-Total scores and BWAS-Dislike subscale scores (Strong et al., 2007), while Srivastava et al. showed that patients with bipolar disorder, major depressive disorder, and creative controls, compared to normal controls, display increased TEMPS-A cyclothymia scores (Srivastava et al., 2010). Similar findings have been made in relation to creative achievement (Ruiter & Johnson, 2015).

Relatives to Patients with Bipolar Disorder. Studies such as Karlsson's and Richards and co-workers' referenced above have suggested that relatives of patients with bipolar disorder may exhibit creative inclination (Karlsson, 1970; Richards et al., 1988), also proposed by Simeonova et al. demonstrating higher BWAS-Dislike subscale scores in bipolar disorder offspring (Simeonova et al., 2005). Other studies have supported increased aptitude in bipolar disorder (MacCabe et al., 2010), and suggested that healthy co-twins to patients with bipolar disorder are characterized by increased "positivity" temperament (Higier et al., 2014). In our own studies, nondiagnosed first-degree relatives of patients with bipolar disorder generally demonstrated similar increases (Figure 7.1), as patients in the rate of creative professions compared to controls (Kyaga et al., 2011; Kyaga et al., 2013).

Autism. Turner looked at individuals aged 6–32 years who were high-functioning (IQ > 75) with autism (*n* = 22), high-functioning controls (*n* = 22), autistic (*n* = 22), and learning-disabled controls (*n* = 22) (Turner, 1999). Persons with autism generally showed reduced fluency for both words and ideation. One study has suggested that patients with autism were more original (Kasirer & Mashal, 2014). We demonstrated that while patients with autism were not overrepresented in creative professions, the opposite was true for nondiagnosed siblings of patients (Kyaga et al., 2013). This increase was especially pronounced in the subgroup of scientific occupations. In line with these findings, Campbell and Wang (2012) made an online survey of an incoming class to Princeton University and found that students seeking technical majors more often than other students had a sibling with autism spectrum disorders. Thus, while there is little empirical support that autism is associated with creativity, there is some support that traits associated with autism may be beneficial in scientific and technological endeavors (Baron-Cohen, Ashwin, Ashwin, Tavassoli, & Chakrabarti, 2009; Roelfsema et al., 2011; Ruzich et al., 2015).

Attention Deficit Hyperactivity Disorder. With the growing incidence of Attention deficit hyperactivity disorder (ADHD), increasingly authors have investigated whether there is a link between ADHD and creative capabilities. Funk and colleagues examined 19 boys with previously diagnosed ADHD and 21 controls aged 8–11 on two administrations of Torrance Tests of Creative Thinking-Figural (nonverbal) (Funk, Chessare, Weaver, & Exley, 1993). Boys with ADHD were provided with methylphenidate (standard pharmacological treatment for ADHD) only for the first session. Creativity scores for controls were slightly higher than for boys with ADHD. No changes in creativity across medication state were observed. White and Shah (2006, 2011), in contrast, reported in two studies that university undergraduates with ADHD had higher scores on both divergent thinking measures and creative achievements.

Critique of Studies

The results of this literature review support that different aspects of creativity are associated with specific psychiatric syndromes, i.e., bipolar disorder, and subclinical features within the psychotic and affective domain displayed in healthy individuals. Nevertheless, a few of these studies have received serious methodological critique. Some authors are defiant toward the idea of mental illness having any association with creativity, and claim that there still is no empirical support (Rothenberg, 1995, 2001; Schlesinger, 2009, 2012, 2014), or very weak empirical support for any association (Sawyer, 2012a,b).

The Insanity Hoax. The psychologist Judith Schlesinger argued in her book entitled *The Insanity Hoax* that "The mad genius is a beloved cultural artifact, a popular spectacle, and a favorite playing-field leveler … There is simply no good reason to believe that exceptionally creative people are more afflicted with psychopathology than anyone else" (Schlesinger, 2012, p. 171). Her critique is based on the argument that authors of studies supporting the supposed association between creativity and mental illness both selected study subjects, and in general themselves established the diagnoses without support in recognized diagnostic manuals. This would lead to results being both biased, and to difficulties in generalization.

Much of Schlesinger's criticism is aimed at only three studies, notwithstanding studies that are commonly referred to as landmark studies supporting the mad genius link. These are Andreasen's study on creative writers at the Iowa writer's workshop (Andreasen, 1987), Jamison's study of British artists and authors (Jamison, 1989), and Ludwig's compilation of just over one thousand prominent individuals (Ludwig, 1992, 1995).

With regards to Andreasen's study, Schlesinger mentions four key problems (Schlesinger, 2009). The first is that the study design was not blind in that Andreasen herself made all the diagnoses while fully aware of whom she was meeting. This would potentially introduce an information bias resulting in misclassification. This problem may have been augmented in that Andreasen used a self-developed instrument to aid diagnostics. While the latter is accurate, Schlesinger does not acknowledge that most of the world uses the International Classification of Diseases (ICD) to establish diagnoses, a system with prototypical diagnoses and clinical judgment rather than structured manuals at its core (World Health Organization, 1967, 1977, 2004). Schlesinger's second objection is that a selection bias may have been present, in that those writers applying to the Iowa writer's workshop may have done this as a way to recover from setbacks and burnout (Schlesinger, 2009). This would almost certainly make them more susceptible to mental illness than average writers. Third, the investigated writers were mainly male (27 of 30) with a mean age of 37 years, making the results only generalizable to this group. Finally, the data on relatives to writers came from secondary sources as Andreasen did not meet them in person. There is no question that these are all legitimate concerns; however, none is new. In fact, Albert Rothenberg raised these counterarguments 10 years before Schlesinger (Rothenberg, 1995, 2001), and contrary to Schlesinger, he also provided interesting empirical data challenging the idea of a link between creativity and mental illness (Rothenberg, 1983).

In 1983, Rothenberg presented a study in which he had measured a type of creative cognition termed janusian thinking (opposite response). Specifically, timed word association tests were provided to 12 creative scientists who were Nobel laureates, 18 hospitalized patients, and 113 college students divided as controls into high and low creative achievers. Results demonstrated that Nobel laureates provided the highest proportion of opposite responses at the fastest rate of all groups, whereas patients gave the lowest proportion of opposite responses, and at the slowest rate. However, the Nobel laureates only included scientists – physics ($n = 5$), chemistry ($n = 2$), and medicine and physiology ($n = 5$) – and were all males with ages ranging from 44 to 73 years. The patients, on the other hand, were hospitalized with a wide range of diagnoses – schizophrenia ($n = 2$), borderline personality disorder ($n = 9$), brief reactive psychosis ($n = 1$), major depressive disorder ($n = 2$), anorexia nervosa ($n = 1$), opioid abuse ($n = 1$), alcohol dependence ($n = 1$), and narcissistic personality disorder ($n = 1$). There were four men and 14 women among patients with ages ranging from 19 to 40 years. Five patients were provided with psychotropic medication and 13 were not. This group was merely lumped together as "patients." Students were Yale University undergraduates divided into a high creative ($n = 63$) and a low creative ($n = 50$) group. High creativity and low creativity was defined on the basis of documented creative achievements in the arts and sciences and the strength of their creative interests. All students were male with an age range from 16 to 22 years. No distinction was provided with regards to artistic or scientific achievements or interests. The analyses did not account for differences in sex, age, domain of creativity in the different groups, or type of diagnosis in the patient group. In light of this, Rothenberg's criticism of Andreasen's study for matching controls on age, education, and sex, but not on variables of occupation, intelligence, or achievements is clearly not coherent (Rothenberg, 1995).

In consequence, given that Rothenberg's study is frequently used as an argument against the results of Andreasen's study, the critique does not seem balanced. True, Andreasen did not include an acknowledged diagnostic manual, but then Rothenberg did not even consider what diagnoses his patient group had. These were simply lumped together, and though there may have been selection bias in Andreasen's study from a limited group of authors seeking the Iowa writers' workshop, Rothenberg only included patients receiving inpatient treatment. Obviously being eligible for inpatient treatment indicates that one might have critical difficulties with everyday activities. To discover that this group was less capable of providing rapid and opposite responses is not so surprising. Lastly, the critique of Andreasen using secondary sources in her investigation of relatives of writers may be reasonable; however, Rothenberg did not even include relatives of patients.

All of this should not be taken as an account of saying that Rothenberg's study is lacking merit or that Andresen's study is without limitations. Quite the contrary; however, the strengths and weaknesses of individual studies need to be considered also in relation to what previous scientific literature was present upon publication. Schlesinger's critique of Andreasen's study and those of Jamison and Ludwig seem to be targeted on proving her standpoint, by single-mindedly focusing on studies published more than 20 years ago (Jamison, 1989; Ludwig, 1992, 1995; Schlesinger, 2009, 2012, 2014). She generally refrains from mentioning more recent studies addressing such limitations as lack of controls, use of standardized diagnostics, and number of subjects (Schlesinger, 2009, 2012, 2014).

Aspects of Creativity Research

Genius and Everyday Creativity

An important aspect in creativity research is the distinction between genius (big-C) and more modest creative achievements (little-c) (Kozbelt, Beghetto, & Runco, 2010). Increasingly, research on creativity and mental illness has come to focus on other aspects than merely those alluring in geniuses, as a too-narrow focus on big-C could risk missing interesting facets such as creative *potential* (Kozbelt et al., 2010; Runco, 2007b). This is imperative because more recent studies have suggested that patients with psychiatric disorders may well exhibit creative potential that is not fulfilled due to the debilitating consequences of the disorder suffered.

The Four P's

Person. Research is often directed at one of four aspects of creativity: the creative *person*, *process*, *product*, or social pressures (*press*) (Rhodes, 1987). Studies focused on *person* have demonstrated that creative individuals in general exhibit broad interests, high energy, value aesthetic qualities and autonomy, with self-confidence and a firm sense of self as creative (Barron & Harrington, 1981). An important aspect is also motivational research (Hennessy, 2010), where the suggested link between bipolar disorder and extraordinary achievements have been proposed to be the result of changes in the Behavior Activating System (BAS), which is a construct in Gray's theory of personality (Gray, 1981; Johnson, Edge, Holmes, & Carver, 2012).

Process. Many studies address the creative *process* with the aim to better understand the mental aspects fundamental for creativity (Kozbelt et al., 2010). Studies have suggested stages in the creative process (Wallas, 1926), and more recently focused on its cognitive aspects (Kozbelt et al., 2010).

Divergent Thinking. A central feature of the creative process is divergent thinking (Runco, 2010). It is engaged in open-ended tasks such as "How can you use a brick?" Tests assessing divergent thinking usually allow scoring four different aspects: fluency (the total number of ideas), originality (the number of unusual ideas), flexibility (the number of different categories of ideas), and elaboration. These tests have been viewed as some of the most promising candidates for assessment of creativity based on psychometric considerations, but there have also been concerns raised regarding their usefulness (Silvia et al., 2008). The main limitation is related to the fact that classic scoring of these assessments mainly captures the quantity of ideas, i.e., fluency. However, several attempts have been made to differentiate fluency from truly creative ideas.

Silvia and colleagues (2008) used a method that incorporated subjective ratings by a small number of raters, and they were able to demonstrate good reliability and high predictive validity for divergent thinking scores without the fluency confound. The study also included information on whether participants had pursued arts majors in college as indicators of their occupational and lifespan goals. It was found that this information had a moderate effect size (β = .339) on the variance of divergent thinking in addition to Big Five personality traits. We recently found that pursuing art majors in college or studying artistic subjects at university in a national sample including 194,039 individuals was associated with an increased risk of being hospitalized with a diagnosis of schizophrenia, bipolar disorder or unipolar depression (MacCabe, Larsson, Sariaslan, Lichtenstein, & Kyaga, 2015).

Product and Press. An important advantage in creativity research aimed at creative *products* is that these can be counted. The Creative Achievement Questionnaire (CAQ) is an often-used instrument tapping into this area as well as into the creative person. It is based on the assumption that creative achievements reflect both intrapersonal and interpersonal factors (Carson, Peterson, & Higgins, 2005). Intrapersonal factors may include cognitive abilities (e.g., IQ, divergent thinking), personality traits (e.g., confidence, contrarianism), and intrinsic motivation, while interpersonal factors may comprise familial resources (e.g., ability to provide practical support), societal factors (e.g., opportunity for interaction with experts in the chosen field of creativity), and cultural considerations, such as sufficient political or economic stability. The latter are generally addressed in studies categorized under press (Rhodes, 1987). Here, focus lies in both general (e.g., cultural, organizational, or familial presses), and more specific (e.g., interpersonal exchanges or environmental settings) influences on creative performance (Runco, 2004).

An Integrated Perspective

A variety of theories on creativity have been advanced stressing personality, process, product, and press to a varying degree (Kozbelt et al., 2010). One of these is the *Darwinian model of creativity* by Dean K. Simonton, integrating an evolutionary perspective to include all these four aspects (Campbell, 1960; Simonton, 1984, 1999b, 2003). This model addresses person (and potential) by presuming dispositional and developmental individualities specifically linked to the actualization of creative achievements from promising potential. It integrates the creative process by forwarding a two-stage model, in which the ideational phase is unconscious and ensuing from a blind combination of concepts to generate *novel* ideas. Some of these are in turn cognitively selected for and consciously elaborated into creative products. Four variables accordingly account for creative achievements; creative potential, career duration, ideation rate, and elaboration rate (Kozbelt et al., 2010). Simonton has performed historiometric studies to provide extensive empirical support for this theory (Simonton, 1977a,b, 1984, 1985, 1988a,b, 1991a,b, 1997, 1998, 1999a,b, 2000, 2003).

Biological Perspectives

Two main areas can be identified in recent years' progress on the biology of creativity: genetics and neuroimaging. These are both areas in which new methodologies have been established for diverse aspects of psychology and psychiatry in the last decades (Gazzaniga, Ivry, & Mangun, 2009; Plomin, DeFries, Knopik, & Neiderhiser, 2012).

Genetics. Early attempts to address the genetics of creative achievements include work pioneered by Francis Galton on inheritance (Galton, 1869). Contemporary investigations have assessed both specific candidate genes (Reuter, Roth, Holve, & Hennig, 2006), and utilized whole-genome approaches (Power et al., 2015).

The heritability of creativity has previously been estimated at 22%–78% in different studies; however, these studies have generally used different methods to define creativity (Kyaga, 2014). For divergent thinking specifically, the estimated heritability ranges between 22% and 43% (Kyaga, 2014). Investigated candidate genes for creativity are generally related to the monoaminergic neurotransmission or more specifically to neuronal development. Monoamines include the catecholamines (dopamine, norepinephrine, and epinephrine) and serotonin. Dopamine and serotonin are essential in controlling movement, mood, and behavior (Egerton et al., 2009; Schatzberg & Nemeroff, 2009), and dopamine specifically has been proposed as a central agent for the creative process (Flaherty, 2005).

One study found an association between a polymorphism of the Neuregulin 1 gene, the CAQ, and the "Just suppose test" in 200 healthy individuals (Kayser, 2013; Keri, 2009). This gene has been proposed as a risk factor for psychosis (Bousman et al., 2013), with the corresponding protein implicated in neuronal growth, myelination, and protection of dopaminergic neurons. So far these findings have not been replicated.

More recently, Power and colleagues tested polygenic risk scores for schizophrenia and bipolar disorder (Power et al., 2015). They found that higher scores were associated with holding an artistic society membership or creative profession in Iceland. These results were replicated in cohorts in the Netherlands and Sweden, and there was also a trend for these polygenic risk sores to predict estimates in an adapted version of the CAQ.

Neurophysiology and Neuroimaging

Handedness and Creativity. There is some support for nonright-handedness, conceived as a marker of altered brain lateralization, being linked to creativity (Preti & Vellante, 2007). Burke and co-workers investigated 12 left- and 12 right-handed college students and demonstrated that left-handed individuals did slightly better on figural tests of divergent thinking (Burke, Chrisler, & Devlin, 1989). Left-handed persons have also been found to outnumber right-handed persons in creative and eminent samples (Peterson & Lansky, 1974, 1977). Both mixed-handedness and left-handedness is increased in schizophrenia (Dragovic & Hammond, 2005), and mixed-handedness is more often seen in people with psychosis proneness (Chapman & Chapman, 1987; Kim, Raine, Triphon, & Green, 1992; Preti, Sardu, & Piga, 2007; Shaw, Claridge, & Clark, 2001). Creative artists more often use their left hand than controls, while also scoring higher for psychosis proneness (Preti et al., 2007). In fact, squeezing a hand gripper with the left hand led to enhanced performance on a creativity task compared to squeezing the gripper with the right hand in a recent study (Rominger et al., 2014). It was suggested that this increase was moderated by positive schizotypy, because the change in creativity was only evident when this was low.

Structural Neuroimaging Studies. A few studies have investigated structural aspects of the brain in relation to creativity (Arden, Chavez, Grazioplene, & Jung, 2010). One study using volumetric MRI in a sample of 61 young adults found that gray matter cortical thickness in a region in the lingual gyrus was associated negatively with figural divergent thinking, but positively with a different region in the right posterior cingulate (Jung, Segall, et al., 2009). The study also acquired participants' scores on the CAQ, in which lower gray matter volume was associated with higher achieved creativity in the left lateral orbito-frontal region, but higher volume correlated with achieved creativity in the right angular gyrus. The authors suggested that "a possible interpretation of our findings is that the generation of novel, original ideas is associated with less cortical thickness within frontal and (certain) posterior cortical regions, requiring higher functional activation to initiate cognitive control" (Jung, Segall, et al., 2009, p. 404), and stressed that the results were not limited to one lobe of the brain, or to one hemisphere, or suggesting that with regards to cortical thickness "more is better," a notion otherwise characterizing cognitive neurosciences. This conclusion was further suggested in a study examining white matter integrity with diffusion tensor imaging (Jung, Grazioplene, Caprihan, Chavez, & Haier, 2010). Results demonstrated an inverse relationship between fractional anisotropy in the inferior frontal white matter and creativity, established through divergent thinking measurements using the Consensual Assessment Technique. Areas involved were those linking the thalamus to prefrontal cortices. Interestingly, previous studies have also demonstrated lower fractional anisotropy in bipolar disorder and schizophrenia (McIntosh et al., 2008). Analyses suggested that findings of lower fractional anisotropy in creativity were due to lower levels of myelination rather than loss of axonal integrity. The findings were corroborated by a third study, which used magnetic resonance spectroscopy (Jung, Gasparovic, et al., 2009). This study found an inversed correlation between the metabolite *N*-acetyl-aspartate (NAA) in right anterior gray matter and creativity. NAA is a marker of myelin synthesis.

PET, SPECT, and fMRI Studies. Studies using PET and SPECT reveal metabolic processes in the brain, and require injection of radioactive ligands. While these investigations may provide information on receptor densities in the brain, most studies have used these methods to investigate cerebral blood flow (Arden et al., 2010; Bechtereva et al., 2004; Carlsson, Wendt, & Risberg, 2000; Chavez-Eakle, Graff-Guerrero, Garcia-Reyna, Vaugier, & Cruz-Fuentes, 2007; Starchenko, Bekhtereva, Pakhomov, & Medvedev, 2003). Similar to studies using fMRI (Asari et al., 2008; Fink et al., 2009; Goel & Vartanian, 2005; Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005; Jung-Beeman et al., 2004; Kowatari et al., 2009; Mashal, Faust, Hendler, & Jung-Beeman, 2007; Son et al., 2015; Takeuchi et al., 2015), these studies have used different experimental paradigms and it is therefore difficult to draw any clear conclusions. Contrasting studies based on combining information vs. self-generation of unusual responses have nevertheless suggested that combination tasks activate more anterior areas of the lateral prefrontal cortex compared to tasks including self-generation of unusual responses (Gonen-Yaacovi et al., 2013). A recent study investigated the five-repeat allele of a common polymorphism in the dopamine D4 receptor (*DRD4*) gene, which has been associated with ADHD, and demonstrated increased originality proposed to be due to reduced task-induced deactivation in areas generally deactivated during attention-demanding working memory tasks (Takeuchi et al., 2015).

Thinking Outside The Box. An interesting PET study was performed by de Manzano and colleagues to assess dopamine D2 receptor (DRD2) density in relation to divergent thinking (de Manzano, Cervenka, Karabanov, Farde, & Ullen, 2010). There was a negative correlation between divergent thinking and dopamine receptor binding potential in the thalamus (Figure 7.2). Considering the central role of the thalamus in information processing, the authors suggested that the result of these findings could be a reduction in filtering of information flow (noise) and a subsequent excitation of cortical regions through decreased inhibition of prefrontal neurons. The result would be a decrease in prefrontal signal-to-noise ratio, with prefrontal cortical regions more easily switching to a wider association range (an increase in divergent thinking). This decreased signal-to-noise ratio should be disadvantageous in tasks requiring selective attention, and thus lead to an increased risk of unwarranted signals from the thalamus overwhelming cortical neurotransmission with cognitive disorganization and psychosis as a result. To conclude, the authors suggested that the decreased dopamine receptor binding potential in the thalamus could be due to increased endogenous dopamine providing thoughts framed within a less intact box.

Dopamine Metabolites in the Cerebrospinal Fluid. Dopamine has long been considered essential for creative cognition (Flaherty, 2005). It has been proposed that the focus and goal-directedness attained in creative arousal may be driven by mesolimbic dopaminergic activity (Flaherty, 2005). Consistent with this, dopamine antagonists, generally used as antipsychotics, suppress free associations vital for creative cognition (Flaherty, 2005).

Dopamine activity is commonly assessed by investigating the dopamine metabolite

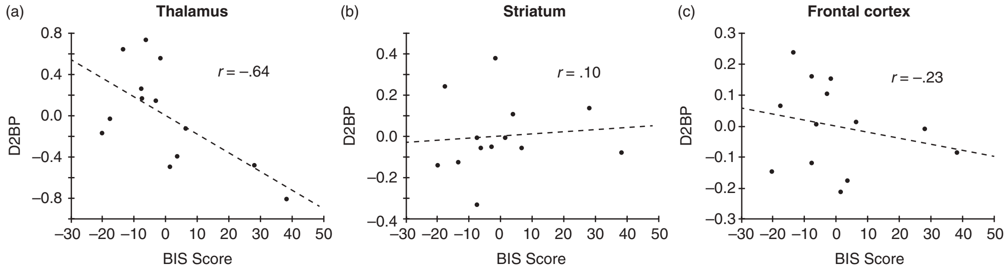

Figure 7.2 Correlations between divergent thinking (BIS score) scores and thalamic dopamine D2 binding potential.
Source: de Manzano, Cervenka, Karabanov, Farde, & Ullen (2010).

homovanillic acid (HVA) (Amin, Davidson, & Davis, 1992). HVA can be quantified in blood or urine, but is preferably quantified in cerebrospinal fluid (CSF) because this offers the opportunity to estimate dopamine activity in the brain without the contribution of HVA from other tissues (Amin et al., 1992); however, because sampling CSF requires a lumbal punction, CSF-HVA is generally less available for research than HVA in blood or urine samples.

We assessed CSF-HVA in 73 healthy individuals and compared levels of CSF-HVA to the CAQ (Kyaga, Fogelberg, Sellgren, & Landén, 2014). This was the first study to directly quantify a metabolite of dopamine in human CSF in relation to assessed creativity. Surprisingly, rather than supporting a positive correlation between dopamine activity and creativity, we found an inversed correlation between CSF-HVA and CAQ. These findings do not necessarily challenge previous proposals of increased dopaminergic activity in the limbic system, as the reduction in CSF-HVA may more accurately reflect a decrease of endogenous dopamine in prefrontal parts of the brain with sustained dopaminergic activity at, for example, the thalamus due to reduced density of D2 receptors (de Manzano et al., 2010). In support of this argument, studies of monkeys have shown that CSF-HVA reflects HVA in frontal cortical areas but not in other cortical areas (Elsworth, Leahy, Roth, & Redmond, 1987).

The Prefrontal Cortex. The prefrontal cortex (PFC) has been the focus of much interest from researchers in creativity (Gonen-Yaacovi et al., 2013; Runco, 2007a). Interestingly, following repetitive transcranial magnetic stimulation (rTMS) to create temporary "lesions" of the frontotemporal lobes, subjects created drawings judged as more life-like, flamboyant, and complex (Synder et al., 2003). It has been proposed that once a new idea has emerged it will be subjected to a value assessment by the PFC (Dietrich, 2004). This evaluation is essentially in parallel with the selection part of the Darwinian model of creativity discussed earlier in this chapter (Simonton, 1999a).

Provided that any person's cultural values and belief system are held within the PFC (Damasio, 1994), the evaluation will be colored by the individual's already upheld world view and previous experiences, i.e., "common sense." Common sense has been suggested to represent a form of knowing that provides the contextual assumptions about the world forming the basis of shared human existence (Owen, Cutting, & David, 2007). Such knowledge is essential, but largely taken for granted.

Patients with schizophrenia and those at risk of developing schizophrenia have regularly been found to exhibit structural abnormalities in the PFC, and have also been suggested to suffer impairments in common sense (Owen et al., 2007). Notably, this impairment has, however, also been shown to make patients less restrained by common sense in making *correct* logical deductions when in contrast to common knowledge. One may speculate that this tendency could also lead to a propensity in providing more original ideas (Kidner, 1976).

Implications

Given that the association between creativity and mental illness has important clinical implications, and that creativity and related areas such as inventions and innovations have such an impact on modern society, it is surprising that the consequences of recent findings in creativity and mental illness remain a highly fascinating topic for discussion, but fail to impact aspects of clinical care and societal structures.

Clinical

Psychiatric care has seen an astonishing development in the last decades. Today, almost all psychiatric disease areas exhibit evidence-based interventions that can provide a significant difference for patients. While brain stimulation therapies such as electroconvulsive therapy (ECT), rTMS, and deep brain stimulation (DBS) have seen recent advances (National Institute of Mental Health), the main therapeutic efforts in psychiatry are still focused along psychotherapeutic and pharmacological treatment alternatives. Both these areas could benefit from findings linking an association between creativity and psychopathology. This is not least as focus has shifted in treatment aims from mere reductions in symptomatology to improved social functioning and quality of life (Juckel & Morosini, 2008). Clearly, the ability for everyday creativity is related to both function and quality of life at its highest (Fayers & Machin, 2007).

Psychotherapy. Psychotherapy aims to help patients understand their illnesses, and to develop strategies and tools to address harmful thoughts and behaviors (National Institute of Mental Health). Today, psychiatry is dominated by cognitive behavioral therapy (CBT), which is a merger of two therapies: cognitive therapy (CT) and behavioral therapy (BT). CT is focused around a person's thoughts and beliefs, while BT aims to change unhealthy behavior.

Recent research into the association between creativity and bipolar disorder has suggested that CBT aimed to improve goal regulation skills for those with bipolar disorder may prove to be a valuable addition to current psychotherapeutic interventions (Johnson & Fulford, 2009). Similarly, art therapy has gained some empirical support as an addition to standard treatment in, for example, schizophrenia, where it has been suggested to be beneficial in addressing otherwise difficult to treat negative symptoms, such as lack of motivation and drive (Guhne et al., 2012).

Pharmacological. The discovery and subsequent introduction of pharmacological compounds during the 1950s enabled the deinstitutionalization of and home-care for many patients (Juckel & Morosini, 2008). In the beginning, focus of treatment was rather basic with the control of aggression, the reduction of self-harm and better hygiene as main drivers.

In schizophrenia, antipsychotics were mainly targeted to reduce positive symptoms such as hallucinations and delusions; however, increasingly, focus has been to treat negative symptoms and to reduce side effects. Today this ambition has been extended to provide benefits in social functioning and quality of life (Juckel & Morosini, 2008).

In general, antipsychotics exert their clinical effects by antagonizing dopamine D2 receptors (Stahl, 2013). Thus antipsychotics have been suggested to reduce creative abilities dependent on intact dopamine transmission (Flaherty, 2005). Given that the antagonizing effect differs between compounds, it seems likely that any resulting detrimental effect on creativity, and related social functioning and quality of life, should also differ between diverse antipsychotics. To date no study has specifically investigated the effects on creativity by antipsychotics.

In bipolar disorder, lithium has been the standard for treating bipolar disorder since the 1970s and remains the gold standard today (Hirschowitz, Kolevzon, & Garakani, 2010; Schou, Thomsen, & Armitage, 1971). Three studies have investigated lithium in relation to creativity specifically, although only two provide clear results. Shaw and colleagues examined the effect of lithium on the productivity and idiosyncrasy of written associations in 22 euthymic outpatients with affective disorder (Shaw, Mann, Stokes, & Manevitz, 1986). Lithium discontinuation produced a significant increase in associational productivity and idiosyncrasy, while restoration of lithium dosage reversed both these effects. On the other hand, Schou interviewed 24 "manic depressive" artists with lithium treatment about their creative abilities during treatment, and most (*n* = 12) reported favorable effects on artistic productivity in the long run (Schou, 1979).

In ADHD, stimulant medication remains at the core of treatment (Kooij et al., 2010). It not only improves symptoms and dysfunctional behaviors, but also improves related problems such as low self-esteem, anger outbursts, mood swings, cognitive problems, and social and family function. One study assessed creativity in 19 boys with ADHD and 21 comparison boys aged 8–11 (Funk et al., 1993). No changes in performance over medication state in the ADHD group were observed. Similarly, a study on healthy individuals found no evidence of hampered divergent thinking in relation to intake of mixed amphetamine salts compared to placebo (Farah, Haimm, Sankoorikal, & Chatterjee, 2009). In this author's clinical experience several ADHD patients with creative professions report alterations in creative thinking with stimulant medication ranging from small to noticeably hampering effects on idea generation, while most affirm a beneficial effect in relation to handling activities such as exhibitions and administrative duties. Thus, with the evolution of social functioning and quality of life as treatment aims, there is clearly an increasing need to investigate how different pharmacological interventions relate to creative abilities.

Society

Modern society is increasingly dependent on creativity (Florida, 2002), aptly framed by J. P. Guilford in his 1949 Presidential address to the American Psychological Association, as a natural resource that can pay high dividends to the whole of society (Guilford, 1950; Runco, 2014). Today both companies and states struggle to increase innovation. However, while most people have a positive attitude toward creativity, many are reluctant to embrace the new ideas of creative individuals (Torrance, 1995). Findings of a link between creativity and psychopathology could possibly serve to increase tolerance toward generally less-accepted behaviors by highlighting the need to embrace individual variation, and thereby facilitate a working environment which is more inclusive.

In fact, the main predictor of overall job performance among the big five personality traits is conscientiousness (Barrick, Mount, & Judge, 2001), which makes this trait likely to be exploited in the increasing use of psychometrics in recruitment (III, 2013). Importantly this trait is negatively correlated to aspects of creativity (Feist, 1998), and therefore any recruitment resting on this trait alone could potentially select against creative individuals.

Future Research

This chapter has suggested that objections to a link between creativity and psychopathology today do not accurately reflect the development of research in this field. Nevertheless, there are shortcomings in the present studies that need to be properly addressed. To a large extent these reflect the difficulties inherent in both research in creativity and psychiatry, the main being the definition of creativity and psychiatric disorders, respectively. Much has been said about the need to move the field of creativity research forward by increasingly differentiating the various aspects of creativity examined (Kaufman & Sternberg, 2010), so much so that some authors have even suggested abandoning the term *creativity* altogether (Runco, 2007a). Similarly, the development of psychiatric nosology in recent decades has been challenged (Andreasen, 2007; Insel, 2013). Thus, there is a need to further investigate the association between creativity and psychopathology using validated assessments of creativity and psychopathology in large samples, which has presently not been done. Some argue that it is time to move beyond repeating these findings (Claridge, 2012), and instead to expand this question to new ways of defining creativity in related areas. There is also a surprising lack of investigations into clinical aspects to provide support for decisions that may have great impact on patients' function and quality of life. Lastly, there is little empirical investigation into the actual mechanistic underpinnings of the link between creativity and psychopathology. This is most evident in the area of neuroscience, where we will likely see new exciting research in the coming years.

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8 Creativity and Psychopathology: A Relationship of Shared Neurocognitive Vulnerabilities

Shelley H. Carson

Creativity has been defined as the ability to generate ideas or products that are original and in some way useful or adaptive (Barron, 1969). The benefits of creativity to the individual and to society have been well documented. At the level of the species, human creativity and ingenuity have allowed for adaptation to a changing environment and improved survival odds (Richards, 1990). Creative work in the arts, music, literature, science, and medicine have added comfort and ease to daily living and have enriched the human experience. Humanists, such as Abraham Maslow (1970) and Carl Rogers (1961), have suggested that creativity is the pinnacle of psychological health and self-actualization. Indeed, recent research has suggested that engaging in creative activity has physical and mental health benefits (Cohen, 2006; Eschleman, Madsen, Alarcon, & Barelka, 2014).

However, there is a paradox. Creative genius has also long been associated with a tendency toward eccentricity and psychopathology. Both Plato and Aristotle made note of this (Aristotle, 1984; Plato, 360 BC), as did Shakespeare, who wrote “The lunatic, the lover and the poet / Are of imagination all compact” (Shakespeare, c. 1596/1891), and later still the enlightened poet/playwright John Dryden would add, “Great wits are sure to madness near alli’d/And thin partitions do their bounds divide” (Dryden, 1681). Lives of creative luminaries such as William Blake, Robert Schumann, Vincent van Gogh, Virginia Woolf, William Faulkner, Ernest Hemingway, Sylvia Plath, and John Forbes Nash, as well as the lives of contemporary creatives such as Robin Williams, Michael Jackson, and Amy Winehouse, seem to support the words of these historical thought leaders. They suggest that great wits may indeed be “near alli’d” with madness. But do these quotes and examples represent coincidence, or do they represent an actual underlying relationship between creativity and psychopathology?

In this chapter I will review psychometric, clinical, and neuroscientific research surrounding this controversy. I will describe several theories of the connection between creativity and psychopathology, with emphasis on the shared vulnerability model (Carson, 2011). This model, recently updated, suggests that neurocognitive mechanisms that underlie specific mental illnesses may be shared with, and may facilitate, high levels of creative ideation and production. Other neurocognitive variables may act as protective factors that, when combined with shared vulnerabilities, distinguish the poet from the psychotic. Resolving the creativity/psychopathology paradox and understanding the nature of the relationship of creativity to mental illness has implications for both the treatment of mental disorders and for the enhancement of creativity, a faculty that is important for the survival and enrichment of all humankind (Carson, 2014a).

Creativity and Mental Illness: What Does the Research Tell Us?

While early references to the creativity/mental illness connection consist of observations, such as those by Aristotle and Shakespeare, and examples from the lives of creative luminaries (see Lombroso, 1891/1976, for an early compendium), actual empirical evidence for the connection between creativity and psychopathology began to emerge in the mid-twentieth century. Studies of creative achievers at Berkeley's famous Institute for Personality Assessment and Research (IPAR) found that creative writers and creative architects had elevated scores on the Minnesota Multiphasic Personality Inventory (MMPI) scales of Schizophrenia and Paranoia (Barron, 1955; MacKinnon, 1962). Heston (1966) found that the adopted-away children of mothers with schizophrenia were more likely to hold creative jobs and have colorful lives than were the adopted-away offspring of mothers without schizophrenia. Shortly thereafter, Karlsson (1970) reported that males in Iceland born between 1881 and 1910 who had a psychotic relative were almost three times as likely to be registered in *Who's Who* for excellence in a creative field than those without a psychotic relative, and suggested that "some type of mental stimulation is associated with a genetic relationship to psychotic persons" (p. 180).

These findings sparked a new generation of researchers, beginning in the late 1980s, to examine the overlapping incidence of psychopathology with high creative achievement. Several categories of disorders associated with creativity emerged: mood disorders (especially bipolar disorder), schizophrenia-spectrum disorders (psychosis proneness), substance abuse disorders, and to a lesser extent, attention-deficit disorders (ADHD).

Creativity and Mood Disorders

While some researchers have compared the rates of mood disorders in highly creative subjects to those of matched controls, other researchers have used general population norms as control statistics. The National Comorbidity Survey Replication (Kessler et al., 2005) reports lifetime rates for mood disorders in the USA at 16.6% for major depression, 3.9% for bipolar 1 and bipolar II combined, and 20.8% for any mood disorder across the general population.

Inspired by the earlier Heston (1966) and Karlsson (1970) studies, noted schizophrenia researcher Nancy Andreasen (1987), using a case-study method, found that authors of the prestigious Iowa Writers' Workshop were four times more likely to suffer from bipolar disorder than the controls, and that fully 80% of the writers reported suffering from a mood disorder. In a similar subsequent study, Ludwig (1994) reported that rates of both depression (56%) and mania (19%) were higher in a group of 59 female writers in the University of Kentucky National Women Writer's Conference than those of controls matched for age and education.

Jamison (1989) also used case studies to examine mood disorders, and found an unusually high percentage of mood disorders generally (38.3%), as well as bipolar disorder specifically (6.4%) in award-winning writers and artists in the UK. She also charted periods of creative productivity against periods of elevated and depressed mood in her subjects, and reported that periods of creative productivity appeared to be associated with upswings in mood. Of interest, there is now a growing body of research that connects upswings of positive mood with increased expansive ideation and creative thinking in nondisordered groups as well (Ashby, Isen, & Turken, 1999; Frederickson, 2001).

Several studies have examined mood disorders and creativity from a historiometic perspective utilizing biographical information on creative luminaries. Post (1994) discovered that, in the 291 eminent men he evaluated for psychiatric disorder, the creative subjects in all professional categories demonstrated higher rates of mood disorder than members of the general population, with particularly high rates in authors. Ludwig (1992, 1995) analyzed psychiatric conditions in over 1,000 deceased individuals in 19 different professions using biographical data, and reported significantly higher rates of mood disorders among persons who were known for their contributions in creative arenas than among those from other professions. Schildkraut and his colleagues (1994) found that 57% of the 14 abstract expressionist painters from the New York school suffered from mood disorders, and Wills (2003) reported that 28.5% of 40 musicians who were considered innovative in the jazz industry between 1945 and 1960 suffered from mood disorders.

In two large population-based reports, Kyaga and colleagues (2011; 2013) examined creative professions and psychopathology status gleaned from Swedish registries. They found that individuals in artistic occupations had higher rates of bipolar disorder than those in noncreative professions, but lower rates of many other psychiatric illnesses, while writers had higher rates of unipolar depression (as well as other forms of psychopathology) than did nonwriters. First-degree relatives of those diagnosed with bipolar disorder were more likely to be in creative professions than persons without a psychiatric family history.

Baas and colleagues (2016) recently conducted two meta-analyses of the relationship between creativity and mood disorders. In an analysis of 28 studies, they found a positive and significant relationship between bipolar disorder and creativity; however, their analysis of 39 studies of unipolar depression and creativity yielded a less significant and small negative relationship (Baas, Nijstad, Boot, & De Dreu, 2016).

Examining creativity and mood disorders from the clinical perspective, Johnson and colleagues (2015) found that bipolar participants trended toward higher levels of creative accomplishment and also exhibited significantly larger variations in their level of creative achievements than control subjects (Johnson, Tharp, & Holmes, 2015). Richards and colleagues (1988) studied creativity and mental illness across the bipolar spectrum, and found that the first-degree relatives of subjects who had bipolar disorder, as well as subjects who had a less-severe form of the illness (cyclothymia), had greater creative accomplishments and interests than either nondisordered controls or the full-blown bipolar-disordered subjects themselves. Their results suggest that either milder forms of mood disorder or a hereditary risk for disorder may enhance creativity, but that full-blown bipolar illness may interfere with creative achievement. This inverted "U" hypothesis of creativity to psychopathology (Richards et al., 1988) is supported by the experiences of mood-disordered individuals themselves. For example, writers from Andreasen's (1987) Writers' Workshop study reported that both full-scale depressive and manic episodes interfered with their ability to work.

As we have seen, a number of different methods have been employed to study the relationship of creativity and mood disorders. The methodologies of some of these studies have been questioned (see Sawyer, 2012; Schlesinger, 2009). However, as Simonton (2014) points out, the convergence of evidence from such a variety of methods and alternative approaches is itself an endorsement of the existence of a creativity/mood disorders effect.

Creativity and Schizophrenia-spectrum Disorders

There is a rich literature describing psychotic and odd or eccentric behavior in creative individuals. William Blake, for example, described having hallucinations since childhood and believed that many of his poems and paintings, and an etching technique he developed, were channeled to him through spirits (Galvin, 2004). Isaac Newton, in addition to displaying eccentric behaviors, appears to have had a full psychotic break at the age of 51 (Westfall, 1994). The composer Robert Schumann believed that Beethoven and Mendelssohn were channeling musical compositions to him from their tombs (Jenson, 2001; Lombroso, 1892/1976), and Nobel prize-winning mathematician John Forbes Nash believed that aliens from outer space were contacting him with instructions on how to save the world (Nasar, 1998).

Despite the examples of psychosis within certain creative luminaries, most biographers have pointed out that these luminaries did not produce quality creative work when in a psychotic state (e.g., Nasar, 1998; Westfall, 1994). In fact, Eisenman (1990) found that psychotic persons were less creative than normal controls, and Kyaga et al. (2011) found that siblings of individuals with schizophrenia (but not the diagnosed schizophrenics themselves) were more likely to hold a creative profession than the norm. These findings suggest that some but not all of the schizophrenia genotype enhances creativity. Creative individuals are, indeed, more likely to exhibit subclinical traits related to psychosis rather than actual psychotic illnesses (Brod, 1987; Claridge, 1997). The predisposition to psychosis is referred to as schizotypal personality or schizotypy, and is often elevated in subjects who do not display actual psychopathology but may be considered odd or eccentric (see Claridge, 1997).

A number of studies in the 1980s and 1990s found that creative individuals had elevated scores compared to less-creative controls on a standard measure of schizotypy (Brod, 1987; Cox & Leon, 1999; Green & Williams, 1999; Poreh, Whitman, & Ross, 1994; Schuldberg, French, Stone, & Heberle, 1988). Prentky (2000–2001, p. 99) suggested that schizotypal scores may be elevated because creative individuals live "closer to the fringes of deviation."

Recent studies have made the distinction between *positive* and *negative* schizotypy. Positive schizotypy, or psychosis-proneness, is characterized by unusual perceptual experiences and magical thinking. These characteristics are subclinical manifestations of hallucinations and delusions – the *positive* signs of schizophrenia. Negative schizotypy is characterized by social anhedonia (lack of desire or pleasure in socializing with others) and cognitive disorganization – subclinical manifestations of the *negative* signs of schizophrenia (Mason & Claridge, 2006).

A number of studies have found that creativity in the arts seems to be associated elevated positive schizotypy but not negative schizotypy traits (e.g., Burch, Pavelis, Hemsley, & Corr, 2006; O'Reilly,Dunbar, & Bentall, 2001). Additional studies have suggested that while positive schizotypy is associated with creativity in the arts, negative schizotypy is associated with creativity among scientists and mathematicians (Nelson & Rawlings, 2010; Nettle, 2006; Rawlings & Locarnini, 2008). In sum, the results of these studies suggest that individuals in fine arts fields (artists, writers, and musicians) may have a pattern of elevated predisposition to psychosis, while scientists do not tend to show this pattern. A meta-analysis of 45 studies yielded a mild but significant positive relationship between positive schizotypy and creativity, but a less-robust negative relationship between negative schizotypy and creativity (Acar & Sen, 2013).

In support of the "inverted U" hypothesis of creativity and psychopathology, Kinney et al. (2000–2001) found that schizophrenia-spectrum traits tend to run in families, and that creativity levels were higher in subjects who displayed schizotypal traits than in subjects with either no schizotypal traits or with full-blown schizophrenia.

Creativity and Alcoholism

Since the time of the ancient Greeks, creative luminaries have used alcohol and other psychoactive drugs as a method of summoning the muse (Aristophanes, 424 BC). Novelist William Styron has described alcohol as "the magical conduit to fantasy and euphoria, and to the enhancement of the imagination" (Styron, 1990, p. 40). Research on creativity and alcoholism does indeed indicate a greater prevalence of alcoholism among creative groups than in the general population, especially among creative writers. Thirty percent of the writers from Andreasen's (1987) Iowa Writers' Workshop study suffered from alcoholism, compared to 7% from the control group. Fourteen percent of the writers, composers, and artists from Post's (1994) biographical review of famous men met diagnostic criteria for alcoholism, more than twice the rate found in the general public, which is estimated at 5.4% in the National Comorbidity Survey Replication (Kessler et al., 2005). Ludwig (1992) found elevated alcoholism across creative professions: artists (22%), composers (21%), musical performers (40%), actors (60%) fiction writers (37%), and poets (30%). Of the eight American novelists who won the Nobel Prize before 1990, five were confirmed alcoholics (Dardis, 1989).

Some experimental studies have found that a dose of alcohol can indeed stimulate certain stages of the creative process, generally during the insight phase (Jarosz, 2012; Norlander, 1999); however, other work indicates that creativity-related *expectancies* of alcohol consumption interact with alcohol's effects, such that alcohol only enhances creative insight in those who expect it to do so (Hicks, Pedersen, Friedman, & McCarthy, 2011).

As with other disorders, it appears that there is an "inverted U" association between alcoholism and creativity. Although creative individuals may have expectancies that drinking inspires creativity (Hicks et al., 2011), full-blown alcoholism appears to be detrimental to creative efforts. In a review of the effects of alcohol on the creative production of 34 heavy-drinking creative achievers, Ludwig (1990) found that 59% believed that alcohol facilitated their creativity during the early phases of their drinking. However, 75% of the sample believed that alcohol had a direct negative effect on their work in the later phases of their drinking careers.

Creativity and ADHD

There is a growing body of research that indicates a relationship between symptoms of ADHD and enhanced creativity. A number of creative luminaries, past and present, have displayed characteristics of ADHD. According to Cramond (1995), these include Thomas Jefferson, Robert Frost, Frank Lloyd Wright, Samuel Taylor Coleridge, Virginia Woolf, and Nikola Tesla. Kyaga et al. (2013) found higher rates of ADHD in members of the writing profession than in nonwriters in the Swedish population. Several studies have reported increased scores on aspects of creativity or divergent thinking tasks in children or adolescents with ADHD (Abraham, Windmann, Siefen, Daum, & Güntükün, 2006; Cramond, 1994; Fugate, Zentall, & Gentry, 2013; Shaw & Brown, 1991; Zentall, 1988). Studies have also shown an elevated level of ADHD symptomatology in creative or gifted children (Healey & Rucklidge, 2006). Additional studies indicate that adults diagnosed with ADHD score higher on both cognitive (White & Shaw, 2006, 2011) and real-world creative accomplishments (White & Shaw, 2011).

In support of the inverted-U hypothesis of creativity and psychopathology, Healey and Rucklidge (2006) found that in a group of highly creative children, 40% had elevated scores on a measure of ADHD symptoms (about four times greater than would be expected in the general population); however, none of the gifted children met full criteria for an actual ADHD diagnosis.

One of the features of ADHD is a pattern of mind-wandering that appears to be under bottom-up, rather than top-down, control (Seli, Smallwood, Cheyne, & Smilek, 2015). Mind-wandering has been shown to be important to the creative process, with several studies linking mind-wandering to an increase in creative problem-solving (Tan, Zou, Chen, & Luo, 2015; Zedelius & Schooler, 2015). In the brain, mind-wandering is related to activation of the default mode network (DMN), a set of midline brain regions including the medial prefrontal cortex, posterior cingulate, and the precuneus (Buckner, Andres-Hanna, & Schachter, 2008). The DMN is active during imagination, and is thus considered an important aspect of the neurobiology of creativity (Agnati, Guidolin, Battistin, Pagnoni, & Fuxe, 2013).

In summary, a review of research on creativity and psychopathology supports two conclusions: (1) there is an association among symptoms of mood disorders (especially bipolar disorder), psychosis-proneness, alcoholism, possibly ADHD, and high levels of creativity; and (2) there is a dose-dependent relationship between creativity and psychopathology, with milder symptom sets being more conducive to creativity than more severe forms of disorder.

Creativity and Psychopathology: Possible Explanations for a Connection

A number of theories have been proposed to account for the higher incidence of certain forms of psychopathology among highly creative individuals (e.g., Becker, 2000–2001; Richards, 1990). Sociocultural models suggest that there is a cultural expectation that creative people will display eccentric or bizarre behavior and that, by exhibiting "symptoms" of mental illness, creative people are either purposely enhancing their creative credentials, or are merely acting out the part that the culture has assigned to them. Another sociocultural model, the "social drift" theory, suggests that people with mental illness tend to drift away from standard nine-to-five occupations which may require rule-based behaviors, and in turn drift toward creative professions such as writing, art, or music that accommodate their more unconventional lifestyles (Ludwig, 1995). Finally, labeling a creative person as "mentally ill" may be a method of silencing innovative ideas that threaten the status quo.

Sociocultural theories are likely to explain some portion of the overlap between creativity and psychopathology. However, family and adoption studies that show heritability patterns of creativity and psychopathology (e.g., Heston, 1966; Jamison, 1993; Karlsson, 1970; Kyaga et al., 2013), neuroimaging research that describes underlying anatomical and functional correlates of of creativity and psychopathology (e.g., de Manzano et al., 2010), and molecular genetic studies that indicate common genetic alterations (e.g., Kéri, 2009) suggest that there may be an underlying biological relationship between creativity and psychopathology.

The shared neurocognitive vulnerability model suggests that psychopathology and creativity may share genetic components that are expressed as either psychopathology or creativity depending upon the presence of other moderating factors (Berenbaum & Fjuita, 1994; Carson, 2011). This model could explain why highly creative individuals are at greater risk for psychopathology than the general population. It could also explain why not all highly creative individuals express psychopathology and, conversely, why not all mentally ill individuals express unusual creativity. It could explain the increased levels of creativity in first-degree relatives of individuals with serious psychopathology (e.g., Heston, 1966; Karlsson, 1970; Kyaga et al., 2013). Finally, it could explain why certain mental disorders remain in the gene pool despite their obvious negative consequences for humanity and the lower incidence of reproduction among those who suffer from them. The shared vulnerability model suggests that aspects of the genotype of such disorders may confer positive advantage for humanity by increasing creativity when paired with protective factors, thus promoting human adaptability.

The Shared Neurocognitive Vulnerability Model of Creativity and Psychopathology

The disorders that have been associated with creativity, as well as creativity itself, are both heritable and polygenetic (Berrettini, 2000; Whitfield et al., 1998). Molecular biology studies indicate that these disorders themselves may share some of their genetic underpinnings (e.g., Sharp et al., 2014). The polygenetic nature of creativity-related disorders suggests that an aggregation of gene-related contributions is necessary for these disorders to be fully expressed. However, persons who inherit a subset of this genetic aggregation may express cognitive effects that are beneficial to human experience, especially when combined with a set of protective mechanisms. For example, certain mental illnesses may provide entry into altered brain states that allow access to material that is normally filtered from conscious awareness. This could provide a neurobiological pathway through expanded *doors of perception* (Huxley, 1954), thereby promoting experiences of creative insight.

Support for the model was recently provided by Power and colleagues (2015), who completed a number of landmark studies that tested whether polygenetic risk scores for bipolar disorder and schizophrenia would predict creativity in large Icelandic, Swedish, and Dutch samples. They found that higher composite risk scores for the two disorders were associated with several indicators of creativity, including membership in an artistic society, a creative profession, or high creative achievement scores. Although the specific polymorphisms included in the polygenetic risk profile were not specified, they were computed from the results of the genome-wide association studies published by the Psychiatric Genomics Consortium (Power et al., 2015).

Genetic polymorphisms, such the D2 dopamine receptor (*DRD2*) gene TaqI A+ allele, have been associated with alcoholism (Connor, Young, Lawford, Ritchie, & Noble, 2002), schizophrenia (Golimbet, Aksenova, Nosikov, Orlova, & Kaleda, 2003), bipolar disorder (Wang et al., 2014), and creativity (Reuter, Roth, Holve, & Henning, 2006a). An allele of the D4 dopamine receptor (*DRD4*) gene has been associated with both creativity and ADHD (Takeuchi et al., 2015). Other polymorphisms, including the dopamine transporter (*DAT*) gene and the catechol-*O*-methyltransferase (*COMT*) gene which controls an enzyme that degrades dopamine and other catecholamines, have been associated with creativity and mental illness. These polymorphisms have been shown to have complex interactions relative to creativity (e.g., Murphy, Runco, Selcuk, & Reiter-Palmon, 2013; Zabelina, Colzato, Beeman, & Hommel, 2016; Zhang, Zhang, & Zhang, 2014), which are only just beginning to be understood. These findings suggest that there is a shared genetic vulnerability between creativity and the forms of mental disorder we have been discussing, even if the specific nature of that vulnerability has yet to be unraveled.

Individuals with a predisposition to mental disorder may utilize uncommon strategies, or they may use familiar strategies in unusual ways, to solve creative tasks (Carson, 2014c). Many biographical accounts of the creative process (see Ghiselin, 1952) include descriptions of creative ideas and solutions that arose from unknown sources and came into the person's conscious awareness in a manner somewhat similar to the delusional subtype of thought insertion. John Forbes Nash, in fact, said that his delusions about aliens from out space and his creative mathematical formulae "came to me in the same way" (Nasar, 1998, p. 11). Clearly, as the work of Power et al. (2015) indicates, some part of the polygenetic risk for bipolar disorder or schizophrenia is contributing to creative tendencies.

I have proposed several mechanisms, often associated with psychopathology, that could enhance creativity (Carson, 2011): cognitive disinhibition (which may promote access to material normally outside of conscious awareness), novelty-seeking (which may provide motivation for novel or original tasks), and unusual neural hyperconnectivity (which may lead to unusual associations or combinations of pre-existing information). These mechanisms constitute the set of currently identified shared vulnerability factors. Currently identified protective factors include high IQ, enhanced working memory capacity, and cognitive flexibility (see Figure 8.1). The shared vulnerability model is fluid and will expand as our knowledge of brain function and gene interactions increases.

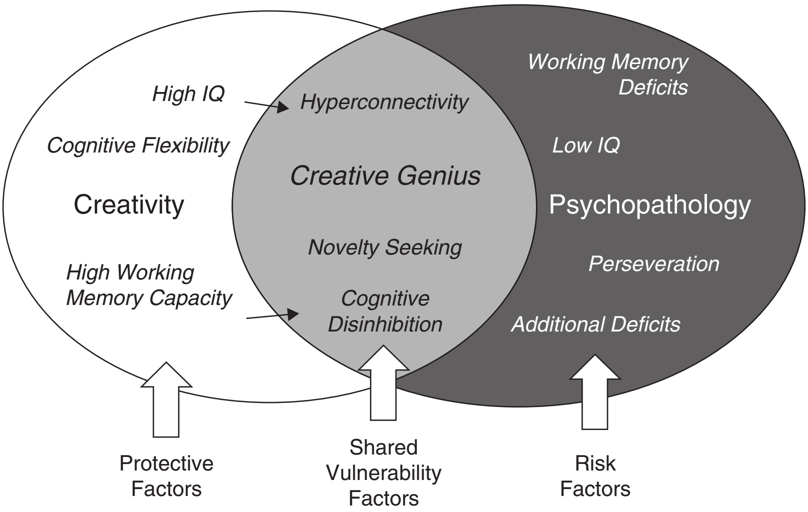

Figure 8.1 The shared neurocognitive vulnerability model of creativity and psychopathology.

Shared Vulnerability Factors

Cognitive Disinhibition. Latent inhibition (LI), a form of cognitive inhibition, is the capacity to screen from conscious awareness stimuli previously experienced as irrelevant. Thus, LI acts as a kind of cognitive filter. When LI is reduced, cognition is disinhibited and information that would typically be categorized as irrelevant is allowed into conscious awareness (Lubow & Gewirtz, 1995). Reduced LI has been associated with schizophrenia, schizotypal personality, and high levels of psychosis-proneness (Baruch, Hemsley, & Gray, 1988a,b; Lubow, Ingberg-Sachs, Zalstein-Orda, & Gewirtz, 1992). Reduced LI has also been noted in subjects with ADHD (Lubow & Josman, 1993) and in alcoholics (Fink, Slamar-Halbedl, Unterrainer, & Weiss, 2012), suggesting that reduced LI is a salient trait in many of the mental disorders associated with creativity.

Relative to creativity, reduced LI has been associated with openness to experience, a personality trait robustly correlated with measures of creativity (Peterson & Carson, 2000; Peterson, Smith, & Carson, 2002), and with high creative achievement scores in high IQ samples (Carson, Peterson, & Higgins, 2003; Fink et al., 2012; Kéri, 2011). When reduced cognitive inhibition was induced experimentally in the lab, subjects produced more frequent and more original responses to a divergent thinking creativity task (Radel, Davranche, Fournier, & Dietrich, 2015). While considered a risk for psychosis and attention disorders across a normal distribution of the population, cognitive disinhibition may enhance creativity, especially when combined with exceptional cognitive abilities, by increasing the inventory of unfiltered stimuli available in conscious awareness and thereby improving the odds of synthesizing novel and useful combinations (Carson et al., 2003).

Cognitive disinhibition in the form of reduced LI is associated with increased dopaminergic activity in the striatal system of the brain, with D2 receptors playing a pivotal role (Diaz, Medellín, Sánchez, Vargas, & López, 2015). Administration of D2 agonists, such as D-amphetamine, known to produce psychosis-like symptoms in humans, reduces LI in both animals and humans (Gray, Pickering, Hemsley, Dawling, & Gray, 1992). While no human genes have so far been implicated in cognitive disinhibition, a variant of the Neuregulin 1 (*NRG-1*) gene has been associated with reduced LI in mice (Rimer, Barrett, Maldonaldo, Vock, & Gonzalez-Lima, 2005). A polymorphism of the promoter region of the *NRG-1* gene, which has been associated with susceptibility to psychosis, has also been found to be prevalent in high creative achievers with high IQs (Kéri, 2009). Kéri (2009) hypothesized that reduced LI might be the result of this polymorphism in humans. The findings related to dopamine D2 binding and *NRG-1* polymorphisms support cognitive disinhibition, expressed as reduced LI, as a viable candidate for shared vulnerability between creativity and mental illness.

Novelty-seeking. Novelty-seeking is a motivational tendency to explore novel aspects of ideas, objects, or environments. Creative individuals tend to be novelty-seekers and to prefer novel or complex stimuli over familiar or simple stimuli (McCrae, 1993; Reuter et al., 1995). Novelty-seeking is associated with activation of the dopaminergic reward system and with increased internal reward for attending to novel stimuli (Cloninger, Svrakic, & Przybeck, 1993), suggesting an intrinsic motivation for intellectual curiosity and for attending to novel ideas and projects in creative individuals (Schweizer, 2006). However, novelty-seeking is also associated with alcohol abuse and addiction (Grucza et al., 2006), ADHD (Lynn et al., 2005), and with comorbid states of bipolar disorder and alcoholism (Frye & Salloum, 2006). Novelty-seeking may, therefore, be both a motivation for creative work and a risk factor for psychopathology.

Cloninger (1987, p. 574) described novelty-seeking as a “heritable tendency toward intense exhilaration or excitement in response to novel stimuli.” Genetic studies have linked the A1+ allele of the TAQ 1A polymorphism of the *DRD2* (D2 dopamine receptor) gene with novelty-seeking, and also with schizophrenia and addiction (Golimbet et al., 2003; Noble, 2000; Reuter, Schmitz, Corr, & Henning, 2006b). This same allele of the *DRD2* gene was linked to creativity in a sample of German university students (Reuter et al., 2006a). The dopamine D4 receptor (*DRD4*) gene and the dopamine transporter gene (*DAT*) have also been linked to novelty-seeking (Ekelund, Lichtermann, Jarvelin, & Peltonen, 1999), risk for schizophrenia and bipolar disorder (Serretti & Mandelli, 2008), and risk for adult ADHD (Hasler et al., 2015). Novelty-seeking may thus be considered another shared vulnerability factor between creativity and certain disorders of psychopathology.

Hyperconnectivity. Hyperconnectivity refers to the abnormal neural linking of brain areas that are not typically functionally connected, or to linking that is unusually pervasive in the areas involved. Unusual patterns of cortical connections, both hyperconnectivity and hypoconnectivity, have been associated with schizophrenia (Whitfield-Gabrieli et al., 2009), bipolar disorder (e.g., Favre, Baciu, Pichat, Bougerol, & Polosan, 2014), schizotypal personality (Folley & Park, 2005), and ADHD (Hoekzema et al., 2014). Likewise, unusual connectivity patterns have been noted in high-scoring creativity subjects (Takeuchi et al., 2010, 2012). Hyperconnectivity may also be indicated by simultaneous activation of cortical areas. Brain imaging studies (e.g., Fink et al., 2009) have reported more alpha synchronization, within and across hemispheres, in high versus less-creative subjects while performing creativity tasks. McCrea (2008) has suggested that the association of brain regions that are not normally connected in the average brain may be a factor in the production of creative insights and original works. If that is the case, it provides a stunning neural basis for Mednick’s (1962) theory that unusual and remote associations among objects or ideas can lead to creative production.

An unusual pattern of connections has been noted in the DMN of individuals with high creativity scores and those with certain mental illnesses. The DMN has been shown to be active during daydreaming and imagining; it is typically anticorrelated with the task-positive network of lateral prefrontal areas that are active during attention-demanding tasks (Fox et al., 2005). Connectivity within the DMN appears to be influenced by striatal dopamine, including dopamine transporter binding and genetically determined dopamine D2 receptor signaling (Sambataro et al., 2013). The DMN has been shown to be particularly important to creative ideation (Kühn et al., 2014). However, recent studies have indicated unusual activations between parts of the DMN and the task-positive network in creative subjects (Beaty et al., 2014; Takeuchi et al., 2011), as well as schizotypal subjects (Fink et al., 2014), subjects at high risk for psychosis (Falkenberg et al., 2015), alcoholics (Sayette, Reichle, & Schooler, 2009), and subjects with ADHD (Fassbender et al., 2009; Metin et al., 2015). In all of these studies regions of the DMN in target groups remain active when selective attention is required for optimal task performance, suggesting abnormal connectivity between anticorrelated networks. Takeuchi et al. (2011) suggested that this abnormal activation may indicate the inefficient reallocation of attentional resources. In creative individuals with adequate protective factors, this abnormal connectivity could increase the availability of disparate stimuli to combine in novel ways.

Protective Factors

High IQ. High IQ acts as a protective factor in risk for a variety of mental disorders (Barnett, Salmond, Jones, & Sahakian, 2006). Low IQ, on the other hand, has consistently been associated with risk for schizophrenia (Woodberry, Giuliano, & Seidman, 2008), and children with ADHD typically score lower on IQ tests than those without ADHD (Healey & Rucklidge, 2006). The relationship between IQ and creativity is complex; however, research suggests that a threshold IQ score of around 120 is necessary for high-level creative work in many domains (Sternberg & O'Hara, 1999). Within every mental illness there is a distribution of IQ (Černis et al., 2015), even if the distribution is positively skewed toward lower IQ – as in the case of schizophrenia and ADHD. We would expect, then, that creativity scores would be higher in those individuals who display high IQ concurrent with vulnerability to disorder than those who display lower IQ and the same vulnerability.

Healey and Rucklidge (2006) found that a group of gifted (high-IQ) children with ADHD symptoms indeed scored higher on creativity measures than a group of equally gifted children without ADHD symptoms or ADHD children who were not gifted. Likewise, in a study of children in a summer camp for the gifted, Fugate et al (2013) found children of high IQ who displayed ADHD characteristics had higher scores on divergent thinking creativity tasks than high-IQ children without ADHD characteristics. These studies point to a creative advantage for the combination of high IQ and some sort of attentional deficits.

My colleagues and I tested the hypothesis that cognitive disinhibition (as measured by reduced LI) combined with high IQ would predict creativity. We speculated that if reduced LI increases the amount of stimuli available in conscious awareness, then high IQ might allow the individual to process and manipulate those additional stimuli to formulate more creative associations. We found that this was in fact the case; our group of low-LI/high-IQ subjects had significantly higher creative achievement scores than either the high-IQ/high-LI or moderate-IQ/low-LI groups. In fact, reduced LI and high IQ predicted up to 30% of the variance in creative achievement scores (Carson et al., 2003) (see Figure 8.2).

These results have been replicated in a Hungarian sample (Kéri, 2011), and partially replicated in a study of subjects who recalled memories of past lives (Meyersburg, Carson, Mathis, & McNally, 2014). High IQ combined with shared vulnerability factors may enhance creativity, as well as protecting against more serious manifestations of mental disorder.

Working Memory Capacity. Working memory (WM) is the capacity to hold information

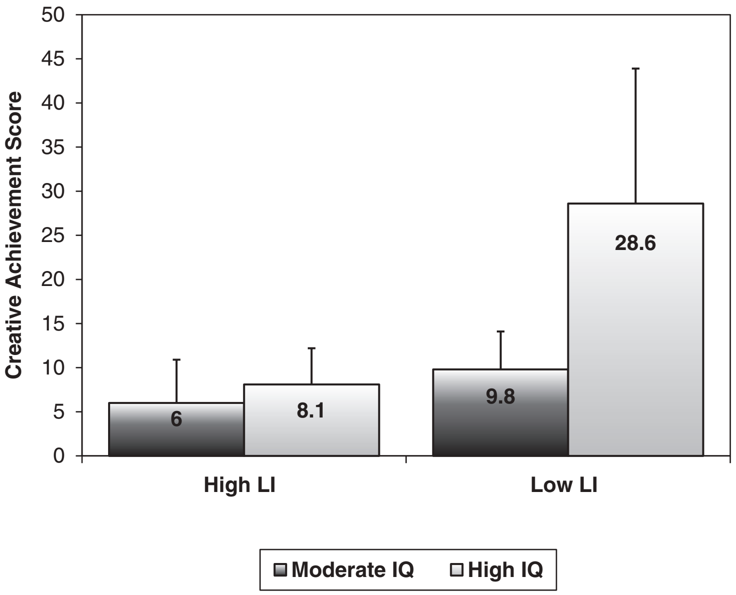

Figure 8.2 High IQ and reduced latent inhibition predict creative achievement in eminent achievers and controls. Printed with permission from Carson et al. (2003).

in mind, to process it, and to manipulate it (Diamond, 2013). WM is important to the creative process, allowing a search through the initial problem space (Wiley & Jarosz, 2012) and the ability to hold information that can then be manipulated to make novel and original combinations. The more difficult and complex a problem, the more important WM appears to be in its solution (Ash & Wiley, 2006).

In creative work, the form of information to be manipulated and processed may be abstract or almost formless. It may consist of seeds of ideas that have not fully developed, described by Einstein as “elements of thought … before there is any logical construction with words or other kinds of signs that can be communicated to others” (quoted in Ghiselin, 1952, p. 32). Like high IQ, WM capacity for elements of thought may allow the additional stimuli generated through cognitive disinhibition to be processed and manipulated in what Einstein referred to as “combinatory play” (Ghiselin, 1952, p. 32). In a test of this hypothesis in our lab at Harvard, we found that high scores on a measure of abstract WM combined with reduced LI predicted creative achievement scores in a group of high-achieving students (Carson, 2001). WM for abstract forms was also associated with solving creative insight problems in a sample of college undergraduates (DeYoung, Flanders, & Peterson, 2008). If creative ideas arise from combining and rearranging elements of thought that are only remotely associated with each other, as proposed by Mednick (1962), then the ability to hold and process a large number of elements simultaneously in mind without becoming confused or overwhelmed should enhance creative rather than disordered cognition.

WM is also considered an executive function that is headquartered in the lateral prefrontal cortex. A number of studies have provided evidence for the importance of the dopamine D1 receptor family in performance on WM tasks (Puig, Rose, Schmidt, & Freund, 2014). Decreased WM capacity is associated with schizophrenia-spectrum disorders (Goldman-Rakic, 1994) and ADHD (Alderson, Kasper, Hudec, & Patros, 2013), with alterations in dopamine D1 receptor availability in the prefrontal cortex (PFC) that may be related to the WM impairments. D1 agonists have also been found to improve WM performance in impaired schizotypal subjects (Rosell et al., 2015).

Cognitive Flexibility. Cognitive flexibility is the ability to disengage attention from one stimulus or concept and refocus it on another through top-down mental control. As an executive function, cognitive flexibility may offer creative persons the ability to change perspectives and also disengage from obvious problem solutions to find less common solutions. Dietrich (2003) has suggested that creative individuals have the ability to modulate neurotransmitter systems in the brain to allow flexibility in shifting from a state of attentional focus to one of temporary cognitive disinhibition. This type of cognitive flexibility could allow individuals to experience disinhibition but also allow them to disengage from unusual thoughts or perceptions, rather than interpreting them in a psychotic manner (O'Connor, 2009).

Cognitive flexibility is dependent upon dopamine availability in the prefrontal cortex and striatal pathways, and individual differences are related to variants of several dopaminergic genes (Samanez-Larkin et al., 2013). Deficits in cognitive flexibility are seen in people with schizophrenia (Thoma, Wiebel, & Daum, 2007) and ADHD (Kramer, Cepeda, & Cepeda, 2001). However, cognitive flexibility is a major aspect of creative thought and production (Baas, De Dreu, & Nijstad, 2008). It is possible that creative individuals with shared vulnerabilities are able to use cognitive flexibility to promote alternating states of cognitive disinhibition and conscious executive control of attention, first allowing novel stimuli to slip into conscious awareness and then allowing the deliberate and rational evaluation of these ideas (Carson, 2014b).

In summary, a set of shared neurocognitive vulnerability factors have been identified that may be common to both high levels of creativity and certain mental disorders. These vulnerability factors appear to involve abnormal availability of dopamine (in particular D2 pathways) in the striatal areas of the brain. The identified vulnerability factors disinhibit cognition, thus increasing the availability of stimuli in conscious awareness, promote attention and internal reward to novel stimuli, and allow for a broader array of unusual cognitive associations. A complimentary set of protective factors that promote healthy creative thought has also been identified. These protective factors appear in part to involve availability of dopamine (in particular D1 pathways) in the prefrontal areas of the brain. Identified protective factors enhance the ability to solve problems fluidly, retain and manipulate elements of thought, and flexibly direct attention from one idea to another. These protective factors are typically absent or poorly represented in persons with vulnerability to disorders. However, when shared vulnerability factors and protective factors coincide, they may spark extraordinary creative accomplishment.

The Shared Vulnerability Model and Other Theories

Baas and colleagues (2016) have presented a theory of the relationship between creativity and psychopathology based on the biological systems of approach and avoidance. They provide evidence that creativity is positively associated with disorders of the dopamine-mediated approach system (including bipolar disorder, positive schizotypy, and ADHD), and negatively associated with disorders of the avoidance system (including unipolar depression, anxiety disorders, and negative schizotypy). To their analysis, I would add alcoholism as an additional disorder of approach, as it is also associated with dopamine dysregulation (Volkow et al., 2013), behavioral approach system (BAS) activation (Alloy et al., 2009), is highly comorbid with other approach system disorders (Capusan, Bendtsen, Marteinsdottir, Kuja-Halkola, & Larsson, 2015; Kessler et al., 2005), and is elevated in many studies of creative luminaries (e.g., Ludwig, 1995). Baas et al. (2016) demonstrate that the BAS is associated with several of the vulnerability factors (including novelty-seeking, reduced LI, and broad activation of associational networks), as well as one of the protective factors (cognitive flexibility) that are part of the shared vulnerability model. Thus, the two models are complementary and overlapping, but they approach (no pun intended) the creativity/psychopathology question from either the perspective of overarching motivational systems (Baas et al., 2016) versus more fine-grained neurocognitive mechanisms (Carson, 2011).

I began this chapter by discussing the paradox of creativity and mental health. On the one hand, there is evidence that creativity is a crucially important human trait that is associated with positive mental health, while on the other hand there is evidence of some increased risk for mental illness in high-level creative achievers. Simonton (2014) refers to this as the "mad genius paradox," and suggests a theory to explain it. He proposes that, across the spectrum of creative accomplishment, creativity is related to positive mental health and creative people are at less risk for mental illness than those who are not creative. However, as the level of creative achievement increases the risk for psychopathology also increases. Thus, the risk for mental disorder is borne by those at the highest end of the creative achievement distribution, accounting for the bulk of the findings connecting creativity to psychopathology. This theory dovetails well with the shared vulnerability model (see Figure 8.3). Individuals who are armed with protective factors but lack the vulnerability factors within the model represent the large group who contribute the ordinary magic of human creativity. Only those creators with shared vulnerability factors and protective factors will be at greater risk for psychopathology. However, that shared vulnerability is what I contend provides the extra "spark" that takes creativity from the realm of ordinary magic to the level of genius.

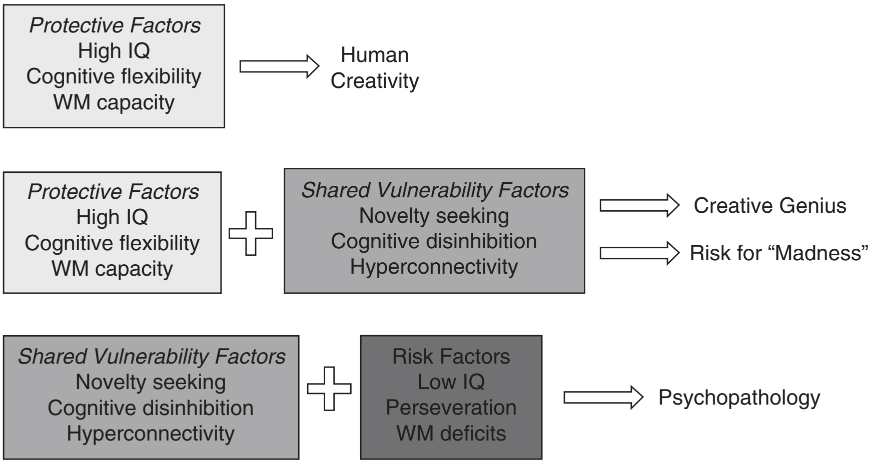

Figure 8.3 The mad genius paradox and the shared neurocognitive vulnerability model of creativity and psychopathology.

Notes. For details on the mad genius paradox, see Simonton (2014).

Conclusions

Creativity is an important and sought-after trait that confers adaptability and richness to the lives of humans. However, in this chapter, I have reviewed a large body of research that suggests creative individuals are at greater risk for certain forms of psychopathology than are members of the general public. The research does not suggest that all, or even a majority, of those who achieve high levels of creative accomplishment suffer from mental illness; they merely appear to display a somewhat greater *risk*, often manifesting in subclinical trait presentation. Although the validity of some of this research has been disputed, the confluence of evidence from biographical, empirical, neuroscientific, and molecular genetics sources seems to support the presence of some sort of connection between creativity and psychopathology. Hypotheses as to the nature of this connection span sociocultural, psychological, and biological speculations. A shared neurocognitive vulnerability model of the relationship of creativity and psychopathology appears to accommodate the existing data.

Creative individuals may display neurocognitive vulnerabilities that are also present in specific mental illnesses, such as mood disorders, schizophrenia-spectrum disorders, alcoholism, and ADHD. These vulnerabilities may provide access to disinhibited states of consciousness, increase attention to novelty, promote unusual associations through uncommon neural connectivity, and focus attentional resources inward. Cognitive strengths, such as high IQ, strong WM capacity, and cognitive flexibility may interact with these vulnerabilities to enhance creativity and perhaps protect against severe forms of the relevant disorders.

Additional shared vulnerabilities and protective factors will warrant inclusion in future iterations of the model as our knowledge of the amazing human brain develops. Future protective factors may encompass environmental as well as neurocognitive factors as research continues to explore the fascinating world of gene × environment interactions. Kéri (2011), for example, demonstrated that social support networks (a robust protective factor for many mental disorders) interacted with reduced LI and high IQ to predict creative achievement.

We do not know where our human creativity will lead us. The future often appears chaotic, and it has been suggested that psychopathological risk may allow at least some of our most creative individuals to stand on the brink of chaos and find a way to make order out of the confusion. The more we can learn about the perilous balance of creative achievers on this brink, the more we can help them avoid the most severe repercussions of their risk and the more we can devise ways to enhance creativity in us all.

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Part III

Attention and Imagination

00:15:14

9 Attention and Creativity

Darya L. Zabelina

> I need solitude for my writing: not “like a hermit” – that wouldn’t be enough – but like a dead man.
>
> (Franz Kafka)

> Marie Curie’s focus allowed “no lapses of attention.” She concentrated her attention “without even hearing the mounting roar of chatter.”
>
> (Curie & Scheean, 2001, p. 97)

Creativity is a way of embracing originality and making unique connections between seemingly disparate ideas. The root meaning of the word “create” means to “arise, grow,” therefore creativity and innovation is a growing of sorts – from an individual to the entire civilization. Although not all creations are byproducts of novel or creative cognition, as some are “created” upon existing knowledge and routine building, nonetheless from the invention of the wheel to Mozart’s sonatas some of the world’s major achievements are the result of creative thinking.

Although they were arguably both creative individuals, Franz Kafka, one of the most influential authors of the twentieth century, was so distracted by noise that he needed complete solitude, “like a dead man,” for his writing; while Marie Curie, a physicist and chemist who conducted pioneering research on radioactivity, was able to tune out noise so well that she didn’t hear “the mounting roar of chatter.” Described below are three most prominent theories on the link between creativity and attention, followed by most recent evidence suggesting that, indeed, different forms of attention are linked with different types or measures of creativity.

What is Attention?

The main function of attention amounts to the selection of relevant information, and rejection of irrelevant information (Posner, 1988). Without selective attention, we would have to process too many details, which, in consequence, would inevitably result in cognitive overload. Moreover, without selective attention we would have to process entirely irrelevant details, which could result in many cognitive faults and biases. Thus, in order to deal efficiently with cognitive tasks, we need to take into account only a small fraction of potentially available, and relevant, information. In other words, attention is necessary to select what is important and to ignore what is unimportant or irrelevant to a given situation. Attention, however, varies by type (e.g., diffused, focused, flexible), by degree, and by individual. A question posed here is: What type of attention is conducive to creativity?

What is Creativity?

Creativity can be defined as the ability to produce work that is simultaneously novel and meaningful or useful, as opposed to trivial or bizarre (Sternberg & Lubart, 2002). People differ in the capacity to be creative, and there are various ways of measuring creative ability. One of the most commonly used measures to evaluate creative thinking is a test of divergent thinking (DT), which assesses the ability to generate ideas by exploring many possible original solutions to a given problem, within a limited amount of time, and in laboratory settings (Guilford, 1950; Torrance, 1974). Although DT tests modestly predict real-world creativity (Runco & Acar, 2012; Torrance, 1969), it is not clear whether the type of attention required to perform well on DT tests is the same type of attention employed by people who are creative in the real world. Indeed, considering that DT tests are time-limited (typically 2–3 minutes per task), and often emphasize the number of responses (i.e., fluency as opposed to originality), they may require a different type of attention than does real-life creativity.

While some consensus exists regarding how attention is associated with creativity, findings often seem to contradict one another. Here I briefly describe prior theories of the link between attention and creativity, and present three seemingly contradictory views: creativity through diffused or "leaky" attention, creativity through focused attention, and creativity through flexible attention. Indeed, all three forms of attention may contribute to the creative process. I highlight, however, that what matters is the operational definition of creativity – that is, how we measure it. I present behavioral and neurophysiological evidence suggesting that creativity assessed with divergent thinking tests is linked with selective, yet flexible attention. Alternately, creativity assessed with a more ecologically valid survey of people's real-world creative accomplishments is linked with "leaky" attention. I discuss this evidence in the context of a newly developed Model of Creativity and Attention (MOCA), and conclude with suggestions for future research.

The Role of Attention in Creativity: A Review

A large body of literature suggests that creative people have diffused or leaky attention; that is, creative people show the propensity to notice information that may not be particularly relevant to the task at hand (Carson, Peterson, & Higgins, 2003; Mendelsohn & Griswold, 1964; Rawlings, 1985). On the other hand, some have suggested that creative people are more likely to pay attention to the fine-grained details, and thus have more focused attention than less creative people (Nusbaum & Silvia, 2011). Finally, evidence exists that creative people do not necessarily differ in their predominant mode of attention, but can switch between various modes of attention more easily, and therefore have flexible attention (Vartanian, Martindale, & Kwiatkowski, 2007; Zabelina & Robinson, 2010). Here I review evidence for each view, and suggest that these views need not compete. Rather, they may all operate, but on different types or measures of creativity, with different factors of attention at work.

Creativity and Broad or "Leaky" Attention

Some empirical evidence suggests that creative people may have particularly diffused or leaky attention, or the propensity to notice information that other people may dismiss as irrelevant. Historical evidence suggests that there may indeed be an association between high levels of creativity and leaky attention. For example, in 1981 Gabriel Marcia Marquez was interviewed for the winter issue of *The Paris Review*, and when asked to conclude with what his next project would be, he noted: "I'm absolutely convinced that I'm going to write the greatest book of my life, but I don't know which one it will be or when. When I feel something like this – which I have been feeling for a while – I stay very quiet, so that if it passes, I can capture it," highlighting the distracting nature of extraneous stimuli for the creative process. Numerous other eminent creators, including Richard Wagner, Marcel Proust, Charles Darwin, Edgar Allen Poe, Anton Chekhov, and Johann Goethe lamented about noise as a source of intrusion or distraction (see Kasof, 1997).

As a consequence of such leaky attention, creative people are prone to errors on typical attention tasks. For example, one study simultaneously presented participants with pairs of words under the instructions to repeat or shadow words presented to one ear, while attempting to remember words presented to the other ear (divided attention condition; Rawlings, 1985). Creative participants of the Wallach and Kogan (1965) test (Pattern Meanings: viewing abstract designs and suggesting interpretations of the patterns, and Similarities: generating ways in which pairs of objects were similar for 10 object pairs) experienced more intrusion errors from the non-shadowed ear than less-creative participants. This finding suggests that people who perform well on this creativity task may have leaky attention.

Leaky attention, however, may be a double-edged sword: it may serve as a cost in some circumstances; for instance, when people are trying to focus on a conversation in a noisy café. However, it may also serve as a benefit by helping people introduce unusual and original pieces of information into their cognition, resulting in a creative thought. In support, creative people incorporate seemingly irrelevant cues when solving word puzzles, such as anagrams (creativity assessed by the Remote Associates Test, RAT), on which participants are asked to come up with a word that forms a common compound or a phrase with the three presented words (Ansburg & Hill, 2003; Mednick, 1962; Mendelsohn & Griswold, 1964), recall words or phrases (creativity assessed by RAT; Russell, 1976), or perform auditory attention tasks (creativity assessed by the Creative Achievement Questionnaire, CAQ; Carson et al., 2003).

In support of leaky attention, creative people often say that they are sensitive or oversensitive. Indeed, highly creative people show several physiological and behavioral correlates of reaction to noise and efforts to block it: more-creative participants (creativity assessed by RAT × DT fluency), for example, show more alpha-blocking in response to onset of a tone than their less-creative counterparts (Martindale & Armstrong, 1974), suggesting that more-creative participants exhibit higher arousal to onset of tones than less-creative participants. They also show larger skin potential responses to moderately intense tones, and take twice as long to habituate to the tones than less-creative participants (creativity assessed by RAT × DT fluency; Martindale, Anderson, Moore, & West, 1996). These findings suggest that creative people may indeed have shown signs of leaky attention, making it more difficult to block out irrelevant stimuli, and/or increasing their physiological sensitivity.

Finally, there is evidence that exposure to arousing stimuli reduces breadth of attention (Easterbrook, 1959). Particularly, arousal is increased and breadth of attention is decreased by crowding (Evans, 1979; Nagar & Pandey, 1987), evaluation apprehension (Cottrell, Wack, Sekerak, & Rittle, 1968), time pressure (Karau & Kelly, 1992), and the presence of others (Bond & Titus, 1983). Correspondingly, creativity is generally hindered by crowding (creativity assessed by DT; Aiello, De Risi, Epstein, & Karlin, 1977), evaluation apprehension (creativity assessed by subjective ratings of collages; Amabile, Goldfarb, & Brackfield, 1990), time pressure (creativity assessed as a real-world five-year evaluation of innovation and productivity in scientists and engineers, Andrews & Farris, 1972; creativity assessed by groups generating planning tasks, rated by judges for originality and creativity, Karau & Kelly, 1992), and presence of others (creativity assessed by generating word associations, Matlin & Zajonc, 1968; creativity assessed by the Wallach & Kogan Creativity Battery, Milgram & Milgram, 1976).

Neuroimaging evidence provides partial support for the role of leaky attention in creative thinking. A meta-analysis of functional imaging data reported activations in the brain regions associated with spontaneous imaginative processes, namely the precuneus (Gonen-Yaacovi et al., 2013). The precuneus, a core hub of the default mode network (DMN) – a set of midline and inferior parietal regions that activate in the absence of most external task demands (Gusnard & Raichle, 2001), has been implicated in both structural (Fink, Koschutnig, et al., 2014; Jauk, Neubauer, Dunst, Fink, & Benedek, 2015; Jung et al., 2010; Takeuchi et al., 2010) and functional (Benedek et al., 2014; Fink, Weber, et al., 2014; Takeuchi et al., 2011) imaging studies of creativity. Moreover, activation of the inferior parietal lobule (IPL), another core hub of the DMN (van den Heuvel & Hulshoff Pol, 2010), has been reported in several neuroimaging studies of creativity (Abraham, Beudt, Ott, & von Cramon, 2012; Benedek et al., 2014; Fink et al., 2009, 2010).

Thus, it appears that leaky attention can be of particular importance for some forms of creativity, specifically for making connections between ideas, e.g., words on the RAT, and for acquiring creative accomplishments in the real world. Namely, leaky attention may help people be more sensitive to and make connections between distantly related concepts or ideas. Leaky attention may also afford people with a larger repertoire of potential stimuli for production of an unusual or creative idea.

Creativity and Focused Attention

An alternative proposal of how attention relates to creativity suggests that creativity benefits from the ability to focus attention. More generally, creativity may rely heavily on executive functions (De Dreu, Nijstad, Baas, Wolsink, & Roskes, 2012; Gilhooly, Fioratou, Anthony, & Wynn, 2007; Nusbaum & Silvia, 2011; Wiley & Jarosz, 2012), i.e., general-purpose control mechanisms such as the ability of the cognitive system to configure itself for the performance of specific task goals (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Miyake & Friedman, 2012). Indeed, in order to create a highly original thought or product, people have to focus and persist in the task at hand. For instance, the preparation stage of creativity involves information-gathering, mastering a knowledge base, and identifying the problem (Wallas, 1926). These behaviors surely benefit from focus and persistence. Leonardo da Vinci, for example, one of the most recognized creative polymaths, was said to have “obsessive attention to detail” (Lester, 2012, p. 191). Marie Currie described her focus during schoolwork as “allowing no lapses of attention” (Curie & Scheean, 2001, p. 72), as well as concentrating her attention “without even hearing the mounting roar of chatter” (Curie & Scheean, 2001, p. 97).

Indeed, persistence in the discovery process does not come easy. There are many conflicting demands, and creative ideas are often, by definition, incompletely formulated or of dubious utility. Even when ideas come in a flash, focus and persistence are required to put them to good use (Gabora, 2010). A considerable body of research suggests that creativity involves the ability to maintain an extended focus (Feist, 1999; Richards, Kinney, Lunde, Benet, & Merzel, 1988). Artists, for instance, spend more time reworking their drawings than do nonartists (Kozbelt, 2008).

Empirical evidence suggests that working memory capacity in particular may benefit some forms of creativity by enabling an individual to maintain attention focused on the task (Baas, De Dreu, & Nijstad, 2008). In support, working memory capacity predicts performance on the DT test, specifically because it allows persistent (rather than flexible) processing (De Dreu et al., 2012). Similarly, greater executive capacity is associated with greater fluency (number of ideas produced within a given time) on the DT task (Gilhoooly et al., 2007). Moreover, fluid cognitive abilities (Gf) predict performance on divergent thinking tasks, and giving people a helpful task strategy exaggerates the difference between people low and high in Gf (Nusbaum & Silvia, 2011).

An increasing body of research confirms that performance on the divergent thinking tests in particular involves task-driven top-down control of attention and cognition. Much of this evidence comes from latent variable studies showing effects of higher-order cognitive abilities, such as fluid intelligence (Beaty, Silvia, Nusbaum, Jauk, & Benedek, 2014; Nusbaum &

Silvia, 2011), working memory capacity (Lee & Therriault, 2013; Süß, Oberauer, Wittman, Wilhelm, & Schulze, 2002), and verbal fluency (Benedek, Könen, & Neubauer, 2012; Silvia, Beaty, & Nusbaum, 2013) on DT. Such abilities are hypothesized to support thinking in a divergent manner by providing the executive control needed to guide memory retrieval and inhibit salient but unoriginal ideas (Beaty & Silvia, 2012; Beaty et al., 2014; Benedek, Franz, Heene, & Neubauer, 2012; Silvia, Beaty, Nusbaum, Eddington, & Kwapil, 2014).

Behavioral evidence for the role of executive processes in performance on the DT tasks has received support from electroencephalogram (EEG) and functional magnetic resonance imaging (fMRI) research. Several studies report task-related activation in brain regions associated with interference resolution, response selection, and cognitive control in the inferior frontal gyrus (IFG) and inferior parietal cortex (Abraham et al., 2012; Benedek et al., 2014; Chrysikou & Thompson-Schill, 2011; Fink et al., 2009; Fink & Benedek, 2014). Fink and colleagues (2009), for example, conducted an fMRI study with a battery of DT tasks that varied in terms of the creativity-related demands required. Tasks with a high-creativity demand required generation of novel uses for common objects – the classic DT task, and tasks with low-creativity demands simply required the generation of typical object characteristics. Compared to tasks with low-creativity demands, performance on tasks with high-creativity demands was associated with increased activation of the left angular gyrus and decreased activation in the right inferior parietal cortex. Moreover, regardless of the task demands, idea generation was related to increased activation of the left IFG, the anterior cingulate cortex (ACC), and the precentral gyrus. Fink and colleagues (2009) interpreted their results as evidence for a role of controlled memory retrieval and internal attention in DT. Taken together, it appears that some forms of creativity, particularly creativity as assessed by timed laboratory tests of DT, may benefit from selective attention.

Creativity and Flexible Attention

Another view of how attention relates to creativity poses that creative people have attentional flexibility to adaptively shift between focused and broad attention (Gabora, 2010; Vartanian, 2009; Zabelina & Robinson, 2010). Indeed, creative acts may require the ability to see the large picture and its details, as well as the flexibility to switch between the two (Gabora, 2010; Martindale, 1995). Indeed, spontaneous shifts between analytic and associative modes of thought have been proposed to be necessary for creative production (Gabora, 2010).

Biographical and personality studies present evidence that the problem-solving behavior of eminent scientists alternates between extraordinary levels of focus on specific concepts to playful exploration of ideas (see Feist, 1999; Martindale, 2001). This suggests that problem-solving may be a function of flexible strategy application in relation to task demands. Thus, attentional flexibility allows people to flexibly switch between broad and focused levels of attention. It is unclear, however, what timescale of attentional flexibility is the most conducive to creative thinking. Rapid flexible attentional switching may be important for creativity in the short term, such as performance on timed tasks of insight problem-solving (e.g., Bowden & Beeman, 1998) or DT tasks (e.g., Torrance, 1974), while real-life creative acts may operate on a longer timescale, requiring maintaining one type of attentional state for a time before switching to another state.

It is also unclear what the mechanism of attentional flexibility is. There are at least two possible mechanisms for achieving attentional flexibility. One potential mechanism is bottom-up leaky attention. Specifically, when people attend to one stimulus, information from the other stimuli may still "leak in," allowing relatively easy processing of the stimuli outside of one's focus, and therefore rapid switching of attention to another target. Alternatively, it is possible that attentional flexibility stems from a selective top-down attention on one stimulus, followed by a rapid disengagement, and rapid selection of the subsequent stimulus. In other words, this mechanism allows for high inhibition of attention, where attention capture is not as long or as lasting, allowing for rapid shifting of attention. This would be analogous to an effect found in the working memory literature, in which both high and low working memory capacity people exhibit attentional capture by distractors, but high-capacity people recover more quickly than their low-capacity counterparts, as indicated by behavioral and event-related potential (ERP) findings (Fukuda & Vogel, 2011). The mechanisms of flexible attention need to be elucidated in order to gain deeper understanding of the association between creativity and attentional flexibility.

Different Types of Attention are Associated with Different Measures of Creativity

The hypotheses of how different types of attention – leaky, focused, and flexible attention – relate to creativity seem to contradict one another. They may not be mutually exclusive, however – they may all operate, but on different components, measures, and stages of creativity, with different factors of attention at work. Specifically, performance on the DT tests may rely on the task-driven (i.e., top-down) ability to rapidly focus, inhibit, and switch attention, supporting attentional flexibility. Real-world creativity, on the other hand, may benefit from the stimulus-driven (i.e., bottom-up) attention that is broad or leaky.

Model of Creativity and Attention (MOCA)

Here I present a newly developed Model of Creativity and Attention (MOCA, Figure 9.1), which depicts the associations between creativity (divergent thinking and real-world creative achievement) and attention (leaky, focused, and flexible). The MOCA proposes that creativity assessed by the DT tests is associated with flexible attention, which is driven by rapid focus, inhibition, and rapid shifting of attention. This ability is evident very early in the processing stream, as DT is also linked with selective sensory processing, assessed by the P50 ERP. Further in the processing stream it is additionally supported by successful upregulation of cognitive control, as assessed by the N2 ERP. Further support comes from the genetics studies which show that DT is linked with dopaminergic polymorphisms associated with high cognitive flexibility and medium top-down control, or with weak cognitive flexibility and strong top-down control.

Creativity as defined by the people's real-life creative accomplishments, on the other hand (although weakly related to DT), is linked with leaky attention, as well as with leaky sensory processing early in the processing stream, as assessed by the P50 ERP. Additionally, high real-world creative achievement is linked with dopaminergic polymorphisms associated with weak cognitive flexibility and weak top-down control, and with psychopathology-spectrum personality characteristics of psychoticism and hypomania.

MOCA also proposes that the outcome of leaky attention and leaky sensory processing may depend on the level of cognitive control. In the presence of low cognitive control, leaky attention may lead to the development of attention disorders, and/or some forms of psychopathology. High cognitive control, on the other hand, would serve as a protective factor, and together with leaky attention may be precisely the mechanism that supports real-world creative achievement. The MOCA notes that more than leaky attention and high cognitive control are required for creative achievements – other factors, such as motivation, grit, and opportunity play a major role in achieving in creative domains in the real world (Amabile, 1985; Runco, 2005).

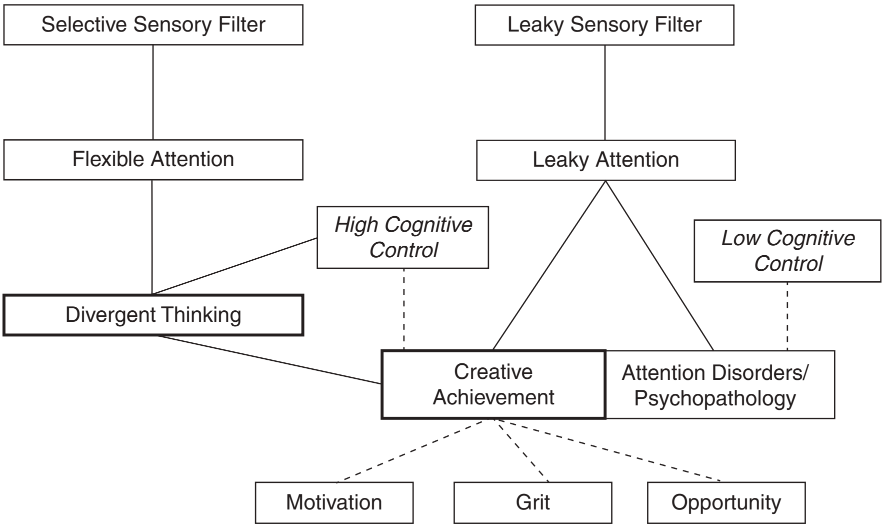

Figure 9.1 Model of Creativity and Attention (MOCA), presenting relations between creative achievement, divergent thinking, and attention. Solid lines denote confirmed associations, dashed lines denote hypothesized associations.

Divergent Thinking and Focused, Flexible Attention

Behavioral Evidence

MOCA suggests that creativity as assessed by DT tests is linked with flexible attention, which is supported by the ability to focus, disengage, and switch attention rather than by leaky attention. This hypothesis was confirmed by two recent experiments examining how DT relates to visual attention (Zabelina, Saporta, & Beeman, 2016). In both experiments, participants identified target letters (S or H) within hierarchical stimuli (global letters made of local letters), after being cued to either the local or global level. In Study 1, in general, participants identified the targets more quickly following valid cues (80% of trials) than following invalid cues. However, this smaller *validity effect* was associated with higher DT, indicating that DT was related to quicker overcoming of invalid cues, and thus to flexible attention (Figure 9.2).

There are several possible mechanisms for why divergent thinking was associated with better overcoming of invalid cues. One possible mechanism is a leaky attention filter. Specifically, when people attend to one level, information from the other level may still “leak in,” allowing relatively easy identification of non-cued targets after invalid cues. Study 2 tested whether DT is related to a leaky attention filter, which would be manifested in the size of the congruency effect, i.e., how selective people are when cued to selectively attend to either the local or global letter stimuli. Participants were again cued to a stimulus level, but unlike in Study 1, the cued level always contained a target (either S or H). However, the stimulus at the other level was congruent, incongruent, or neutral with the target. Thus congruency, not validity, was manipulated, as the cue was always valid. In other words, there was always a target at the cued level of the stimulus, but the other level varied, containing congruent, neutral, or incongruent target information. For instance, when cued to the local level participants could see a local S; on congruent trials the global configuration formed the same letter (large S); on incongruent trials, the global letter was the other target (large H); and on neutral trials the global letter was a nontarget letter (A’s or E’s). *The*

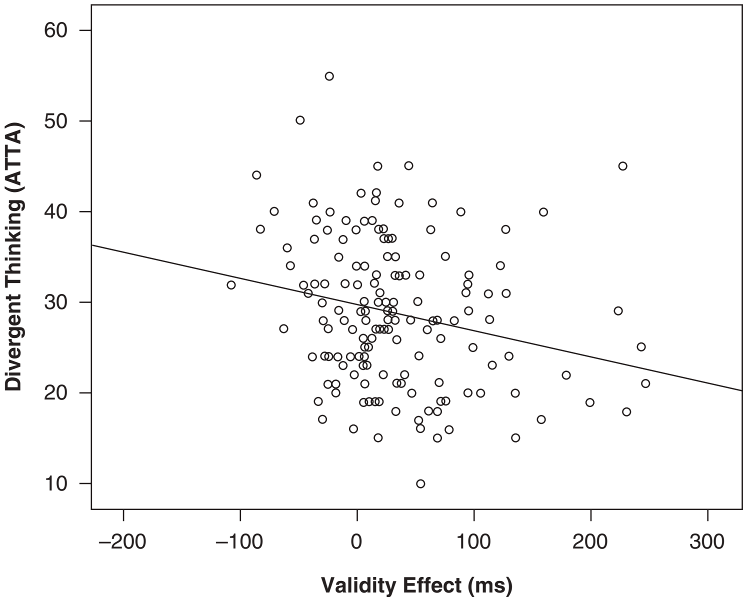

Figure 9.2 A Pearson correlation between divergent thinking and validity effect (RT on invalid trials minus RT on valid trials), demonstrating that people with higher divergent thinking scores have more flexible attention ($r(152) = -.23$, $p = .004$).

congruency effect – how much faster people respond on congruent than on incongruent trials – is an index of how selective (versus how leaky) the attention filter is. If divergent thinkers have selective attention, they should be perfectly good at using the cues to attend to the target level, and the congruency of the distractor level should have no effect. On the other hand, if divergent thinkers have leaky filters, they should respond more slowly on incongruent trials. Thus, if DT in Study 1 was associated with better overcoming of invalid cues due to leaky attention, then high DT should also be associated with a large congruency effect in Experiment 2. In contrast, if better overcoming of invalid cues was associated with better overcoming of invalid cues not due to leaky attention in Study 1, then in Experiment 2 DT should not be related to the congruency effect.

As expected, divergent thinking did not relate to stimulus congruency. DT was not related to either interference or facilitation from stimuli at the uncued level. This finding rules out leaky attention as the explanation for flexible attention (i.e., overcoming invalid cues) displayed by divergent thinkers in Study 1. Therefore, an alternative mechanism may be responsible for divergent thinkers' flexible attention in Study 1. It is possible that a rather selective attention filter is the mechanism for flexible attention in divergent thinkers. In this view, high divergent thinkers, when cued, focus their attention as sharply as (or sharper than) low divergent thinkers and are adept at rapidly processing information at the cued level, rapidly disengaging from it, and/or rapidly shifting to the other level. In other words, even though they are highly selective at attending to cued information, their attention capture is not as strong or as lasting.

Neurophysiological Evidence

Flexible attention supported by the mechanism of focusing, disengaging, and switching

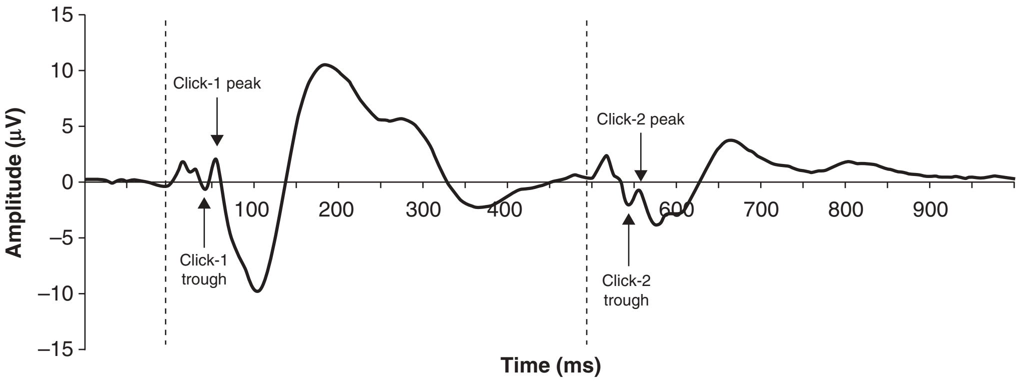

Figure 9.3 Grand averages of the ERPs at Cz. Vertical dashed lines at 0 ms mark onset of Click 1, and at 500 ms mark the onset of Click 2. The P50 ratio is calculated as the P50 peak to trough difference of Click 2 over the P50 peak to trough difference of Click 1. Thus, larger difference in the waveforms would result in a smaller ratio. Smaller ratios represent more selective sensory gating, while larger ratios represent leakier sensory gating.

attention is compatible with recent EEG data showing that DT is linked with an increased ability to filter out “irrelevant” sensory information (Zabelina, O’Leary, Pornpattananangkul, Nusslock, & Beeman, 2015), as measured by the P50 ERP – a neurophysiological response to a stimulus that occurs 50 ms after stimulus onset (for review, see Patterson et al., 2008). In this paradigm, two auditory clicks are presented to a participant, and the extent to which the second click is inhibited compared to the first click is seen as a marker of sensory gating (see Figure 9.3). P50 is a very early, automatic, form of sensory gating, influencing which stimuli capture attention (Banich, 2004; Gjini, Burroughs, & Boutros, 2011). Some view the P50 marker of sensory gating as a marker of some forms of psychopathology, particularly schizophrenia (Olincy et al., 2010).

Data reveal that DT is associated with selective sensory processing very early in the processing stream. Only 50 ms after stimulus onset high divergent thinkers are more likely to inhibit “irrelevant” sensory information than low divergent thinkers (Figure 9.4). Given that the stimuli are meaningless and there are no task requirements, increased sensory gating may indicate that selective sensory processing is a general neural processing characteristic of divergent thinkers.

Additional evidence for the link between divergent thinking and selective attention comes from the study examining performance on the oddball paradigm (Zabelina & Ganis, 2017). Here, participants performed a standard oddball paradigm, in which they saw and responded to frequent and rare stimuli, and their behavioral and neurophysiological responses were measured. More concretely, on each trial participants had to look for a specific letter. Within each run most of the time the stimulus of interest (frequent stimulus) was at one level of attention (e.g., global), but on 10% of the trials the stimulus (rare stimulus) was at the other level of attention (e.g., local), requiring selective attention.

Thus, if divergent thinkers have selective attention, they should not slow down as much on the rare compared to the frequent trials. They should also show a larger N2 difference between rare and the frequent trials, as larger N2 serves as an indicator of upregulation of cognitive control (Folstein &

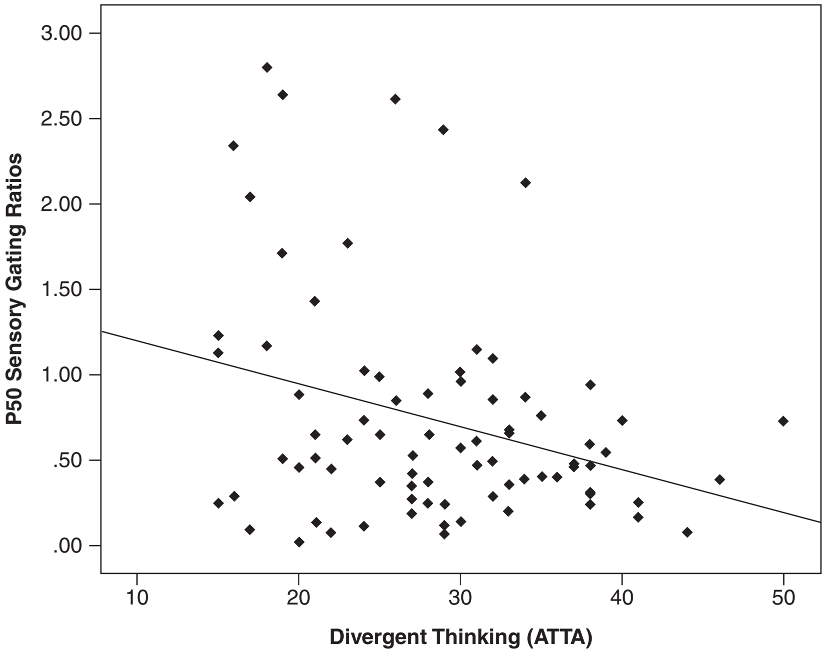

Figure 9.4 Partial regression plot depicting partial correlations between divergent thinking (centered) and P50 sensory gating. This plot demonstrates that higher divergent thinking scores are associated with smaller P50 ratios, i.e., more selective sensory gating ($r(80) = –.30$, $p = 006$; controlling for academic achievement, $p = .03$).

van Petten, 2008; see Figure 9.5a). As expected, evidence from two experiments suggests that higher divergent thinking is not linked with slowing down on rare trials compared to the frequent trials. Additionally, it is associated with larger N2 differences between the rare and the frequent trials, suggesting that divergent thinkers are particularly good at upregulating their cognitive control on rare targets, resulting in faster responses to the rare targets compared to people with lower DT scores (Figure 9.5b).

Biological Evidence

Finally, supporting evidence for the link between DT and selective attention comes from a genetics study investigating the involvement of the dopaminergic system (DA) in divergent thinking. It was revealed that DT can be predicted from interactions between genetic polymorphisms related to frontal (COMT) and striatal (DAT) DA pathways. Importantly, successful performance on the DT test was linked with dopaminergic polymorphisms associated with good cognitive flexibility and medium top-down control, or with weak cognitive flexibility and strong top-down control (Zabelina, Colzato, Beeman, & Hommel, 2016; Figure 9.6).

Considering previous observations that the nine-repeat allele is related to various indications of good cognitive flexibility (Garcia-Garcia, Barceló, Clemente, & Escera, 2010), while the 10-repeat allele is related to low learning abilities and ADHD (Cornishet al., 2005), this pattern makes sense. DT tests require individuals to find new solutions and original answers, requiring some top-down guidance. DT also considers the role of flexibility, which fits rather well with the observation that the performance of individuals with a genetic makeup that supports cognitive flexibility (the 9/-carriers) benefit most from frontal top-down control that is effective, but not overly strong. Individuals with a less

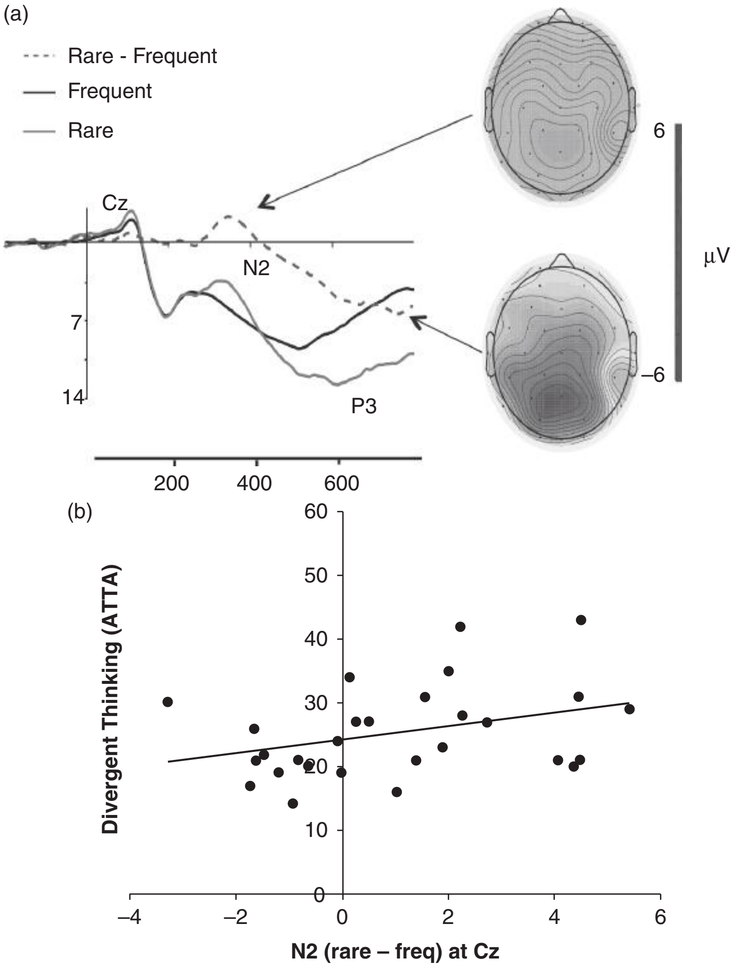

Figure 9.5 (a) Neuropshysiological response to rare and frequent targets on an oddball paradigm, showing a larger N2 ERP on rare compared to frequent targets, particularly at parietal sites, indicating that more cognitive control is required on rare compared to frequent targets. For a color version of this figure, see the color plate section. (b) A Pearson correlation between divergent thinking and N2 difference (rare targets minus frequent targets), demonstrating that people with higher divergent thinking scores upregulate their cognitive control to a larger degree on the rare compared to the frequent targets compared to people with lower divergent thinking scores (*r*(26) = .50, *p* = .004).

flexibility-supportive genetic makeup, however, presumably require strong frontal guidance and attentional focus to overcome or compensate for the lack of flexibility. These findings are in line with the dual pathway to creativity model, which proposes that generation of original and appropriate ideas can be achieved through either cognitive flexibility or through cognitive persistence (Nijstad, De Dreu, Rietzchel, & Baas, 2010).

Real-world Creative Achievement and "Leaky" Attention

Behavioral Evidence

In contrast to people who perform successfully on laboratory tests of DT, behavioral, neurophysiological, and genetics data provide evidence for leaky attention in people with high

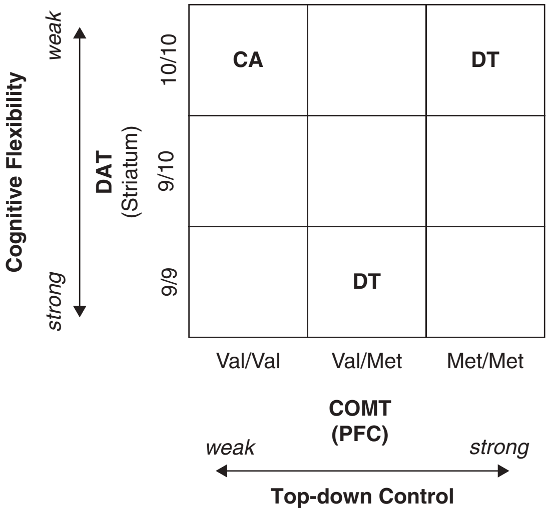

Figure 9.6 Putative associations between COMT (tied to DA availability in the prefrontal DA pathways) and top-down cognitive control; and DAT (tied to DA availability in striatal pathways) and cognitive flexibility. Data presented in the figure suggest that divergent thinking is linked with DA polymorphisms associated with good cognitive flexibility and medium top-down control, or with weak cognitive flexibility and strong top-down control, while creative achievement is linked with DA polymorphisms associated with weak cognitive flexibility and weak top-down control.

real-world creative achievements. For example, whereas the congruency effect – how much faster people respond on congruent than on incongruent trials – does not relate to DT (see above), people with more real-world creative achievements exhibit a larger congruency effect – they respond slower on the incongruent compared to congruent trials, indicating leaky attention (Zabelina et al., 2016; Figure 9.7).

Neurophysiological Evidence

Neurophysiological evidence provides further support for the link between creative accomplishments and leaky attention. In the study using the same P50 ERP paradigm as described above, where participants passively listen to auditory clicks, it was revealed that the more real-world creative achievements people had, the less likely they were to filter out the second click (Zabelina et al., 2015; Figure 9.8). This result indicates that people with real-life creative achievements have “leaky” sensory processing very early in the processing stream (as early as 50 ms after stimulus onset). Again, because the task is passive and involves meaningless stimuli with no task requirements, reduced sensory gating suggests that leaky sensory processing is the general characteristic of real-life creative achievers.

Additionally, unlike divergent thinkers, real-world creative achievers do not upregulate their cognitive control on rare compared to frequent targets on the oddball paradigm, as reflected in the N2 differences (see above, Zabelina & Ganis, 2016), indicating that people with real-life creative achievements may not be particularly good at engaging cognitive control on this task. It is possible that creative achievers exhibit poor self-control on laboratory tasks of attention, which are typically quite long and not very engaging. Were creative achievers to work on their own creative project, or something they found particularly interesting and worth investing in, they would be just as good, if not better, than divergent thinkers to engage their cognitive control. Further studies are needed to examine whether the link between creative achievement

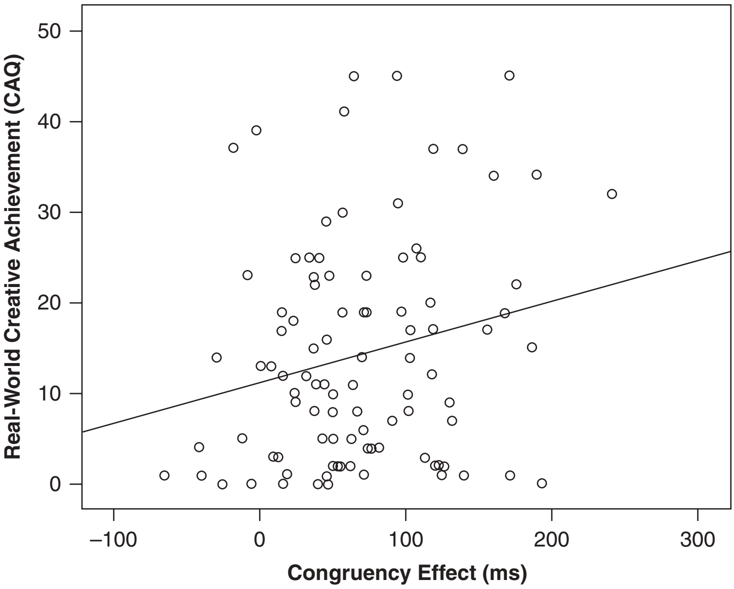

Figure 9.7 A Pearson correlation between creative achievement and congruency effect (RT on incongruent trials minus RT on congruent trials), demonstrating that people with higher real-world creative achievements have more “leaky” attention ($r(94) = .22, p < .03$).

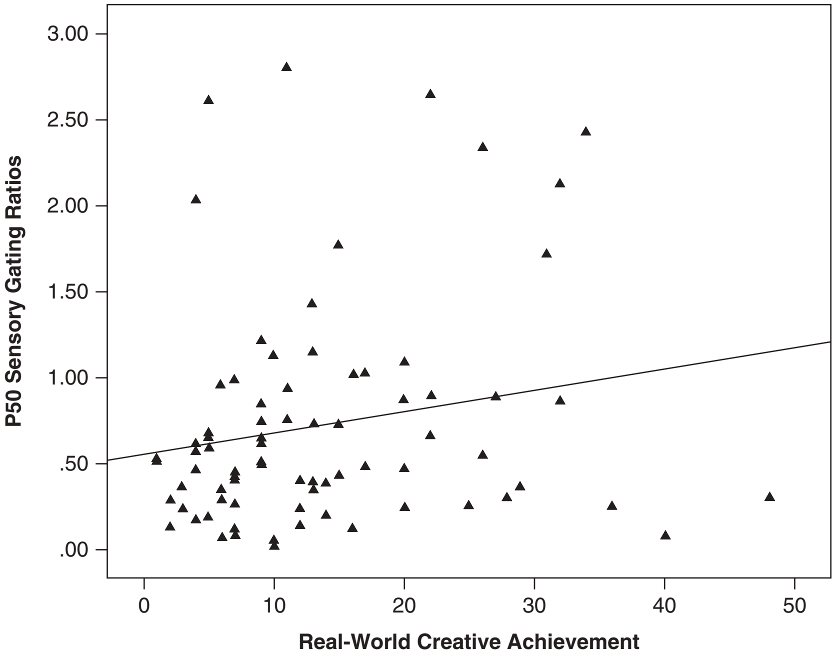

Figure 9.8 Partial regression plot depicting partial correlations between creative achievement (centered) and P50 sensory gating. This plot demonstrates that higher creative achievement is associated with larger P50 ratios, i.e., leakier sensory gating ($r(81) = .20, p = 07$); controlling for academic achievement, $p = .001$).

and cognitive control varies depending on the level of interest in the task at hand, as well on the stage of the creative process (e.g., creative achievers may show low levels of cognitive control during uninteresting tasks, as well as at the early stages of the creative process, while engaging tasks, as well as later stages of the creative process may be linked with higher levels of cognitive control in creative achievers).

Biological Evidence

Finally, results from the study investigating involvement of the DA system in creative achievement reveal a particular benefit of the 10-repeat carriers associated with weak cognitive flexibility, in combination with the ValVal polymorphism associated with particularly weak frontal top-down control (Zabelina, Colzato, et al., 2016; Figure 9.6). Although the link between creative achievement and DA transmission has not been previously investigated (but it has been proposed [Carson, 2011]), this observation fits well with previous reports that excellent performance on the CAQ is associated with "leaky" attention (Zabelina, Saporta, & Beeman, 2016), with electrophysiological indications of reduced sensory gating (Zabelina et al., 2015), and with low latent inhibition (Carson et al., 2003). As pointed out above, leaky attention may help individuals to take into consideration nominally irrelevant information, and integrate it with relevant information to create new ideas and insights.

Conclusion

Recent convergent evidence suggests that different aspects or measures of creativity are associated with different types of attention. Thus conflating different types or measures of creativity into a monolithic "creativity" may hinder our understanding of the sources of the apparent variability in the literature on the link between creativity and attention (see Dietrich & Kanso, 2010; Sawyer, 2011; but see Nijstad et al., 2010).

The Model of Creativity and Attention (MOCA) suggests that creativity as measured by two different measures – via laboratory tests of divergent thinking and via a survey of people's real-life creative accomplishments – relates to different forms of attention: divergent thinking is linked with flexible attention, potentially driven by the ability to focus, inhibit, and switch attention, while creative achievement is linked with leaky attention. What is the source of these differences, considering that measures of divergent thinking and creative achievement are weakly, but consistently correlated? It appears that divergent thinking tests with their focus on generation of as *many* creative uses for a common object as possible within a *limited amount of time* may rely on selective attention and good cognitive control more than previously thought. In fact, DT scores show consistent association with successful academic performance, specifically with enhanced performance on academic achievement tests (SAT and ACT; see Zabelina, Condon & Beeman, 2014).

Creativity as measured by surveying people's real-life creative accomplishments, on the other hand, is linked with leaky attention. Such perceptual openness, or "open-mindedness" as the literature suggests (Feist, 1999), may help creative achievers notice information which others may disregard as irrelevant, thus leading to a creative idea. However, such leaky attention can also serve as a double-edged sword, and lead to heightened distractibility, as well as to predisposition to attention disorders and various forms of psychopathology.

Numerous open questions remain. Future investigations need to consider how attention relates to creativity within different stages of the creative process. For example, leaky attention may be associated with the initial stages of the creative process, such as idea generation, while more focused attention may be beneficial during the later stages of the creative process, such as idea implementation. Neuroimaging studies can help determine neural mechanisms associated with various forms of attention and how they relate to creativity. Additionally, future investigations need to explore temporal dynamics within the resting state connectivity to determine how it changes with attentional engagement. Finally, the involvement of external versus internal attention in creativity, although previously discussed (Zabelina & Andrews-Hanna, 2016), needs further examination.

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10 Internally Directed Attention in Creative Cognition

Mathias Benedek

Attention is a fundamental cognitive function needed to select and focus on relevant information. The current focus of attention is determined by our goals (i.e., what we want to pay attention to) and by stimulus salience (i.e., what attracts our attention; Corbetta & Schulman, 2002). An effective interplay between these modes of top-down and bottom-up control is crucial to all forms of cognitive performance (Kane, Bleckley, Conway, & Engle, 2001). We can further distinguish between externally directed attention and internally directed attention: while external attention refers to a focus on sensory information, internal attention refers to a focus on self-generated mental representations (Chun, Golomb, & Turk-Browne, 2011). Due to the limited capacity for conscious information processing, external and internal attention are competing mental states. We can typically only focus on external or internal information at one time, but attention can shift swiftly between external and internal worlds. Importantly, externally and internally directed cognition are thought to involve different brain mechanisms (Dixon, Fox, & Christoff, 2014).

Cognitive science has traditionally focused on the study of externally directed cognition. Following the influential notions of behaviorism, empirical investigations have been largely interested in behavior attributed to externally presented stimuli. Recent research, however, suggests that we spend 25%–50% of our waking time engaged in thoughts unrelated to what is going on around us (Kane et al., 2007; Killingsworth & Gilbert, 2010). During these states our attention is directed to internal trains of thought that are commonly concerned with past experiences or future plans (Baird, Smallwood, & Schooler, 2011). These stimulus-independent thoughts can be spontaneous or goal-directed. Spontaneous stimulus-independent thought includes the phenomenon of mind-wandering, where thoughts are unintentionally drawn away from a task (Smallwood & Schooler, 2015). In contrast, goal-directed stimulus-independent thought includes activities like deliberate planning or idea generation (Christoff, 2013).

There are different theoretical views on the role of attention in creative cognition. Creativity has been associated with concepts like defocused attention (Martindale, 1999; Mendelsohn, 1976), broad attention (Kasof, 1997; Rowe, Hirsh, & Anderson, 2007), flexible attention (Vartanian, 2009; Zabelina & Robinson, 2010), reduced latent inhibition (Carson, Peterson, & Higgins 2003; Zabelina, O'Leary, Pornpattananangkul, Nusslock, & Beeman, 2015), and attentional control (Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014; Wiley & Jarosz, 2012). Most of these accounts do not explicitly refer to the role of internal versus external attention, but, if anything, suggest a higher permissiveness to external information outside the main focus of attention (Gabora, 2002; Zabelina, Saporta, & Beeman, 2015). The underrepresentation of internal attention in accounts of creativity seems at odds with its relevance for creative thought. Core processes in creative thinking such as imagination and the forging of novel combinations between remotely associated concepts (Benedek, Könen, & Neubauer, 2012; Koestler, 1964; Mednick, 1962) typically involve an internal focus of attention rather than attention to sensory information.

The role of internal attention seems particularly relevant to the process of individual idea generation. For instance, when we are engaged in writing, and look for a good way to express our thoughts, we may be found sitting with eyes wide open, but barely acknowledging what is going on around us. Our eyes may be directed toward the screen or paper, but our attention is directed to internal processes, such as retrieving relevant content from memory, and mental simulations of potential next sentences. Once we are satisfied with an idea, we will refocus on the external world in order to write down those lines and make sure they read well. Writing is just one example activity where the more creative part is certainly associated with an internal focus of attention. The same process is consistently evident in empirical research on divergent thinking. After prompting participants with a task cue, they commonly engage in idea generation for minutes without a need to process any external information (e.g., Benedek, Mühlmann, Jauk, & Neubauer, 2013), because all relevant information is self-generated.

Because internal attention is relevant to creative thought, and characterized by distinct brain mechanisms, this chapter aims to explore the role of internal attention in creative cognition and neuroscience. Most of the pertinent research has been conducted by means of the electroencephalogram (EEG) and functional magnetic resonance imaging (fMRI). As these two lines of research have developed largely independently, I will first consider relevant EEG research, followed by fMRI research, and finally look for potential common ground related to internal attention in creative cognition.

Creativity and Internal Attention in EEG Research

Research on Creativity and EEG Alpha Activity

The first investigations of the brain activation associated with creativity were carried out by means of the EEG. EEG recordings assess electrocortical oscillations that can be divided into different frequency bands. The dominant frequency band in the human brain represents brain oscillations from 8 to 13 Hz, and is called alpha activity (Klimesch, 2012). EEG alpha activity is typically highest in states of rest and when eyes are closed, and alpha activity is reduced during many cognitive tasks (von Stein & Sarntheim, 2000). Colin Martindale, a pioneer in the neuroscientific investigation of creativity, hypothesized that primary process cognition in the creative process should be reflected in reduced level of cortical arousal and hence higher alpha activity (Martindale & Armstrong, 1974; cf. Kris, 1952). Martindale indeed found that EEG alpha activity was higher during the imagination of a creative story as compared to a later period when a story was elaborated and written down (Martindale & Hasenfus, 1978). Another study showed that more-creative people show higher alpha activity than less-creative people during various cognitive tasks (Martindale & Hines, 1975). These initial findings suggested a positive association between EEG alpha activity and creativity.

More recent EEG studies have also measured changes in alpha activity between a task and a pre-task reference period, which allows discovery of whether alpha activity actually increases or decreases during a task. Task-related alpha increases are called alpha synchronization, whereas task-related decreased are called alpha desynchronization (Pfurtscheller, 1999). This method revealed that alpha activity is not only relatively higher during tasks with higher creative task demands (as already observed by Martindale & Hasenfus, 1978), but actually increases during creative thought relative to a pre-task resting baseline especially at frontal brain regions (Fink, Benedek, Grabner, Staudt, & Neubauer, 2007; Jaarsveld et al., 2015; Schwab, Benedek, Papousek, Weiss, & Fink, 2014). Specifically, alpha synchronization was found to be higher when generating creative uses for objects versus generating words for given suffixes (Fink et al., 2007), and when generating creative versus common uses and associations (Jauk, Benedek, & Neubauer, 2012).

A number of other studies have corroborated the creativity–alpha association from different perspectives. The generation of highly creative ideas was associated with higher EEG alpha activity than the generation of less-creative ideas (Fink & Neubauer, 2006, 2008; Grabner, Fink, & Neubauer, 2007). Creative people were found to show higher task-related alpha synchronization than less-creative people (Fink et al., 2009; Fink, Graif, & Neubauer, 2009; Jaušovec, 2000). Finally, EEG alpha activity was shown to be increased by creativity training (Fink, Grabner, Benedek, & Neubauer, 2006) and cognitive stimulation (Fink, Schwab, & Papousek, 2011). Together, these findings provide strong empirical support for an association between creativity and EEG alpha activity (for reviews, see Dietrich & Kanso, 2010; Fink & Benedek, 2013, 2014). Regarding topographical effects, creativity was generally characterized by alpha synchronization in frontal brain regions and in posterior regions of the right hemisphere, and by reduced alpha desynchronization in occipital brain regions.

EEG alpha has originally been viewed as an indicator of cognitive inactivity, whereas task-related alpha decreases were thought to indicate active brain regions during a given task. Thus, researchers were quite surprised to find a robust association between creativity and EEG alpha increases, as this seemed to imply that creativity-related cognition is essentially associated with decreases of brain activation. Different explanations have been offered for this apparent discrepancy. It was proposed that alpha increases do not reflect deactivation but rather reduced cortical arousal, possibly indicating a state of defocused attention (Martindale, 1999). Similarly, alpha increases in frontal regions were seen to represent reduced executive control, which was termed *hypofrontality* (Dietrich, 2003). Moreover, right hemispheric alpha increases were assumed to indicate a more diffuse and coarse semantic coding of information, characterized by the activation of larger semantic maps that serve to facilitate more remote associations (Fink et al., 2007; cf. Jung-Beeman, 2005).

EEG Alpha Activity as Indicator of Internal Attention

Task-related EEG alpha increases have not only been observed during creative thinking, but also in other fields of research. For example, EEG studies on memory reported “paradoxical” alpha effects as well: alpha synchronization was observed in tasks with high demands on short-term memory (Klimesch, Doppelmayr, Schwaiger, Auinger, & Winkler, 1999) and to increase as a function of memory load (Jensen, Gelfand, Kounios, & Lisman, 2002). Other lines of research suggested that alpha activity might be related to attentional demands. Ray and Cole (1985) compared EEG alpha activity between cognitive tasks that did not require processing of external stimuli (e.g., mental arithmetic or the visualization of an imaginary walk) and other tasks that did (e.g., visual detection tasks). Performance of the *sensory-independent* tasks elicited much higher alpha activity than the *sensory-intake* tasks, especially in parietal brain regions. Similarly, Cooper, Croft, Dominey, Burgess, and Gruzelier (2003), presented participants either series of visual, auditory, or haptic stimuli (i.e., external condition), or asked them to imagine these stimuli after being trained to do so (i.e., internal condition). The internal condition was again associated with higher alpha activity than the external condition, and this was true across all sensory modalities. Moreover, alpha activity increased further with task difficulty within internal tasks. The findings by Ray and Cole (1985) and by Cooper and colleagues (2003) suggest that EEG alpha activity reflects increased internally directed attention rather than reduced cortical activity or arousal.

This inference poses the question whether the relationship between creativity and EEG alpha activity can also be explained by internal attention demands. We sought to address this question in an EEG study, which independently manipulated the level of creativity-related demands and of internal attention demands in four experimental conditions (Benedek, Bergner, Könen, Fink, & Neubauer, 2011). All conditions presented nouns consisting of four letters (e.g., POST). Low creative task demands were realized with a convergent thinking task, which asked participants to find correct anagram solutions (e.g., "STOP"). Higher creative task demands were realized with a divergent thinking task (namely, creative idea generation task), which asked participants to generate creative four-word sentences using the four letters as initials in any order (e.g., "Oldies sometimes provoke tears"). Additionally, the level of internal attention demands was manipulated by a conditional masking of the stimulus words. In half of the trials the stimulus was masked shortly after their presentation (0.5 s), thereby enforcing increased internal attention demands as the task had to be completed in the mind's eye. The findings of this study were straightforward: task-related alpha activity was higher in conditions of high internal attention demands as compared to unmasked task performance that granted continuous sensory access to the stimuli. While alpha activity varied as a function of attentional demands, it was largely independent from the type of task. Convergent and divergent thinking did not differ notably in alpha activity, except for slightly higher parietal alpha activity during divergent thinking. These findings support the view that EEG alpha activity during creative thought reflects increased internal attention demands rather than other creativity-related cognitive processes.

One specific finding of this study was quite puzzling though: Why was alpha synchronization during divergent thinking only observed in the internal attention condition but not in the external attention condition? In the external condition, the stimuli remained visible throughout the task, which is just the normal case used in all previous research that had reported alpha synchronization during divergent thinking. Perhaps this discrepancy was due to the specific divergent thinking task chosen in this study. Creative sentence generation requires the processing of four letters that can be used in any sequence, and therefore arguably implies higher sensory intake than previously used divergent thinking tasks, such as the alternate uses task, which presents only one single concept (e.g., "brick") that can easily be kept in mind and does not require any reprocessing during task performance.

We tested this potential explanation in another EEG study, which now employed two divergent thinking tasks: one sensory-intake task (creative sentence generation) and one sensory-independent task (alternate uses task; Benedek, Schickel, Jauk, Fink, & Neubauer, 2014). Stimuli were again masked in half of the trials for both tasks. It was hypothesized that stimulus masking should have a stronger effect on the sensory-intake task than on the sensory-independent task because it only affects the process of bottom-up stimulus processing. In fact, EEG alpha activity was found to be increased in posterior regions of the right hemisphere in all cases, except for the sensory intake task performed in the unmasked condition. In other words, alpha increases were observed in all conditions involving high internally directed attention, such as in the sensory-independence task (for both masking conditions) and in the sensory-intake task when the task had to be completed in the mind's eye due to stimulus masking.

These two experimental EEG studies may help to clarify the role of alpha activity in creative thought. Alpha activity was found to be specific to internal attention demands rather than specific to creative task demands (Benedek et al., 2011). As a consequence, alpha levels may vary even between creative thinking tasks: those which are intrinsically sensory-independent are accompanied with higher alpha activity than those which require regular processing of external information (Benedek, Schickel, et al., 2014).

The presented findings suggest that pronounced alpha activity during creative thought is explained by the internal nature of creative cognition. It is interesting to apply this internal attention interpretation of alpha activity to other findings of the creativity–alpha relationship. For example, the finding that more-creative ideas are preceded by higher alpha activity than less-creative ideas suggests that the generation of highly creative ideas may be accompanied by deeper levels of absorption during creative thought. Being fully engaged with internal cognitive processes, and not distracted by external interference, may enable the generation of more elaborate and vivid mental representations, which may ultimately result in more creative ideas. Relatedly, the occurrence of spontaneous insights in creative problem-solving was also shown to be preceded by increases of alpha activity in the right posterior–occipital cortex (Jung-Beeman et al., 2004). This finding was proposed to reflect a strong temporary inward focus, or a "mental blink" (Kounios & Beeman, 2009, p. 212), and thus could be seen as a moment of "in-sight" as the solution appears in the mind's eye. This interpretation was supported by an eye-tracking study, which showed that solving problems with insight is accompanied by longer blinks and more gaze aversion (Salvi, Bricolo, Franconeri, Kounios, & Beeman, 2015). Moreover, idea generation was found to be accompanied by longer and more frequent blinks, reduced microsaccade activity, and a reduced angle of eye vergence reflecting visual disaccommodation (Benedek, Stoiser, Walcher, & Körner, 2017; Walcher, Körner, & Benedek, 2017). Hence, alpha activity appears to serve as a sensitive indicator of transient changes in the internal focus over time, and the actual level of internal focus may predict the outcome of creative thought.

We can also consider implications of the internal attention interpretation of alpha activity on individual differences findings. When creative people show higher alpha activity, this might signify that they are better able to enter and maintain states of deep absorption during creative thought. Sustained attention on relevant (internal) content while gating out irrelevant sensory input is commonly seen as a sign of executive control (Engle, 2002; Kane et al., 2001). The importance of executive control for creative thought has been repeatedly demonstrated (e.g., Nusbaum & Silvia, 2011; Silvia, 2015). Studies consistently found that executive abilities in terms of working memory capacity, cognitive inhibition and intelligence predict higher performance in creative idea generation (Benedek, Franz, Heene, Neubauer, 2012; Benedek, Jauk, et al., 2014) including metaphor production (Beaty & Silvia, 2013) and humor production (Kellner & Benedek, 2017). While executive control can contribute to creative thought in many ways (e.g., Beaty, Silvia, Nusbaum, Jauk, & Benedek, 2014; Benedek & Jauk, in press), a most general way would be to facilitate sustained internal attention during the cognitively demanding process of creative idea generation.

Taken together, there is substantial evidence that EEG alpha activity (particularly at right posterior–parietal brain regions) indicates states of internally directed attention. While many cognitive tasks are accompanied by decreases of alpha activity, increases in alpha activity increases are observed in cognitive activities that require sustained internally directed attention. Conforming to this interpretation of EEG alpha activity, the consistent association between creativity and alpha activity can be explained by central role of internal attention for creative thought.

Functional Mechanisms Underlying EEG Alpha Activity

Let us go one step further and explore the functional role of EEG alpha activity for internal attention. EEG alpha activity was initially assumed to represent a state of cortical idling (Pfurtscheller, Stancák, & Neuper, 1996), but more recent theoretical accounts assign it a more active role in human cognition. EEG alpha is proposed to reflect active top-down inhibition of task-irrelevant brain regions (Jensen & Mazaheri, 2010; Klimesch et al., 1999). The inhibition of irrelevant sensory processing may help to shield internal representations from interference. This active inhibition view is supported by EEG studies examining alpha activity in visuo-spatial attention tasks. For example, alpha activity was found to increase in occipital cortex regions contralateral to the position of stimuli that should be ignored (Händel, Haarmeier, & Jensen, 2011; Rihs, Michel, & Thut, 2007; Worden, Foxe, Wang, & Simpson, 2000). Recent evidence suggests that right-posterior alpha increases are also observed when people try to ignore auditory stimuli (Dubé, Payne, Sekuler, & Rotello, 2013).

The top-down modulation of sensory processing may be achieved by phase coupling between prefrontal and posterior regions in the alpha band range. Sauseng et al. (2005) showed that active manipulation of information in memory was associated with increased functional coupling between prefrontal and occipital regions potentially reflecting top-down control by anterior over posterior brain regions. Moreover, when prefrontal function was perturbed by means of TMS, top-down modulation in a selective-attention task decreased, particularly in people with stronger frontoposterior functional connectivity (von Stein, Chiang, & König 2000; Zanto, Rubens, Thangavel, & Gazzaley, 2011). The active role of EEG alpha activity in internal cognition may include selective attention and maintenance of internal representations in working memory (Klimesch, 2012; Palva & Palva, 2007). Higher alpha activity is thought to correspond to increasingly reduced attention to external stimuli (Jensen, Bonnefond, & VanRullen, 2012) and highest alpha levels are associated with a complete break-down of sensory processing as observed during loss of consciousness (Supp, Siegel, Hipp, & Engel, 2011).

Creativity and Internal Attention in fMRI Research

Default Mode Network Activation as an Indicator of Internal Attention?

The investigation of the neural correlates of creative cognition by means of fMRI was met with much enthusiasm in the beginning of this millennium, but was followed by disenchantment when the first reviews were unable to identify consistency across findings (Arden, Chavez, Grazioplene, & Jung, 2010; Dietrich & Kanso, 2010). This inconsistency may in part be explained by the heterogeneity of tasks that shared the label of creativity, but not necessarily common cognitive processes. More recent reviews focusing on more closely defined activities (e.g., creative idea generation, or musical improvisation) reveal a more consistent picture (Beaty, 2015; Fink & Benedek, 2014; Gonen-Yacoovi et al., 2013).

As one of the more consistent findings, MRI studies on creativity commonly demonstrate brain activation in regions pertaining to the default mode network (DMN; Benedek, Beaty, et al., 2014; Fink et al., 2014; Jauk, Neubauer, Dunst, Fink, & Benedek, 2015; Jung et al., 2010; Takeuchi et al., 2011). The DMN mainly consists of regions along the anterior and posterior midline, the posterior inferior parietal cortex and the medial temporal lobe, and this network deactivates in many cognitive tasks but shows increased activation during periods of rest (Buckner, Andrews-Hanna, & Schacter, 2008; Gusnard & Raichle, 2001). The DMN is consistently activated in many active cognitive tasks as well, including autobiographical memory retrieval, prospection, mental navigation, theory of mind, and mind wandering (Fox, Spreng, Ellamil, Andrews-Hanna, & Christoff, 2015; Spreng, Mar, & Kim, 2009). Many of these tasks do not require much processing of external information but are achieved with an internal focus of attention, suggesting that the DMN represents an "introspective network" (Pinho, Ullén, Castelo-Brancod, Fransson, & de Manzano, 2015). On the other hand, it is also often emphasized that the DMN is particularly involved in constructive, self-generated thought based on content retrieved from memory. Because most internal cognition tasks crucially depend on such generative processes, it is hard to keep apart attention-specific and task-specific processes when comparing brain activation between internal and external cognition. Thus, the question remains as to what extent DMN activation is actually specific to internally directed attention, or to constructive, self-generated thought that is prevalent in internally directed cognition.

We examined the brain mechanisms associated with internal attention in creative thought in a recent fMRI study (Benedek et al., 2016) that employed essentially the same experimental design as in one of our previous EEG studies (Benedek et al., 2011). The study used a divergent and a convergent thinking task, and we assumed that the divergent thinking task (generating creative four-word sentences) involved considerably higher levels of self-generated thought processes than the convergent thinking task (finding correct anagram solutions), because it required participants to produce novel content going beyond the four stimulus letters. Internal attention demands were experimentally manipulated by masking the stimulus in half of the trials immediately after it was read. This design was used to disentangle brain activation associated either with internal attention or with more creative, self-generated thought processes, and clarify the role of DMN with respect to these conditions. The study revealed that internally directed attention was associated with reduced activation in extended regions of the visual network, and with increased activation of the right anterior inferior parietal cortex (aIPL; specifically the posterior part of the right supramarginal gyrus), bilateral lingual gyrus and left cuneus. Interestingly, the right aIPL also showed increased functional connectivity with bilateral occipital cortex regions during internal attention, although these occipital regions actually showed reduced activation during internal attention. This activation pattern suggests that the right IPL may be involved in downregulating visual processing during internally focused attention (Sarter, Givens, & Bruno, 2001). Such a top-down mechanism is in line with the *perceptual decoupling hypothesis* (Smallwood et al., 2011; Smallwood & Schooler, 2015), which assumes that focused internal attention requires that attention is decoupled from perceptual input. Thus, the right aIPL may exert top-down control over occipital regions in order to suppress early visual information processing, which serves to shield ongoing internal processes from sensory interference.

Considering the contrast of divergent thinking versus convergent thinking, divergent thinking was associated with higher brain activation in left frontal cortex and in regions attributed to the DMN including the posterior cingulate cortex, the middle temporal gyrus, and the angular gyrus. This finding underscores the relevance of the DMN together with executive networks for creative thought. The coupling of default and executive networks has been shown to be characteristic for domain-general and artistic forms of creative thought (Beaty, Benedek, Silvia, & Schacter, 2016; Jung, Mead, Carrasco, & Flores, 2013). Moreover, higher creative potential is associated with higher coupling of these networks during creative thought and at rest (Beaty, Benedek, Kaufman, & Silvia, 2015; Beaty et al., 2014; Spreng, Stevens, Chamberlain, Gilmore, & Schacter, 2010). The findings of this study suggest that the DMN is not an indicator of internal attention per se, but is rather specific to constructive, self-generated thought, which is central to most internal cognition tasks (Andrews-Hanna, Smallwood, & Spreng, 2014).

Imagery

Another cognitive activity that appears relevant to internal attention and creativity is imagery. Mental imagery occurs when perceptual information is retrieved from memory to re-establish a previous experience in the form of seeing it with the mind's eye or hearing it with the mind's ear (Kosslyn, Ganis, & Thompson, 2001; Pearson, Naselaris, Holmes, & Kosslyn, 2015). Imagery may not be an essentially creative process as long as it concerns recollection, but as soon as it involves the imagination of something new, it certainly represents a crucial capacity underlying creative thought (Finke, 1996; Jung, Flores, & Hunter, 2016).

The neural foundations of mental imagery have been extensively studied with fMRI and positron emission tomography (PET). Participants are typically shown an image and are later asked to imagine this image again in order to answer questions about it. Visual imagery was found to share many neural systems with visual perception (Kosslyn, Thompson, & Alpert, 1997). One of the key regions for visual imagery is the primary visual cortex (Brodman area 17). Impairing the function of this region by means of transmagnetic stimulation impaired the performance in an imagery task (Kosslyn et al., 1999). Similar to the study of visual imagery, the brain activation underlying auditory imagery has been examined by comparing the imagination of music to actual listening conditions. The brain activation during auditory imagery clearly overlapped with the brain activation for auditory perception including the bilateral superior temporal gyrus and the left supramarginal gyrus (Zatorre, Halpern, Perry, Meyer, & Evans, 1996). Thus, imagery in the visual and auditory domain recruits brain regions associated with perceptual processing of visual and auditory stimuli, respectively.

What about more complex forms of imagery that go beyond mere mental reproduction and involve the production of novel mental representations (i.e., imagination)? There has been a lot of interest in the neural correlates of prospection, and how envisaging the future differs from recalling the past (Schacter et al., 2012). In one of the first studies, Addis, Wong, and Schacter (2007) asked participants to recall past experiences related to given objects or to imagine likely future experiences for the same object. Future events should be novel but plausible and participants were asked to imagine a specific scene with all contextual details from an individual perspective. They found that recalling past experiences from episodic memory and imagining future ones recruited similar brain regions. The core network of common regions between recall and imagination included posterior cingulate cortex, medial prefrontal cortex, hippocampal regions, and inferior parietal cortex, many of which represent core regions of the default mode network (see also Jung et al., 2016). Schacter et al. (2012) concluded that imagination and future thinking crucially rely on memory-based simulations, where information (particularly from episodic memory) is used to imagine, simulate, and predict future events. Imagining future events for objects bears obvious conceptual similarity to the divergent thinking task asking for creative object uses. Therefore, it may not be surprising that divergent thinking performance is correlated with the amount of episodic detail in reporting future events (Addis, Pan, Musicaro, & Schacter, 2016), and that future thinking and divergent thinking share neural substrates including key regions of the DMN (Gonen-Yacovi et al., 2013; Spreng et al., 2009).

Visual imagery activates visual processing areas, auditory imagery activates auditory processing areas, and future thinking activates areas associated with episodic memory retrieval such as the DMN. In other words, we find clear overlap between recall and imagery within domains, but these studies do not reveal a brain region that is common to imagery across domains. The existence of such a common brain region might have been expected because these imagery tasks are thought to share some cognitive processes such as an internal focus of attention. One potential reason is that imagery in terms of the reproduction of previously experienced stimuli is not as cognitively demanding as the production of novel representations and ideas. In fact, musical imagery often happens even involuntarily (Beaty et al., 2013). Therefore, imagery may not require sustained internally focused attention to an equal extent as goal-directed creative thought. Together these findings point to striking conceptual and neurophysiological associations between perception and imagery, as well as between imagery of previous experiences and the imagination of novel representations.

Summary and Conclusions

Creative cognition is commonly characterized by sustained internally directed attention to self-generated thought, such as mental simulations based on content retrieved from memory. Thus, understanding the neuroscience of creativity requires an understanding of the brain mechanisms associated with internal attention in creative thought. This chapter reviewed relevant research in this field and put a particular emphasis on the role of EEG alpha activity and default mode network activity. Alpha and DMN activity share a similar history in neuroscience research. Both have initially been mistaken as idling, resting, or default activity by an empirical tradition that focused on externally directed cognition (e.g., Pfurtscheller et al., 1996; Raichle et al., 2001). Today, it is fully acknowledged that the brain is highly active in the absence of stimulus-driven activity. As a consequence of this awareness, EEG alpha and DMN activity were ennobled to represent internally directed cognition or stimulus-independent thought rather than resting state activity. It was also hypothesized that EEG alpha activity may directly correspond to processes of the default mode network (Mok, 2014). As we have seen, however, these views are only partially supported by empirical research.

EEG research has accumulated substantial evidence that alpha activity, particularly in the right parietal cortex, is indeed associated with internally directed attention (Cooper et al., 2003; Ray & Cole, 1985). The consistent association between creativity and alpha activity reflects the intrinsic role of internal attention in creative cognition (Benedek et al., 2011; Benedek, Schickel et al., 2014; Fink & Benedek, 2013, 2014). EEG alpha activity is currently conceived as a brain mechanism that exerts top-down control in order to suppress the processing of task-irrelevant sensory information, and shield ongoing internal processes from interference. The active role of alpha activity for internal cognition may further include the maintenance of object representations during working memory processing (Jensen et al., 2012; Klimesch, 2012; Palva & Palva, 2007)

Default mode activity is also prevalent in internally directed cognition, including spontaneous forms such as mind-wandering (Fox et al., 2015), and goal-directed forms such as planning or creative thought (Spreng, Mar, & Kin, 2009; Gonen-Yaacovi et al., 2013). However, unlike EEG alpha activity, DMN activity seems not to be related to internal attention per se, but to self-generated thought and mental simulation (Andrews-Hanna et al., 2014; Schacter et al., 2012). Rather, increased internal attention demands have been linked to increased activation in the right anterior inferior parietal cortex, and widely reduced activation in the visual networks (Benedek et al., 2016; Sarter et al., 2001).

The topography of this fMRI activation pattern strikingly corresponds to alpha synchronization effects in internal cognition that are typically most pronounced in right inferior parietal cortex and occipital regions during creative thought (Fink & Benedek, 2013, 2014). EEG and fMRI research thus provide converging evidence for the important role of the right inferior parietal cortex for sustained internal attention. The right inferior parietal cortex may exert top-down control over occipital regions via connectivity in the alpha frequency range (Sauseng et al., 2005; Klimesch, 2012), as observed by increased alpha levels in right parietal and occipital brain regions (Benedek, Schickel, et al., 2014; Fink & Benedek, 2014) as well as increased functional connectivity between right parietal cortex and the visual network (Benedek et al., 2016). The suppression of early visual processing may serve to decouple attention from perceptual input and maintain a coherent train of thought (Smallwood & Schooler, 2015).

While internal attention may be ubiquitous in creative thought, an important question is whether it is actually specific to creativity. Is internal attention just a basic precondition for creative thought that simply needs to be given (like open eyes are required for reading), or is there potentially a closer relationship between internal attention and creativity? Creative people and creative ideas are associated with higher EEG alpha activity, suggesting at least a graded relationship between internal attention and creativity. It may not be enough that attention is directed to internal processes, but the actual depth and stability of internal attention over time may be relevant. Creative thought involves the generation of complex mental representations that need to be maintained over extended periods of time for simulation and elaboration. The effectivity of this process may well depend on the capacity to stay deeply absorbed in self-generated thoughts, despite the constant exposition of potentially interfering sensory stimulation. Future research in this field should take advantage of available physiological indicators of internally versus externally directed attention as provided by the neurosciences to advance our understanding of how internal attention contributes to creative cognition.

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11 The Forest versus the Trees: Creativity, Cognition and Imagination

Anna Abraham

Virtually no topic in psychology has been left unscathed from being examined under the lens of the neuroscientific approach. The field of creativity is no exception. The appeal of adopting a neuroscientific perspective is easy to comprehend on many levels. The predominant charm for a psychologist lies in the fact that the approach affords the chance to peer a little closer into the mysterious workings of the mind, operations to which we are not directly privy to by means of observation, behavior, or introspection. Being able to accurately read the signals is not without its complications, though, because the language of brain activity escapes easy translation. The problem of confirmation bias which seems unavoidable in the life and social sciences (Ioannidis, 2005; Nickerson, 1998) escalates under such contexts of ambiguity. The situation is exacerbated further by our naïve disposition to believe neuroscientific explanations (Weisberg, Keil, Goodstein, Rawson, & Gray, 2008), particularly when they resonate with our own beliefs (Scurich & Shniderman, 2014) (for other explanations, see Farah & Hook, 2013). Even with the best intentions in mind, mistranslations frequently transpire, and, unfortunately, these often spawn correction-resistant research agendas that lead straight down blind alleys. It is for this reason that the initial thrill of new discoveries about the workings of the mind are often followed by acute skepticism of the same, and this has resulted in a field divided along party lines (Uttal, 2011).

Such thorny issues affect disciplines as a whole, but they are particularly relevant in the context of the neuroscience of creativity for several reasons. Many of these are conceptually and methodologically based, such as inability to prompt creativity in as reliable and valid a manner in empirical settings compared to other aspects of cognition (Abraham, 2013; Dietrich, 2015; Sawyer, 2011). Others, however, are rooted in our own naïve beliefs concerning the fundamental nature of creativity, which appears inherently mysterious, magical, and ineffable. The problem of confirmation bias looms particularly large here because of our predisposition to readily accept or lean toward vague and tenuous explanations that fit with such expectations. So this is something we must be continually mindful of when evaluating evidence and theories on the brain basis of creativity. There is much to be cautious about.

However, there is also much to be optimistic about, and the present chapter is about telling that tale. In the ongoing debate on the usefulness of adopting a neuroscientific approach to understand psychological function, what is rarely reflected upon or given its due is how this perspective is unique in allowing for the discovery of commonalities between aspects of psychological function that are not usually considered in relation to one another (Mather, Cacioppo, & Kanwisher, 2013). A case in point is the field of creativity, where adopting a neuroscientific approach has led to novel and fundamental insights in understanding its information-processing mechanisms, particularly in relation to other aspects of cognition and imagination.

The Global View: What Speaks for Dual Systems Ideas?

The notion that the operations of the mind are essentially dualistic in nature is a ubiquitous one and has been applied to explain several different facets of cognitive function (Evans, 2008; Evans & Stanovich, 2013; Schneider & Shiffrin, 1977). The central feature of dual-process and dual-systems theories is that there are two modes of information processing in the brain. One mode is automatic, implicit, unconscious, bottom-up, spontaneous, intuitive, or reflexive. The other is controlled, explicit, conscious, top-down, deliberate, analytical, or reflective. Obvious parallels are found in frameworks applied to creativity where the opposing modes are open, primary process-based, right brain-based, generative, associative, or divergent on one hand compared to closed, secondary process-based, left brain-based, explorative, evaluative, executive, or convergent on the other hand (Abraham, 2014; Beaty, Silvia, Nusbaum, Jauk, & Benedek, 2014; Finke, Ward, & Smith, 1996; Jung, Mead, Carrasco, & Flores, 2013; Martindale, 1999; Taft & Rossiter, 1966).

It is interesting to note that in contrast to the generic notion that divergent thinking or right-brained thinking (or its derivatives) are held to be synonymous with creative thinking, the truth is that even the earliest advocates of these distinctions were clear in their formulations that the operation of *both* processing modes were necessary to generate a truly creative response (Miran & Miran, 1984; Nicholls, 1972; Wilson, Guilford, Christensen, & Lewis, 1954). Such “confluence”-based ideas have since received empirical support from neuroimaging studies where creative thinking has been assessed using different experimental paradigms, from problem-solving to improvisation (Abraham, Pieritz, et al., 2012; Beaty, Benedek, Kaufman, & Silvia, 2015; Limb & Braun, 2008). To summarize (and generalize) the findings, it appears that the open, divergent or generative mode engages the default mode network of the brain, whereas the closed, convergent, or evaluative mode recruits the cognitive control network of the brain.

The default mode network encompasses five core regions that include (i) the ventral and dorsal medial prefrontal cortex, (ii) the retrosplenial and posterior cingulate cortices along the medial parietal wall, (iii) the anterior lateral temporal cortex including the temporal poles, (iv) the inferior parietal cortex as well as the temporo-parietal junction, and (v) medial temporal lobe structures, such as the hippocampal formation (Andrews-Hanna, Smallwood, & Spreng, 2014; Buckner, Andrews-Hanna, & Schacter, 2008; Raichle, 2015). The key point to note is that this brain network is consistently engaged during different types of noncreative imaginative thinking, such as autobiographical and episodic memory (e.g., reminiscing about my last vacation), episodic future thinking (e.g., imagining what my next job might be like), mental state reasoning or theory of mind (e.g., guessing what someone else is thinking about), self-referential thinking (e.g., reflecting on my own ideas and behaviors), and moral reasoning (e.g., judging the permissibility of an action – my own or someone else’s) (Andrews-Hanna et al., 2014; Mullally & Maguire, 2013; Schacter et al., 2012; Spreng, Mar, & Kim, 2009). These operations can be either directly prompted or spontaneously elicited under conditions of rest and during cognitively undemanding tasks during which active internal mentation or mind-wandering takes place (Andrews-Hanna, Reidler, Huang, & Buckner, 2010; Fox, Spreng, Ellamil, Andrews-Hanna, & Christoff, 2015).

From the preceding paragraph, we can glean the first critical and unique insight that came about by adopting a neuroscientific approach to the study of creativity. The functional profile associated with the default mode brain network is primarily discussed in the context of reasoning about the perception, cognition, or behavior of one’s self and/or others (Bubić & Abraham, 2014), although it is clearly also involved in nonsocial or nonpersonal aspects of imaginative thinking, such as semantic future thinking (Abraham, Schubotz, & von Cramon, 2008), counterfactual or “what-might-have-been” reasoning (Levens et al., 2014), and creative divergent thinking (Abraham, Pieritz, et al., 2012). What these findings push us to consider, though, is the underlying similarities between the information-processing mechanisms that underlie noncreative intentionality-based processes of imagination and the open, divergent and generative mode of creative thinking (Abraham, 2016). Without the neuroscientific evidence, there would be no reason to consider their similarities. However, the evidence now decrees that neuroscientists of creativity are duty bound to do so, particularly in the context of formulating new neuroscientific theories about the same.

The cognitive control or central executive network of the brain encompasses a decidedly wider set of brain regions that largely corresponds to the fronto-cingulo-parietal network encompassing (i) the lateral prefrontal cortex, (ii) the anterior prefrontal cortex, (iii) the anterior cingulate, and (iv) the posterior parietal cortex including the intraparietal sulcus, as well as their intricate connections to basal ganglia and cerebellar structures (Blasi et al., 2006; Cole & Schneider, 2007; Niendam et al., 2012; Robbins, Gillan, Smith, de Wit, & Ersche, 2012; Seeley et al., 2007; Spreng, Sepulcre, Turner, Stevens, & Schacter, 2013).

In the context of creativity, the structures that occupy the focus of discussion are the anterior prefrontal cortex (Brodmann area 10) and lateral aspects of the prefrontal cortex (dorsal: Brodmann areas 8, 9, 46; and ventral: Brodmann areas 45, 47) that are held to orchestrate varying levels of cognitive control with a concrete–abstract division of information processing along the posterior–anterior continuum, with the anterior-most regions subserving the most complex and/or abstract aspects of cognitive function (Badre, 2008; Badre & Wagner, 2007; Donoso, Collins, & Koechlin, 2014; Koechlin, 2015; Ramnani & Owen, 2004; but see, Nee & D’Esposito, 2016). Evidence for the involvement of these anterior and lateral prefrontal structures in creative thinking is considerable and consistent across different experimental paradigms that have assessed creativity in problem-solving, analogical reasoning, conceptual expansion, metaphor processing, musical improvisation, lyrical improvisation, and story generation (Abraham, Pieritz, et al., 2012; Fink et al., 2009; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2012; Kröger et al., 2012; Limb & Braun, 2008; Liu et al., 2012; Rutter, Kröger, Stark, et al., 2012; Shah et al., 2013; Vartanian, 2012).

So what the neuroscientific evidence tells us about the global view of creative function is that dual systems corresponding to the open, generative, and divergent mode relative to the closed, evaluative, and convergent mode are subserved by the default mode and cognitive control brain networks, respectively. It has been suggested that this might indeed be what is singular about creativity in relation to brain function – that unlike other aspects of psychological function, it necessitates the combined operations of cognition and imagination as facilitated by these large-scale brain networks (Ellamil, Dobson, Beeman, & Christoff, 2012).

The Global View: What Speaks Against Dual Systems Ideas?

When the activity of two enormous brain networks is called into play to facilitate creative thinking, the most pressing issue to clarify is the relation between these networks. From a functional neuroanatomical standpoint, there is evidence suggesting that the default mode network and the cognitive control network are anticorrelated (Fox et al., 2005; Fox, Zhang, Snyder, & Raichle, 2009). Furthermore, the differential engagement of these networks are held to be facilitated via the salience brain network (Chand & Dhamala, 2015; Chen et al., 2013; Goulden et al., 2014; Sridharan, Levitin, & Menon, 2008), which includes structures like the dorsal anterior cingulate cortex and the orbital frontoinsular cortices (Seeley et al., 2007; Uddin, 2015). Regions of the insula, in particular, are held to mediate "dynamic interactions between other large-scale brain networks involved in externally oriented attention and internally oriented or self-related cognition" (Menon & Uddin, 2010).

While there is some evidence of insular involvement in creativity (Beaty et al., 2015; Boccia, Piccardi, Palermo, Nori, & Palmiero, 2015; Ellamil et al., 2012), how this region facilitates switching between networks as a function of creativity is unclear. The insula is characterized by its sensitivity to bottom-up salience (Menon & Uddin, 2010), but studies that try to experimentally decouple the generative and evaluative phases of creativity do so via top-down instruction. Participants are, for instance, asked to generate ideas in a first phase and evaluate ideas in a second phase (Ellamil et al., 2012). It is important to note, though, that although such experimental paradigms have face validity, they do not adequately take into account the fundamentally spontaneous nature of creative thinking where idea generation is immediately and involuntarily accompanied by idea evaluation. This is largely unavoidable given the essentially associative, predictive, and proactive nature of information processing in the brain (Bar, 2007; Bubic, von Cramon, & Schubotz, 2010).

The first problem then is that we do not as yet know how the activity of the default mode and cognitive control networks are coupled or incumbent on each other to facilitate different types of creative thinking. Our hypotheses regarding the same cannot be drawn in a simplistic or linear fashion from the published literature on aspects of psychological function that are not specific to creativity given that salience in the case of creativity is likely to be differentially impacted by bottom-up versus top-down factors as well as explicit versus implicit factors.

The involvement of these different dual systems nicely dovetails with the second problem associated with this approach. While the inherent appeal of dual systems lies in their apparent tidiness and simplicity, the truth is that no one duality can capture the full extent of any aspect of psychological function. This is why multiple dual systems have been proposed to better characterize the many nuances of information processing in the mind: top-down/bottom-up, global/local, automatic/controlled, implicit/explicit, intrinsic/extrinsic, spontaneous/deliberate, and these have corresponding brain correlates. However, these neat divisions blur when dualities interact.

A prime example of this was provided by a recent examination of the brain basis of externally directed cognition (EDC) versus internally directed cognition (IDC) as a function of whether these states were spontaneously versus intentionally elicited (Dixon, Fox, & Christoff, 2014). Under conditions of spontaneous processing, EDC and IDC can co-occur without much interference as they engage largely distinct neural structures with EDC relying on primary sensory, primary motor and modality-specific association areas, and IDC relying on limbic and paralimbic regions. However, under conditions of intentional processing, both EDC and IDC engage regions of the lateral prefrontal cortex and are in competition over cognitive resources. So the picture is considerably complicated with the engagement of two or more dualities – which better represents the state of how we operate in our natural environments compared to lab-based settings where these systems are teased apart artificially.

Another problem with the global view is that its foundation is based on brain networks. This might seem counterintuitive because of the contemporary emphasis in brain-imaging studies to focus on interpreting findings in terms of brain networks as opposed to single brain regions (Poldrack, 2012). The importance and advantages of focusing on brain networks cannot be overstated (Ioannides, 2007; Medaglia, Lynall, & Bassett, 2015; Petersen & Sporns, 2015; Sepulcre, Sabuncu, & Johnson, 2012; Smith, 2012). However, what is rarely discussed is the unique problem that comes from interpreting findings to be based on a whole network although only parts of the network were engaged in relation to a specific psychological function. Even a brief perusal through brain-imaging findings in the literature of creativity shows that it is the rule rather than the exception that any given task will activate only partial brain networks, be it default or cognitive control. Are we then accurate in talking about a whole network's involvement if it is only partly engaged? Are there any consensus-based guidelines that outline the extent of a network that needs to be involved (e.g., the number of Brodmann area defined brain regions – one, two or more?) to be able in order to apply network-derived interpretations? These are as yet open questions, but the legitimacy of global views on creativity is necessarily impacted by the answers to such questions.

The Local View: The Case for Focusing on Brain Regions

The alternate neuroscientific approach in the study of creativity to the global view can be dubbed the local view, which is marked by a focus on specific brain regions with the objective of characterizing their roles in orchestrating specific processes relevant to creative thinking. So, specificity is by and large the credo of the local approach both in terms of delineating the particular creativity-relevant mental operations under study together with the engagement and function of select brain regions (Abraham, 2014; Abraham & Windmann, 2007). The local approach is influenced by the dominant theories in cognitive psychology and neuroscience. The methods associated with this approach include brain imaging as well as neuropsychological and electrophysiological techniques. The overarching goal when following this approach is to derive knowledge that leads us closer to understanding the information-processing mechanisms that underlie creativity.

This can been done from either direction – starting from brain structures to glean the nature of processes (region-to-process), and starting from processes to determine the functional roles of brain structures (process-to-region). The mental operations that have been examined in relation to "creative neurocognition" include attentional control (Zabelina, O'Leary, Pornpattananangkul, Nusslock, & Beeman, 2015), executive function (Abraham, Beudt, Ott, & von Cramon, 2012), semantic cognition (Kenett, Anaki, & Faust, 2014; Kröger et al., 2012; Rutter, Kröger, Stark, et al., 2012), episodic cognition (Beaty, Benedek, Silvia, & Schacter, 2016), analogical reasoning (Green, 2016; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010), metaphor processing (Faust & Kenett, 2014; Mashal, Faust, Hendler, & Jung-Beeman, 2007), and problem-solving (Fink et al., 2009; Reverberi, Toraldo, D'Agostini, & Skrap, 2005).

The brain structures of focus are predominantly those of the aforementioned cognitive control network. Regions of the prefrontal cortex (PFC) are usually given the most attention owing to its consistent engagement across a wide array of creativity paradigms (Dietrich & Kanso, 2010). Within the vast expanse of the PFC, the functions of the lateral and anterior regions are of particular interest (Petrides, 2005; Stuss, 2011). The role of the anterior or rostral PFC (Brodmann area 10) is held to reflect the integration of information from multiple cognitive operations (Ramnani & Owen, 2004). The engagement of this structure is seen in creativity tasks that call for the relational integration of multiple distantly related concepts, such as in creative idea generation, conceptual expansion, musical improvisation, analogical reasoning, and metaphor processing (Abraham, Pieritz, et al., 2012; Beaty et al., 2015; Green et al., 2010; Kröger et al., 2012; Limb & Braun, 2008; Rutter, Kröger, Stark, et al., 2012).

Located just posterior to the anterior PFC are the ventrolateral and dorsolateral PFC. The ventrolateral PFC or inferior frontal gyrus (IFG, Brodmann areas 45 and 47) is known for its involvement in semantic aspects of cognitive control such as the selection and retrieval of conceptual knowledge (Badre & Wagner, 2007; Thompson-Schill, 2003), and it is involved in during conceptual expansion, novel metaphor processing, and creative story writing (Abraham, Pieritz, et al., 2012; Kröger et al., 2012; Mashal et al., 2007; Rutter, Kröger, Stark, et al., 2012; Shah et al., 2013).

The role of the dorsolateral PFC, which includes regions of the superior and middle frontal gyri (Brodmann areas 8, 9 and 46), is held to be in the monitoring and maintenance of task-set information in working memory (du Boisgueheneuc et al., 2006; Eriksson, Vogel, Lansner, Bergström, & Nyberg, 2015; Wager & Smith, 2003). It plays a more complex role in creative cognition as deactivations of this region accompany the creative idea-generation stage during poetry composition as well as musical and lyrical improvisation (Limb & Braun, 2008; Liu et al., 2012, 2015), whereas activations of this region, as discussed in the preceding section, are associated with the evaluation stage in creative ideation (Ellamil et al., 2012).

The Local View: The Case for Focusing on Processes

The alternative route is to focus on processes specific to creative cognition (Finke et al., 1996) and to evaluate the brain basis of the same. These include the "aha" experience that accompany the solving of analytical problems (insight), the widening of acquired concepts to include new features or elements (conceptual expansion), and the ability to surpass the distracting influence of recently activated knowledge (overcoming knowledge constraints), and the ability to envision novel and usable objects by combining simple geometric elements (creative imagery).

By far the most widely studied mental operation in relation to creativity is that of *insight* in problem-solving (Kounios & Beeman, 2014). The feeling of insight refers to the phenomenology of suddenness in the arrival of a solution to a problem during the problem-solving process, and it is held to be especially relevant for creativity as the involuntary feeling emerges as a result of overcoming functional fixedness and engaging in a perspective shift. The brain region that is held to be particularly relevant in the context of insight is the right anterior temporal lobe (one of the core regions of the default mode network) encompassing parts of the superior and middle temporal gyri (Chi & Snyder, 2011; Jung-Beeman et al., 2004).

Regions of the cognitive control network including the lateral PFC and the anterior cingulate have also been reported in relation to insight in problem-solving, but the picture is somewhat complicated, with some studies showing the involvement of ventrolateral regions in the same (Aziz-Zadeh, Kaplan, & Iacoboni, 2009), while others have shown that lesions to dorsolateral regions are associated with better performance on insight tasks (Reverberi et al., 2005). Due to the suddenness in the feeling of insight, it lends itself well to EEG-based investigations that can be used to uncover its temporal neural signature. The EEG power indices that are held to be relevant include the "alpha insight effect" over right parietal–occipital regions prior to the response and "gamma insight effect" over right temporal regions at the point of the response (Kounios & Beeman, 2014). The alpha activity is held to reflect neural inhibition in the form of "transient sensory gating that reduces noise from distracting inputs to facilitate retrieval of the weakly and unconsciously activated solution." The gamma activity indexes "a mechanism for binding information" as one becomes conscious or aware of the solution.

Another widely investigated operation of creative cognition is that of *conceptual expansion*, which refers to the ability to broaden our concepts or go beyond the limitations of established conceptual structures of semantic knowledge (Ward, 1994). It is the basis of creative idea generation as any original idea necessitates the modification of existing concepts through the addition of novel elements. Neuroimaging studies have shown that the involvement regions of the anterior prefrontal cortex and ventrolateral prefrontal cortex (of the cognitive control network) as well as the temporal poles (of the default mode network) during conceptual expansion (Abraham, 2014).

These brain regions were more strongly engaged across different experimental paradigms during conceptual expansion relative to general divergent thinking and high cognitive demand (Abraham, Pieritz, et al., 2012), and also during conceptual expansion (semantic novelty and appropriateness) relative to the processing of mere semantic novelty or mere semantic appropriateness (Kröger et al., 2012; Rutter, Kröger, Stark, et al., 2012). ERP studies of the same also revealed a highly interesting pattern. The N400, which indexes semantic novelty regardless of appropriateness, and a late positivity, which indexes the integration of semantic knowledge, jointly provided a coupled neural signature for conceptual expansion (Kröger et al., 2013; Rutter, Kröger, Hill, et al., 2012).

In contrast, *overcoming knowledge constraints* refers to our propensity to be limited by recently activated knowledge in the form of salient examples which serve as distractors that get in the way when trying to generate something new (Smith, Ward, & Schumacher, 1993). Neuropsychological evidence has shown that lesions to parieto-temporal areas of the brain (which overlap partially with the default mode network) lead to a poor ability to overcome knowledge constraints (Abraham, Beudt, et al., 2012). Lesions of this region are typically associated with perseverative responses that are found especially when faced with semantic distractors (Corbett, Jefferies, & Ralph, 2009, 2011). In fact, greater cortical thickness in this region is associated with better creative performance and achievement (Jung et al., 2010).

Interestingly, though, lesions to specific areas of the cognitive control network – the basal ganglia and the anterior PFC – led to enhanced performance or better ability to overcome the constraining influence of examples (Abraham, Beudt, et al., 2012). The advantage was specific to this process as neither neurological group demonstrated advantages on any other aspect of creative cognition. The advantage was also specific to these brain structures as lesions to other aspects of the cognitive control network, such as the lateral PFC, did not have any significant impact, positive or negative, on the ability to overcome the constraining influence of examples during creative ideation.

The final process of creative cognition that will be examined is that of *creative imagery* (Finke, 1990), which is the least studied of the lot. This is somewhat puzzling given the vast number of investigations that have been directed at exploring noncreative imagery (Bartolomeo, 2008; Daselaar, Porat, Huijbers, & Pennartz, 2010; Pearson & Kosslyn, 2015). The studies that have explicitly investigated creative imagery are neuropsychological examinations where the two defining components of creativity – originality and appropriateness associated with the generated object – are distinguished. What is interesting is that lesions to different parts of the brain have a similar negative impact on the ability to produce appropriate or fitting responses during creative imagery. This pattern was consistent across lesion sites – parieto-temporal, basal ganglia and lateral prefrontal. Only lesions of the lateral PFC were also accompanied by a poorer ability to produce original or novel responses (Abraham, Beudt, et al., 2012). So here again, specific components of the cognitive control network (lateral PFC) appear to play a critical role in orchestrating creative imagery.

The Local View: The Case Against Focusing on Processes and Brain Regions

We can infer the first problem with the local view from the two preceding sections, namely the ever-growing list of brain regions of interest, processes of note, operationalizations of these processes, and the rather complex interactions between different types of operations within any particular brain region. It is challenging to get a clear grasp of what it all means or even detect dominant patterns within the abundant findings when having to deal with innumerable details. To make the whole enterprise more manageable, compromises are often made by choosing to focus even more precisely on the one process or brain region of interest while ignoring the rest. This, of course, can lead to serious oversights, particularly on account of the potential influence of confirmation biases.

The truth of the matter, though, is that one cannot but take on the local view if the aim is to outline the information processing mechanisms underlying creative thinking across different contexts of human life, and to be able to generate powerful theories regarding the same. However, the local view is necessarily handicapped at present because it can only flourish with momentum. Other fields of cognition and imagination, such as memory, manage such situations far better because of the sheer number of research groups and scientists the world over that are dedicated to the study of such constructs, the proactive research environments that are conducive to advances being made in the field, and the abundance of funding opportunities and initiatives available to support such research. This is not at all true of creativity research, which, although rapidly burgeoning, generates nowhere near the kind of research impetus required for real and timely progress to be made.

So the main case against the local view is a logistical one – that it is a long, solitary, and arduous struggle to go down that path with developments taking place at the pace of a slow drip, and this is due to the current deficiencies in the research infrastructure associated with the neuroscience of creativity. The consequence of this state of affairs is a lack of innovation on the theoretical side, particularly in contrast to the global view where newer ideas are network and/or evolutionarily derived (e.g., Beaty et al., 2016; Dietrich, 2015; Jung et al., 2013). The field is wanting for new ideas that are empirically testable while also being ecologically and biologically valid. It is little wonder then that few choose to follow the directions of investigation afforded by the local view.

End Point: Creativity in the Wider Context of Cognition and Imagination

This chapter has explored the different approaches that are customarily used in the neuroscience of creativity – both of which are embedded in the context of cognition and imagination. Dividing the approaches themselves into a duality of global versus local views may seem a tad tongue-in-cheek. The point, though, was to showcase the legitimacy of both views, and to evidence that the choice of approach bears both advantages and disadvantages. The global approach is useful when trying to understand the big picture. The one-liner, take-home message. The forest. It is more accessible of an approach as it lends itself to sound-bite science more easily than the local approach. The latter is necessary when trying to work out the details. The context-specific intricacies. The mechanisms under the information processing. The trees. Neuroscientists and other explorers of creative thinking need to bear these in mind, not only when choosing which approach to apply for their own studies, but also when estimating the ideas and findings of others.

The shared conclusion from both views of creativity is that the body of evidence clearly indicates the absolute necessity to investigate creativity from within the larger context of cognition and imagination. There are no unique brain structures or networks that are solely devoted (or are domain-specific) to creativity. This is because our capacity to engage creatively is in itself a domain-general ability, and it is one that we regularly apply across an astoundingly wide range of contexts. The information-processing toolboxes of the brain are one and the same, regardless of whether they are applied to noncreative cognition and imagination or creative cognition and imagination (Abraham, 2013).

Recent attempts at integrating creativity within a larger context have done so by either linking creativity either to specific aspects of imagination (e.g., episodic memory: Beaty et al., 2016) or to cognition and imagination more widely (Abraham & Bubic, 2015).

Drawing on classic conceptualizations within the declarative memory domain, Abraham and Bubic (2015) called for de-emphasizing the somewhat exclusive status accorded to episodic memory in orchestrating imagination-relevant operations (Mullally & Maguire, 2013; Schacter et al., 2012), and proposed an increased recognition of the foundational role of semantic memory operations in the same (Irish & Piguet, 2013; Stocker, 2012). The ideas behind the proposal, although speculative, are based on the neuroscientific literature on creativity, cognition, and imagination. One of the many benefits of focusing on the more foundational construct of semantic memory is that it more easily lends itself to be coupled with other key aspects of information processing to which creativity is necessarily tied, such as perception and action. These domains are not wanting in terms of either theoretical or empirical impetus as they are marked for their immense progress and development in the neuroscience era.

The schematic diagram in Figure 11.1 presents the cognition–imagination cycle beginning

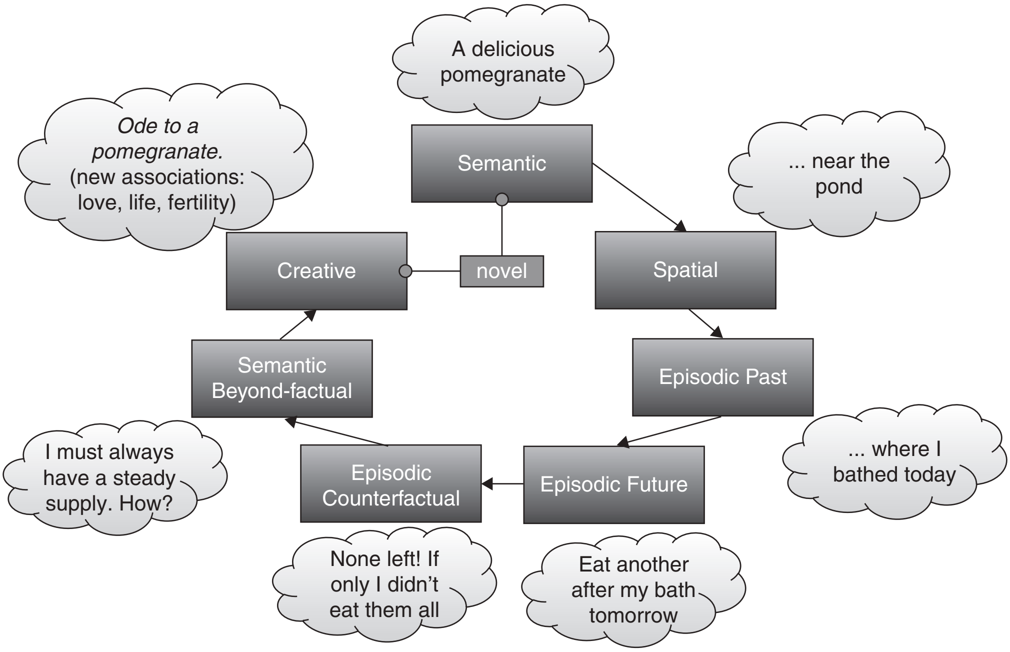

Figure 11.1 An informal characterization of the cognition–imagination cycle via semantic memory operations. The "pomegranate" example provided is for illustrative purposes. For a color version of this figure, see the color plate section.

with how *what*-concepts (semantic) become encoded as *where*-concepts (spatial) and *when*-concepts (episodic retrospection/past) as a function of personal or motivational relevance. This drives *what if*-concepts of goal-directed simulations that are future-oriented (episodic prospection/future) and temporally evaluative (episodic counterfactual), as well as noetic hypothesis testing (semantic beyond factual). This in turn can lead to the generation of creative solutions and creative expressions (original and relevant ideas/products), both of which – whether actively generated by the creator or passively elicited within the recipient upon exposure to these ideas/products – results in the creation of new knowledge or *what*-concepts (semantic). For instance, one may not have known the association between pomegranates and the concepts of fertility or love prior to encountering a work of art where these concepts have been united, such as in the painting of Proserpine by Dante Gabriel Rossetti, or D. H. Lawrence's poem – "Pomegranate," or indeed the image on the cover of Kris Waldherr's book *Persephone and the Pomegranate: A Myth from Greece*. Thereafter, though, these novel and fitting associations are assimilated into one's ever-expanding semantic knowledge store. And the cognition–imagination cycle continues.

The great advantage that will come from making clear tracks in creativity research to tie our findings in meaningful ways to other aspects of cognition and imagination is that it will allow us to get so much closer to understanding the deeply intertwined functions of the brain by moving beyond the generic compartmentalized view of human psychological function as emerging via systems of perception, emotion, cognition, and action. Other domains of psychology can perhaps choose to view their topics of study in such a circumscribed manner, but not creativity. Not if the aim is to derive meaningful knowledge regarding the same.

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12 A Common Mode of Processing Governing Divergent Thinking and Future Imagination

Reece P. Roberts and Donna Rose Addis

Humans have the unique ability to generate, evaluate, and share ideas. These ideas range from trivial descriptions of the current state of affairs in one's environment (e.g., describing the weather) to complex formulations of laws governing the physical world (e.g., $E = MC^2$); they can be grounded in reality, or involve entirely fictitious characters, events, and even universes; ideas can be shared using the mediums of language, music, dance, mathematical formulae, the visual arts, or some combination of these. At the heart of both scientific and artistic endeavors is the generation of ideas – the forging of novel associations between often disparate elements to create new ideas or outputs (e.g., musical pieces, poetry, scientific theories, etc.) that are regarded as useful or valuable (Runco & Jaeger, 2012). As such, it is generally accepted that creative cognition involves both divergent thinking (generating multiple answers to a single cue or question) and convergent thinking (arriving at a single, correct solution in response to a problem) (Ward, Smith, & Vaid, 1997). To date, a great deal of neurocognitive research has focused on divergent thinking, commonly measured by the Alternate Uses Task (AUT; Guilford, 1967) where participants generate alternative uses for common objects. However, it is becoming increasingly apparent that the ability to simulate future events, a cognitive domain that has received a great deal of attention in the last decade (e.g., Addis, Cheng, Roberts, & Schacter, 2011; Addis & Schacter, 2012; Addis, Wong, & Schacter, 2007; Benoit & Schacter, 2015; D'Argembeau, Lardi, & Linden, 2012; Hassabis, Kumaran, & Maguire, 2007; Irish, Addis, Hodges, & Piguet, 2012; Suddendorf & Corballis, 1997; Szpunar, Spreng, & Schacter, 2014), is also a creative endeavor. We propose that these ostensibly different abilities – divergent thinking and future simulation – are in fact governed by the same underlying mechanisms: the ability to forge associations between distinct memory representations, and executive functions that act on these associations. The degree to which the memory representations involved are semantic or episodic differs between the two, but the underlying processes acting upon these representations – associative and executive processes – are the same.

In this chapter, we review behavioral and neuroimaging studies investigating divergent thinking with an emphasis on the relative contributions of associative and executive processes and relevant brain networks engaged by divergent thinking tasks. Next, we highlight the similarities between divergent thinking and future imagination, in terms of both the cognitive and neural processes underscoring the two cognitive abilities. Finally, we review recent work providing empirical evidence for a relationship between these two processes, and propose a novel framework linking divergent thinking and future imagination.

Divergent Thinking

Associative and Executive Contributions to Divergent Thinking

The most common method used to assess divergent thinking is the AUT (Guilford, 1967), which requires participants to generate possible uses (e.g., “build a wall”) for common objects (e.g., “brick”); responses are then typically scored according to fluency (number of responses generated), flexibility (the number of distinct categories the responses can be grouped into), appropriateness (the feasibility of the generated use), elaboration (the amount of detail provided in responses), originality (the relative frequency with which other participants generate the same idea), and/or creativity (an experimenter rating regarding the creativity of the generated use, usually on a five-point scale). Despite the common use of this task, there is substantial disagreement in the literature as to the cognitive processes and neural substrates underlying its successful completion. On the one hand, many authors have stressed the fundamental role of associative processing – the linking of ideas – required to generate potential uses for a given cue (Benedek, Könen, & Neubauer, 2012; Rossmann & Fink, 2010). Variants of the *associative hypothesis* generally regard divergent thinking as being contingent upon spreading activation through semantic networks, a process that is largely independent of cognitive control (Mednick, 1962). In addition to semantic processes, episodic associative processes may also be engaged during divergent thinking, and although this occurs infrequently (Gilhooly, Fioratou, Anthony, & Wynn, 2007), it can nevertheless have an enhancing effect on divergent thinking performance (Madore, Addis, & Schacter, 2015). Conversely, an inability to access episodic memory impairs divergent thinking, as evidenced in hippocampal amnesic patients (Duff, Kurczek, Rubin, Cohen, & Tranel, 2013).

Given the reliance on semantic processes, individual differences in divergent thinking abilities are thought to be governed largely by the hierarchical structure of semantic memory networks, with more creative individuals having “flatter” associative hierarchies, such that activation of a given representation (e.g., table) spreads to representations with a loose semantic association to the original word (e.g., restaurant); by contrast, in less-creative individuals this spreading activation is restricted to closely related ideas or representations (e.g., chair; Mednick, 1962). The importance of spreading activation in divergent thinking tasks is evidenced in studies showing that AUT responses become more unusual over the duration of a trial (Milgram & Rabkin, 1980), the implication being that the spreading of activation across a semantic network takes time, with more remote representations being activated later than those highly related to the cue. More recently, Benedek, Franz, Heene, & Neubauer (2012) have shown that associative abilities explain close to half of the variance in AUT performance (as indexed by the number and originality of ideas), and Rossmann and Fink (2010) have shown that more creative individuals judge unrelated word-pairs as being more related than noncreative people.

Alternative accounts of divergent thinking abilities highlight the role of executive processes in generating original ideas. While some have argued that divergent thinking abilities are contingent on low cognitive control allowing free-flowing exploration of ideas (e.g., Carson, Peterson, & Higgins, 2003), a large body of work now supports the *executive hypothesis*: that higher executive control is positively associated with creative abilities (Beaty, Benedek, Kaufman, & Silvia, 2015; Beaty, Benedek, Silvia, & Schacter, 2016; Beaty & Silvia, 2012; Benedek, Franz, et al., 2012; Gilhooly et al., 2007). Take the aforementioned serial order effect where AUT responses start off being obvious and get more unusual with time (Guilford, 1967; Milgram & Rabkin, 1980): this temporal effect has been linked to the unfolding of executive processes across a trial, such as implementation of different strategies (Gilhooly et al., 2007) and executive switching (Nusbaum & Silvia, 2011) over the duration of a trial. Moreover, Beaty and Silvia (2012) found that fluid intelligence – which loads heavily on such executive processes (Conway, Kane, & Engle, 2003) – moderates the serial order effect. Specifically, they reported that more intelligent individuals tend to *not* show the serial-order effect, most likely because they can quickly establish an effective divergent thinking strategy and inhibit the generation of obvious responses right from the start of the trial (Beaty & Silvia, 2012).

More recently, Beaty, Silvia, Nusbaum, Jauk, and Benedek (2014) used structural equation modeling to show that associative abilities (i.e., retrieval ability) and executive functions (i.e., fluid intelligence) contribute independently to divergent thinking abilities. Such findings indicate that creative cognition is best described by a "dual-process" model that accounts for the interaction between associative and executive processes in the generation of novel ideas (Allen & Thomas, 2011; Barr, Pennycook, Stolz, & Fugelsang, 2015; Ellamil, Dobson, Beeman, & Christoff, 2012; Mok, 2014). The distinction between the cognitive processes related to associative and executive functioning map onto two well-characterized functional networks of the brain: the default mode and the frontoparietal control networks, respectively. This work will be reviewed next.

Neural Correlates of Divergent Thinking

A consistent observation in neuroimaging studies of divergent thinking is the activation of the default mode network (DMN) – a set of regions including medial frontal and parietal cortices, medial and lateral temporal regions, and the angular gyrus. It is well-established that the DMN is engaged during unconstrained mind-wandering and other forms of spontaneous cognition (Andrews-Hanna, Reidler, Huang, & Buckner, 2010; Andrews-Hanna, Smallwood, & Spreng, 2014; Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016), as well as during tasks requiring self-referential cognition such as theory of mind, episodic autobiographical memory and future imagination tasks (Buckner, Andrews-Hanna, & Schacter, 2008; Buckner & Carroll, 2007; Spreng, Mar, & Kim, 2009). The DMN also overlaps substantially with the set of regions active during semantic memory tasks (Binder & Desai, 2011; Binder, Desai, Graves, & Conant, 2009; Burianova, McIntosh, & Grady, 2010).

The involvement of the DMN in creative cognition is intuitively compelling, as many novel ideas seem to arise from a state of unconstrained mind-wandering that typifies the default mode. Indeed, a number of neuroimaging studies have highlighted the role of these regions in divergent thinking, and creative thinking more generally (Jung, Mead, Carrasco, & Flores, 2013). For example, Abraham et al. (2012) demonstrated that generating responses in a divergent-thinking task recruits core DMN regions, including medial temporal lobes, medial prefrontal and parietal cortices, angular gyri and lateral temporal regions. Mayseless, Eran, and Shamay-Tsoory (2015) report similar findings, with activation during divergent thinking evident in medial prefrontal and posterior cingulate cortices. Adopting an individual differences approach, Kühn et al. (2014) found that the volume of DMN regions, including the ventromedial prefrontal cortex (VMPFC), temporo-parietal junction and precuneus, was positively associated with performance in the AUT (specifically flexibility, originality, and creativity scores). Similarly, Jung and colleagues (2009) have shown that divergent thinking capabilities and creative achievement are positively associated with cortical thickness in right posterior cingulate and angular gyrus, respectively. Using electroencephalography, a number of studies have shown that engaging in divergent thinking leads to an increase in alpha-power (e.g. Jauk, Benedek, & Neubauer, 2012; Schwab, Benedek, Papousek, Weiss, & Fink, 2014), a frequency band linked to DMN function (Knyazev, Slobodskoj-Plusnin, Bocharov, & Pylkova, 2011). These patterns of activation have been shown to extend beyond classical divergent thinking tasks, as shown by Ellamil and colleagues (2012) in an elegant study investigating the neural correlates of visual creativity. In this task, participants designed a book cover on an MRI-compatible tablet while in the scanner, and the researchers broke the task into generative and evaluative components. A number of DMN regions were activated during the generative (medial temporal) and evaluative (medial frontal, medial parietal, and lateral temporal regions) phases of the task. Together, these findings highlight the important role of brain systems supporting spontaneous cognition, as well as episodic and semantic memory systems, in generative creative thought (Beaty et al., 2016).

Patient work on divergent thinking has demonstrated the critical role of two regions known to support *associative* processing: the medial prefrontal cortex and the hippocampus (Chao, Huston, Li, Wang, & de Souza Silva, 2016; Eichenbaum & Cohen, 2004). Shamay-Tsoory, Adler, Aharon-Peretz, Perry, and Mayseless (2011) found that patients with lesions involving the medial prefrontal cortex exhibited significant reductions in flexibility on the AUT and originality on the Torrance test; interestingly, patients with damage limited to the inferior frontal gyrus did not exhibit these deficits. Duff et al. (2013) observed that relative to healthy controls, hippocampal amnesics were significantly impaired on the Torrance Tests of Creative Thinking, including marked reductions in the degree of fluency, flexibility, and originality on the Unusual Uses Task.

A common observation in many neuroimaging studies, however, is that DMN regions do not operate in isolation during creative cognition. Instead, DMN functions appear to be complemented by those carried out by regions in the frontoparietal control network (FPCN), typically recruited by tasks requiring *executive* control (Campbell, Grady, Ng, & Hasher, 2012; Cocchi, Zalesky, Fornito, & Mattingley, 2013), inhibition (Aron, Robbins, & Poldrack, 2004; Erika-Florence, Leech, & Hampshire, 2014), and working memory (Kane & Engle, 2002; Morgan, Jackson, van Koningsbruggen, Shapiro, & Linden, 2012). Interestingly, a number of studies have shown activation of the rostrolateral prefrontal cortices – an area bordering default mode and frontoparietal control networks – in tasks requiring creative cognition (Abraham et al., 2012; Ellamil et al., 2012; Kröger et al., 2012). This region has been strongly implicated in relational reasoning (e.g., Christoff et al., 2001; Wendelken & Bunge, 2009; Wendelken, Nakhabenko, Donohue, Carter, & Bunge, 2007), a process required for generating novel associations between concepts – an important aspect of creativity. In addition, lateral prefrontal FPCN regions, including dorsolateral prefrontal cortices and inferior frontal gyri, are reliably recruited during creative cognition across a number of visual and verbal tasks requiring divergent thinking (e.g., Abraham et al., 2012; Beaty et al., 2015; Benedek et al., 2014; Ellamil et al., 2012; Kröger et al., 2012; Park, Kirk, & Waldie, 2015), highlighting the importance of cognitive control for creativity. Specifically, inferior frontal activity likely reflects inhibitory processes that suppress inappropriate responses (Mayseless & Shamay-Tsoory, 2015; but see Benedek et al., 2014 for an account that attributes activity in this region to semantic processing). Dorsolateral prefrontal regions, on the other hand, may be involved in the evaluation of generated ideas (Ellamil et al., 2012).

Importantly it is not merely the case that regions from DMN and FPCN are active during divergent-thinking tasks, but that creative states can induce a functional coupling of regions from these two independent networks (Beaty et al., 2015, 2016). Similarly, Beaty, Benedek, et al. (2014) have shown that individual differences in divergent-thinking abilities are associated with differences in functional connectivity between the right inferior frontal gyrus and the DMN, such that highly creative people show increased functional connectivity between these regions. This pattern of findings is largely supportive of the dual-process model described earlier, in which creative cognition emerges out of the interaction between DMN regions responsible for the free-flowing generation of ideas, and regions in the FPCN that serve to "control" the generative process by evaluating the outputs of these generative processes (Ellamil et al., 2012; Jung et al., 2013) and/or by inhibiting the activation of task-irrelevant representations (Beaty & Silvia, 2012; Gilhooly et al., 2007; Nusbaum & Silvia, 2011). There is also evidence to suggest that the FPCN modulates the interaction between the dorsal attention network and the DMN (Gao & Lin, 2012; Spreng, Sepulcre, Turner, Stevens, & Schacter, 2013), highlighting its role in mediating the switch from externally to internally directed cognition, which is the mode of processing in which divergent thinking occurs.

Imagining the Future

Associative Contributions

A cognitive domain at the intersection of episodic memory and creative cognition, the ability to simulate future events has received much attention over the past decade. In contrast to divergent thinking which relies on semantic memory with some contribution of episodic memory, future simulation loads heavily on episodic memory with contributions from semantic memory. Despite the differences in content, however, the neurocognitive substrates of future simulation and divergent thinking overlap in some striking ways, which we interpret as reflecting shared cognitive processes: the ability to forge associations between distinct memory representations (whether these representations are weighted more toward the semantic or episodic ends of the memory spectrum), and recruitment of executive processes to guide the creation of these novel representations. Below, we discuss relevant findings from the future simulation literature to highlight the similarities with divergent thinking.

Initial neuroimaging investigations into future simulation showed that, like divergent thinking, it is associated with strong activation of the DMN (Addis et al., 2007; Hassabis, Kumaran, & Maguire, 2007; Okuda et al., 2003; Szpunar, Watson, & McDermott, 2007). This pattern of activation is most apparent when imagining specific (relative to generic) future events (Addis, Cheng, et al., 2011) that involve novel representations (van Mulukom, Schacter, Corballis, & Addis, 2013). Although there is evidence to suggest that very similar patterns of activity are evident for imagining any type of novel scenario, including atemporal scenes (Hassabis, Kumaran, & Maguire, 2007) and imagined past/counterfactual events (Addis, Pan, Vu, Laiser, & Schacter, 2009; De Brigard, Addis, Ford, Schacter, & Giovanello, 2013; Van Hoeck et al., 2013), as we discuss below, it is likely that the unconstrained nature of imagining the future allows for more creative input (Addis, Pan, Musicaro, & Schacter, 2016).

The neuroimaging findings for future imagination have largely been framed in terms of the high degree of overlap with other episodic processes, namely remembering past events (Schacter et al., 2012) but also theory of mind (Andrews-Hanna, 2012) and spatial cognition (Buckner & Carroll, 2007; Hassabis & Maguire, 2007). With respect to remembering and imagining, both abilities have been linked to a "core network" of DMN regions (Benoit & Schacter, 2015) and deficits in remembering episodic memories are associated with corresponding deficits in imagination (Addis, Roberts, & Schacter, 2011; Addis, Wong, & Schacter, 2008; Hach, Tippett, & Addis, 2014; Hassabis, Kumaran, Vann, & Maguire, 2007; Maguire, Vargha-Khadem, & Hassabis, 2010). These findings have been interpreted as evidence that the ability to access episodic memory is a critical component of future imagination (Addis & Schacter, 2012). Recent work has indicated that being able to access semantic representations is also critical to imagining future events, such that patients with semantic dementia struggle to imagine detailed future episodes (Irish et al., 2012; Irish & Piguet, 2013). In these patients, future simulation deficits are associated with the degree of atrophy in bilateral temporopolar cortex, particularly on the left, consistent with the idea that the DMN supports both semantic and episodic representations (Binder & Desai, 2011; Burianova et al., 2010). In other populations with impairments in episodic memory, such as healthy older adults, there is an overreliance (relative to younger adults) on semantic details when describing past and future events (e.g., Addis, Musicaro, Pan, & Schacter, 2010; Addis et al., 2008; Gaesser, Sacchetti, Addis, & Schacter, 2011), and their subjective ratings of the amount of detail comprising future simulations is associated with future-related activity in anterior temporal cortex (Addis, Roberts, & Schacter, 2011). We argue that these findings are consistent with the involvement of DMN in *associative* processes, irrespective of whether the content of the representations is weighted more toward semantic or episodic memory representations and irrespective of whether the resulting representations are remembered or imagined events.

However, it is not just the ability to access information stored in episodic and/or semantic memory that is key to future simulation, but also the act of recombining these details together into a meaningful representation – in other words, additional *associative* processing to forge novel links between potentially disparate ideas. According to the constructive episodic simulation hypothesis (Addis & Schacter, 2012; Schacter et al., 2012; Schacter & Addis, 2007b), the inherently constructive nature of episodic memory enables episodic details to be flexibly extracted from individual memories and bound in novel ways to generate scenarios in one's "mind's-eye" that have not occurred, or may never occur.

In support of this hypothesis, there is evidence of neural differences between past and future events. A recent meta-analysis revealed that a number of DMN regions reliably exhibit increased activity during future imagination relative to episodic memory tasks, including medial prefrontal cortex, posterior cingulate, lateral temporal cortex and hippocampus (Benoit & Schacter, 2015). Of particular relevance to associative processing is the differential activity in hippocampus (Addis, Cheng, et al., 2011; Addis et al., 2007; Benoit & Schacter, 2015; Okuda et al., 2003), given the role of this region in associative processing (Eichenbaum & Cohen, 2004). Neuroimaging findings suggest that it is related, at least in part, to the inherent novelty of imagined events (van Mulukom et al., 2013) and the encoding of these simulations into memory (Martin, Schacter, Corballis, & Addis, 2011). However, these findings likely relate to an alternative explanation advanced by the constructive episodic simulation hypothesis (Schacter & Addis, 2007b): that the primary role of the hippocampus (and other DMN regions involved in associative processing, e.g., medial prefrontal cortex; Benoit, Szpunar, & Schacter, 2014) during episodic simulation is to construct episodes by integrating relevant episodic and semantic details stored in distributed neocortical regions. According to this *associative* view, integrating disparate details that have not occurred together before is particularly taxing on associative processes, leading to increased activity during future imagination relative to remembering. Indeed, we have found the hippocampus to be responsive to the amount of detail comprising future simulations (Addis, Roberts, & Schacter, 2011; Addis & Schacter, 2008). Moreover, even when controlling for differences in novelty and encoding, the hippocampus still shows increased activity during future imagination relative to remembering (Gaesser, Spreng, McLelland, Addis, & Schacter, 2013), suggesting that the associative demands of constructing future simulations are an important driver of hippocampal activity when imagining future episodes.

Benoit and colleagues (2014) focused on VMPFC, which also exhibited stronger activity during imagination than remembering. Their results indicated that during simulation of future events, the VMPFC supports the integration of pre-existing knowledge structures (e.g., about familiar people and places, and the affective value of these elements), exhibiting stronger connectivity with areas of cortex mediating person and place content. Given the strong bidirectional connections between the hippocampus and VMPFC (e.g., Barbas & Blatt, 1995), and the contributions of both regions to associative processing (Chao et al., 2016), it is likely that they work together in a coordinated fashion during simulation, perhaps with the hippocampus creating arbitrary associations between mnemonic elements (Eichenbaum & Cohen, 2004; Kesner, 2013) and the VMPFC selecting relevant associations in reference to previous knowledge (Benoit et al., 2014).

Executive Contributions

In addition to associative processing, another critical aspect of future simulation is *executive* processing. Like remembering, imagining future events involves working memory (to integrate and maintain multimodal information online), shifting (between ideas or aspects of the episode), selecting task-relevant information, and inhibiting task-irrelevant information (Berryhill, Picasso, Arnold, Drowos, & Olson, 2010; Conway & Pleydell-Pearce, 2000; D'Argembeau, Ortoleva, Jumentier, & Linden, 2010; Moscovitch, 1992; Schacter & Addis, 2007a). Indeed, D'Argembeau et al. (2010) found that executive processes were a major component of both past and future thinking, but also reported that future imagination loaded more on executive processes particularly when imagining specific events. Similarly, others have reported that, relative to remembering, future imagination is more strongly associated with the strategic retrieval of relevant episodic details (Addis, Hach, & Tippett, 2016) and places higher demands on selection and inhibition (Anderson, Dewhurst, & Nash, 2012; Berryhill et al., 2010; de Vito et al., 2012). These findings are consistent with the notion that imagining future events is an inherently creative endeavor, unconstrained by past happenings (Addis, Pan, et al., 2016; D'Argembeau et al., 2010), and therefore requires an individual to generate scenarios by settling on a particular course of events, retrieving relevant details, and inhibiting alternative possibilities. That is, the construction of future scenarios involves the generation of ideas that are both *novel* (having never occurred before) and *useful* (relevant to one's current task demands) — two hallmarks of the products of creative cognition (Mumford, 2003; Runco & Jaeger, 2012).

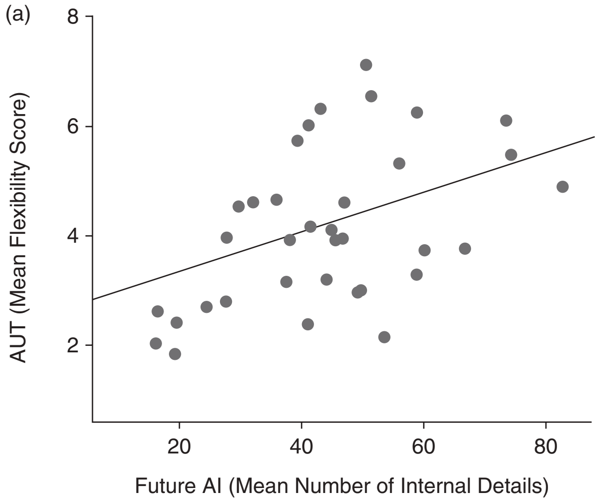
Consistent with the executive contribution to future simulation, it is becoming increasingly apparent that, like divergent thinking, future simulation involves the contribution of not only the DMN but also the FPCN. Importantly, Benoit and Schacter's (2015) meta-analysis revealed that five of the clusters exhibiting reliable increases during future imagination relative to remembering straddled the boundaries of the DMN and FPCN, suggesting that coordinated activation of these two networks is important during future imagination (Schacter et al., 2012). Direct evidence for this proposal comes from studies using task-related functional connectivity to demonstrate inter-network coupling between a number of regions in the DMN (e.g., posterior cingulate, medial prefrontal cortex, temporal pole) and FPCN (e.g., dorsolateral and rostrolateral prefrontal cortex) during future simulation (Gerlach, Spreng, Madore, & Schacter, 2014; Spreng, Stevens, Chamberlain, Gilmore, & Schacter, 2010), highlighting the interplay between associative and executive processes during tasks.

Direct Links between Divergent Thinking and Imagination: Variants of the Same Processing Mode?

As described above, the process of imagining future events is very similar to creativity tasks such as divergent thinking in that both are associated with the interaction of DMN regions instantiating associative processing and FPCN regions mediating executive processing in service of generating novel associations between semantic knowledge and/or episodic details. However, in addition to mere resemblances in the brain regions activated by creativity tasks and episodic simulation, some recent studies that include both divergent thinking and simulation tasks shed light on more direct links between the two.

First, Addis, Pan, et al. (2016) demonstrated that divergent thinking abilities are a reliable predictor of future imagination ability, over and above contributions of episodic memory. In this study, participants completed the AUT and also remembered past events, imagined past events (i.e., counterfactual episodes) and imagined future events. Descriptions of the remembered and imagined events were scored using the adapted Autobiographical Interview (AI): transcripts were divided into discrete details that were then classified as either internal (i.e., episodic details directly related to the event e.g., “It was just before lunch”) or external (i.e., nonepisodic details such as semantic information, e.g., “Lunch is my favourite meal of the day”) (Addis et al., 2008; Levine, Svoboda, Hay, Winocur, & Moscovitch, 2002). First, we found that the amount of internal detail for remembered events (an index of access to episodic details) was a predictor of the amount of internal detail comprising imagined past and future events – a finding commensurate with the construction episodic simulation hypothesis, which proposes future imagination to rely on the retrieval of episodic details as well as the flexible recombination of these details into a coherent future scenario. However, the key finding from this study was that AUT performance significantly predicted the number of internal (episodic) details comprising imagined future events (Figure 12.1); in contrast, AUT scores were not strongly associated with the amount of internal detail comprising imagined past or remembered past events. This observation suggests that divergent thinking is particularly relevant for imagining events where the task is open-ended and unconstrained, as is the case when imagining the future. By contrast, imagining past events requires consideration of what has actually occurred in the past and such constraints may limit the contribution of divergent thinking.

Second, the relationship between divergent thinking and simulation is evident in a series of studies utilizing a specificity induction (Madore et al., 2015; Madore, Jing, & Schacter, 2016). In the initial phase of these studies, participants watch a short video and then experience one of two inductions: a *specificity induction* in which they are guided through a process of recalling episodically specific details related to the video as well as performing mental imagery exercises related to the video, or a *control induction* that involves describing their general impressions of the video. Importantly, the specificity induction elicits an episodic retrieval strategy (Morcom & Rugg, 2012) that should benefit both divergent thinking and future imagination if these two tasks are similarly dependent on retrieving episodic information. Madore, Addis, & Schacter (2015) had participants complete the AUT (scored for flexibility, i.e., the number of categories of appropriate uses); an adapted AI involving the description of imagined future events; a semantic Object Associates Task that requires a degree of generative processing (generation of objects commonly related to an object cue) but arguably less so than the AUT (Abraham et al., 2012); and the Remote Associates Task that taxes convergent as opposed to divergent thinking. Two key findings emerged from this study. First, the specificity induction, relative to the control induction, produced an increase in AUT flexibility scores as well as the number of internal (episodic) but not external (semantic) details comprising future simulations. Second, the enhancing effects of the specificity induction did not extend to the Object Associates or the Remote



(b) Hierarchical Linear Regressions

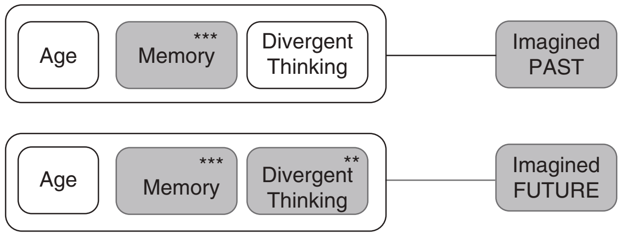


Figure 12.1 (a) Significant positive correlation between flexibility scores on the AUT and the mean number of internal details comprising future events on the AI ($r = .40$, $p < .01$). (b) Hierarchical linear regressions indicated that while the number of internal details for past events ("memory") predicted the number of internal details comprising imagined past *and* imagined future events, AUT flexibility scores ("divergent thinking") only predicted internal details for imagined *future* events. *** $p < .001$; ** $p < .01$. AUT, Alternate Uses Task; AI, Autobiographical Interview. For a color version of this figure, see the color plate section.

Associates Task. Critically, this pattern of findings groups together divergent thinking and future imagination as creative tasks that respond similarly to increasing the episodic specificity of retrieval, but distinct from purely semantic generation or convergent modes of creative thought. In a follow-up study, Madore, Jing, et al. (2016) demonstrated that the specificity induction has the same effect on another divergent thinking task – the Consequences Task (Guilford, 1967; Torrance, 1962) – which requires participants to generate the consequences of novel and improbable scenarios (e.g., flying without mechanical aids). An important aspect of this study was that for both the AUT and the Consequences Task, the authors probed whether the specificity induction simply increases the retrieval of previously established knowledge during divergent thinking, or whether it actually increases the creation of novel ideas. To this end, participants indicated whether each generated idea was "old" (i.e., responses based on previous experiences or previously constructed ideas) or "new" (i.e., newly constructed ideas; see also Benedek et al., 2014; Gilhooly et al., 2007). They found that the specificity induction, as compared to the control induction, increased the generation of new ideas on both the AUT and Consequences Task.

Taken together, these findings suggest that various forms of creative generativity, such as future imagination and divergent thinking, are dependent on episodic memory. Madore, Jing, et al. (2016) argued that the specificity induction elicits a “retrieval mode” that increases retrieval of details from various episodic memories; these details are then available to be recombined to form new ideas, in line with the constructive episodic simulation hypothesis (Schacter & Addis, 2007b). We propose a subtly different explanation: that the specificity induction increases associative processing more generally, thus facilitating not only the retrieval of details from episodic (associative) memories, but also the creation of novel associations of episodic details with other episodic or semantic elements. Thus, the specificity induction benefits not only the simulation of novel events (as per the constructive episodic simulation hypothesis), but also the creation of novel responses during divergent thinking tasks, which requires the initial retrieval and subsequent recombination of mnemonic details – both episodic and semantic – into novel, multifaceted representations.

The findings of a recent fMRI study further support the notion that the specificity induction increases the retrieval of episodic information and/or associative processing (Madore, Szpunar, Addis, & Schacter, 2016). Following the specificity induction, simulation-related activity in the DMN was significantly increased relative to that following the control induction, in regions involved in associative processing (e.g., hippocampus, VMPFC) as well as regions mediating semantic processing (e.g., lateral temporal cortex). Although this study only examined activity during future simulation, it seems feasible that similar effects would be observed during the AUT, although this hypothesis has yet to be tested.

A recent fMRI study from our lab has further investigated the link between divergent thinking and future imagination (Roberts et al., 2017). This study utilized a recombination paradigm (Addis et al., 2009; Martin et al., 2011; van Mulukom et al., 2013), in which participants were presented, on each trial, with a person, place, and object from their personal memories and required to imagine an event containing all three details. Future imagination occurred under two conditions: the *Congruent* condition, in which the episodic details were from the same social sphere (e.g., family, work, sport), and an *Incongruent* condition, in which the details originated from three different social spheres (van Mulukom, Schacter, Corballis, & Addis, 2016). The rationale behind this manipulation was that the Incongruent condition should induce a mode of processing similar to that observed in divergent thinking: in the same way that divergent thinking requires conceptual expansion (i.e., the widening of the conceptual boundaries associated with semantic representations), imagining scenarios in the Incongruent condition requires conceptual expansion in the autobiographical domain (i.e., widening the scope in which episodic details usually co-occur). A task partial least squares (PLS) analysis showed that the Incongruent condition was associated with increased activity in the salience network (SN), including the left mid-anterior insula. Subsequent functional connectivity analyses (using ws-seed PLS; Roberts, Hach, Tippett, & Addis, 2016) revealed that the left insula regions were more strongly coupled with DMN regions (lateral temporal pole and angular gyrus) during the Incongruent condition. These findings are similar to those observed by Beaty et al. (2015), who reported both insula activation and insula–DMN coupling during AUT performance. It is possible that the insula activation and connectivity evident here and in the Beaty et al. study reflects a switching function (Menon & Uddin, 2010) that facilitates the interactivity between the DMN and FPCN. This pattern of DMN and FPCN connectivity, interfaced by the insula, may be the neural correlates of the common processing mode underpinning both divergent thinking and future imagination.

In addition to the future imagination tasks in the scanner, participants completed the AUT outside the scanner, allowing us to adopt an individual differences approach (using behavior PLS) that assessed how activity during the future imagination tasks correlated with flexibility scores on the AUT. As shown in Figure 12.2, this analysis revealed reliable positive associations between AUT flexibility scores and activity in both right lateral temporal and bilateral rostrolateral prefrontal cortices — regions previously associated with both divergent thinking (e.g. Abraham, 2014; Wu et al., 2015) and future imagination (e.g., Irish et al., 2012; Irish & Piguet, 2013; Spreng et al., 2010; Underwood, Guynn, & Cohen, 2015). The effect in lateral temporal regions is commensurate with the importance of access to semantic representations for both divergent thinking and future imagination. In particular, future imagination requires a semantic framework (or "scaffold") within which simulated episodes can occur (Irish, 2016; Irish et al., 2012; Irish & Piguet, 2013), and likely draws heavily on personal semantics mediated by lateral temporal regions (Renoult, Davidson, Palombo, Moscovitch, & Levine, 2012; Stawarczyk & D'Argembeau, 2015; Svoboda, McKinnon, & Levine, 2006). Our finding that lateral temporal lobe activity during future imagination is associated with AUT performance provides a potential answer to one part of the puzzle as to why individuals who perform well in the AUT are also able to imagine more detailed future events: both tasks are deeply contingent on the ability to access semantic information.

Moreover, the relationship between AUT performance and activity in bilateral rostrolateral prefrontal cortical regions sheds light on an additional mechanism required for both divergent thinking and future imagination. Rostrolateral prefrontal cortex (bordering the DMN and FPCN) has been implicated in relational reasoning in a number of domains, and is reliably activated in tasks that require participants to deduce the logical mappings between concepts (e.g., "food is to hunger as water is to …?"; Christoff et al., 2001; Wendelken, Chung, & Bunge, 2012; Wendelken et al., 2007). This process requires the integration of semantic information to determine shared features and properties of disparate representations, and is linked to the process of conceptual expansion, in which the conceptualization of semantic representations are broadened beyond their rigid definitions (e.g., responding "use it as a toothpick" when presented with *paperclip* in the AUT, see Abraham, 2014; Abraham et al., 2012; Kröger et al., 2012). The relational reasoning required during divergent-thinking tasks involves determining structural and functional similarities between paperclips and toothpicks that are not immediately obvious (in this case, the shared feature is that they are both small and sharp enough to extract something from the gaps between teeth).

In much the same way, imagining novel future events involving disparate autobiographical details requires participants to derive semantic properties shared by the details contributing to an imagined event, thereby allowing for a semantic scaffolding to be constructed within which the imagined event may occur. This scaffolding process is likely to be particularly important in experimental settings in which participants are presented with random details from their past and required to generate novel future scenarios (e.g., Addis et al., 2009; Martin et al., 2011; van Mulukom et al., 2013). For example, if a participant is presented with a detail set including *Dale* and *Sydney Opera House*, the successful construction of an event requires generating associative links between the semantic representations associated with these details: Dale loves rugby league; the annual grand final for rugby league is always in Sydney; the Opera house is in Sydney, etc. Generating these associative links, we argue,

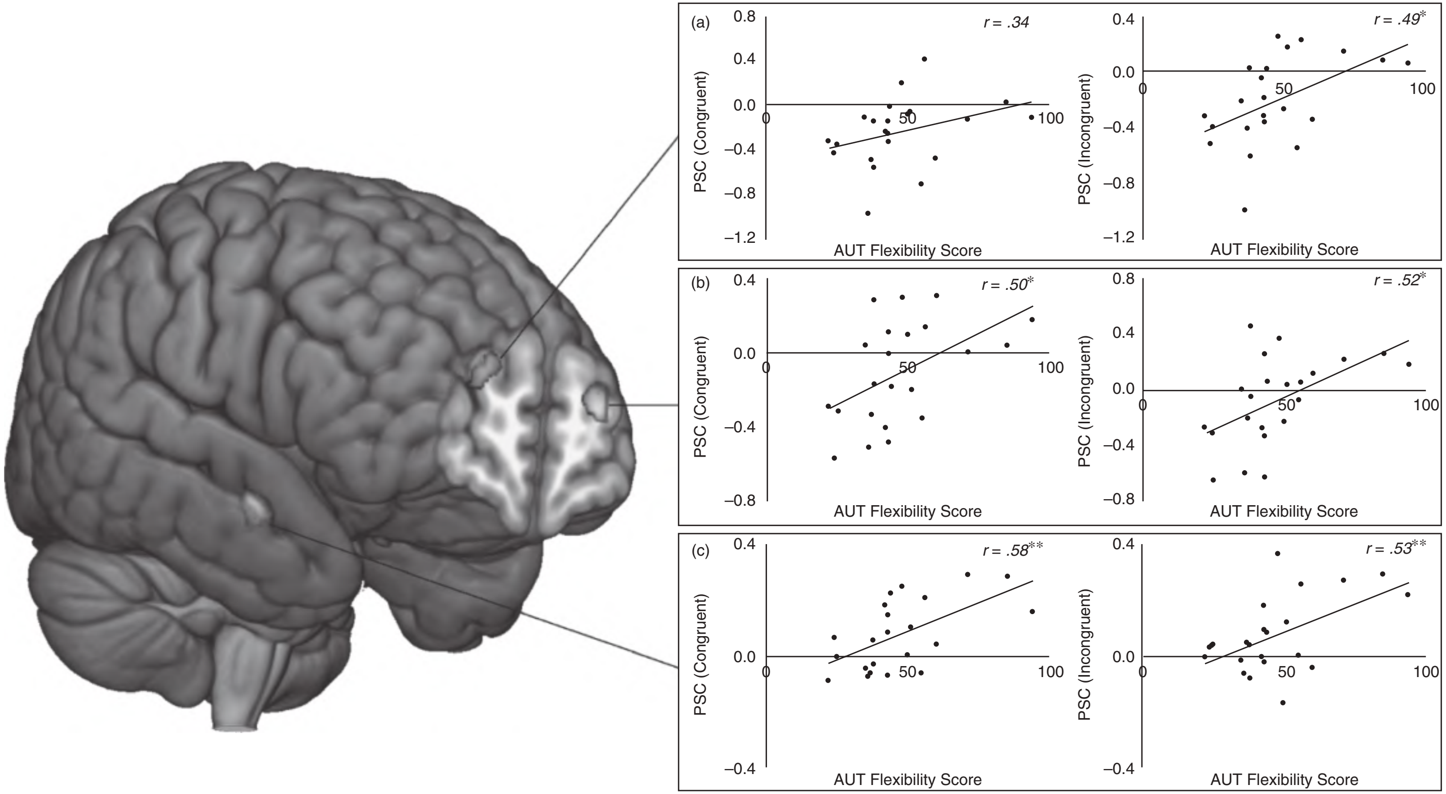


Figure 12.2 Regions reliably contributing to a latent variable showing correlations between brain activity during future imagination (in both *Congruent* and *Incongruent* conditions) and performance on the AUT (flexibility scores). The scatterplots show the relationship for (a) right rostrolateral prefrontal cortex, (b) left rostrolateral prefrontal cortex, and (c) right temporal pole. AUT, Alternate Uses Task; PSC, percent signal change; * $p < .05$; ** $p < .01$. For a color version of this figure, see the color plate section.

requires a form of relational reasoning that shares fundamental features with that observed in conceptual expansion during divergent thinking (i.e., deconstructing semantic representations to uncover shared properties between them). Evidence for our proposal comes from a recent fMRI study by Demblon, Bahri, and D'Argembeau (2016). In this study, participants were presented with pairs of future or past events that were either thematically related, shared the same location, or were entirely unrelated; participants had to respond with the nature of the relationship between the two events (thematic, location, or unrelated). The fMRI analyses showed that the pairs of events sharing a thematic link produced increased activity in the rostrolateral prefrontal cortex, highlighting this region's role in processing the higher-order relationship between representational structures.

Conclusions

Neuroscientific investigations of cognitive processes associated with creative cognition (e.g., divergent thinking) have revealed activation of a widespread set of brain regions — this lack of specificity in findings has led some to argue that the findings emerging from past studies are "uninterpretable" (Arden, Chavez, Grazioplene, & Jung, 2010). In fact, the large number of regions (from distinct functional networks, i.e., DMN, FPCN, SN) associated with more recent studies of divergent thinking and related abilities are beginning to indicate that the production of novel ideas emerges from the dynamic interaction of these whole-brain networks (Beaty et al., 2015, 2016). Under this dual-process framework, the contributions of DMN regions are associative in nature, forging of links between disparate memory representations (both episodic and semantic). The FPCN, on the other hand, supports executive processing including the inhibition of irrelevant representations (Beaty & Silvia, 2012; Gilhooly et al., 2007; Nusbaum & Silvia, 2011) and the evaluation of generated ideas (Ellamil et al., 2012; Jung et al., 2013). The SN (in particular, the insula) likely supports the switching between large-scale networks such as DMN and FPCN (Jung et al., 2013; Menon & Uddin, 2010) during divergent thinking. Many of these findings from the divergent thinking literature are mirrored in the neuroimaging studies investigating future imagination, which have consistently reported activation of DMN (Addis et al., 2007, 2009; Szpunar et al., 2007) and FPCN regions (Gerlach, Spreng, Gilmore, & Schacter, 2011), as well as a coupling between these two networks (Gerlach et al., 2014; Spreng et al., 2010) in service of simulation. In addition, a growing behavioral literature has highlighted the association between divergent thinking and future imagination (e.g., Addis, Pan, et al., 2016; Madore et al., 2015; Madore, Jing, & Schacter, 2016).

We propose, on the basis of the literature reviewed here and our recent neuroimaging work, that the relationship between divergent thinking and future imagination is likely governed by activity in lateral temporal and rostrolateral prefrontal regions, suggesting that both tasks are contingent on access to semantic representations (lateral temporal regions), and a relational reasoning process that forges associative links between these representations within an expanded conceptual space (rostrolateral prefrontal regions). We argue that the findings presented here suggest that divergent thinking and future imagination are not merely similar processes, but are two examples of the *same* processing mode in which creative cognition occurs.

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Part IV

Memory and Language

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13

Going the Extra Creative Mile: The Role of Semantic Distance in Creativity – Theory, Research, and Measurement

Yoed N. Kenett

Introduction

The neurocognitive research of creativity is making progress in examining the contribution of various cognitive processes and capacities, such as executive functions (working memory, fluid intelligence, switching), personality traits (openness to experience), attention, inhibition, and episodic memory to creativity (Beaty, Kaufman, et al., 2016; Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014; Madore, Addis, & Schacter, 2015; Radel, Davranche, Fournier, & Dietrich, 2015; Zabelina, Saporta, & Beeman, 2015). Several classic and more recent theories on creativity acknowledge the contribution of connecting weakly related concepts in memory during the creative process (Beaty, Silvia, Nusbaum, Jauk, & Benedek, 2014; Benedek, Konen, & Neubauer, 2012; Mednick, 1962; Schilling, 2005; Smith & Ward, 2012). Yet, due to the challenge of representing semantic memory and measuring semantic distance, the relationship between semantic processes and creativity has not been thoroughly investigated. This chapter focuses on the role of semantic distance in the creative process.

Semantic memory stores concepts and facts, regardless of time or context. In a more meticulous definition, semantic memory is responsible for the storage of semantic categories and of natural and artificial concepts (Budson & Price, 2005; McRae & Jones, 2013; Patterson, Nestor, & Rogers, 2007). Despite several computational models that have been proposed to represent it (Jones, Willits, & Dennis, 2015), the specific nature of semantic memory, including semantic distance, remains an open issue in cognitive research (McRae & Jones, 2013). The role of semantic distance in creativity is intuitively embedded in the theory of creativity, through the notion that the farther one moves from a concept in a semantic space, the more novel or creative the new concept will be. While the role of connecting more distant concepts in memory in creativity is very intuitive, it is difficult to examine empirically due to the difficulty of measuring semantic distance. Providing an overview of current and novel methods to measure semantic distance can contribute to advancing this field of research by providing researchers with tools to examine the role of semantic distance in creativity at different levels of analysis (i.e., computational, behavioral, and neurocognitive).

This chapter is divided into three parts: (1) Theory, which describes the associative theory of creativity, as proposed by Mednick (1962), laying out the groundwork on the relation of semantic memory structure and creativity. More recent theories and how they integrate the role of semantic memory structure in creativity will also be discussed; (2) Neurocognitive Research, which describes current neurocognitive research on semantic memory structure and creativity; and (3) Measuring Semantic Distance, where the three main methods to measure semantic distance between concepts are presented: frequency-based, Latent Semantic Analysis (LSA)-based, and network-based approaches.

Theories of Creativity and Semantic Distance

The main theory that related creative thinking to semantic memory structure is the associative theory of creativity (Mednick, 1962). According to this theory, creativity involves the connection of weakly related or remote concepts into novel and applicable concepts. The farther apart the original concepts are, the more creative the new combination will be. Building on this general process, Mednick proposed what differentiates low and high creative individuals: low creative individuals are characterized by "steep" associational hierarchies, while high creative individuals are characterized by "flat" hierarchies (Mednick, 1962, pp. 222–223). Mednick's notion of associative hierarchies refers to the idea that for every concept in semantic memory, there is a set of associations that are retrieved according to their associative strength. Thus, low creative individuals will generate only a few common, strong associations to a given stimulus (e.g., responses to the cue word *table* from such an individual are mainly restricted to the common response *chair*; characterizing these individuals as having "steep" associative hierarchies). High creative Individuals, on the other hand, will generate weaker associations to a given stimulus (e.g., responses to the cue word *table* are likely to be weaker, more remote responses such as *leg* and *food*, characterizing these individuals as having "flat" associative hierarchies).

Although never proven empirically, this theory has been debated and challenged over the years, with contradicting evidence both supporting and opposing it (see Benedek & Neubauer, 2013). Leading theories that were developed in the last quarter of the twentieth century have focused on how concepts in memory are manipulated in a creative way based on internal focused attention (Martindale, 1995; Mendelsohn, 1976). For example, Mendelsohn (1976) examined the interaction of informed versus uninformed category sets and creative abilities on anagram tasks. The results indicated that high creative ability was related to internal attentional capacity, which facilitates creative conceptual combination (Mendelsohn, 1976). More recently, the top-down, executive functions account, has been proposed (Beaty & Silvia, 2012; Benedek et al., 2014; see also Chapter 17), emphasizing the importance of cognitive control and executive functions, such as fluid intelligence and retrieval abilities, in the creative process (Benedek et al., 2014; Jauk, Benedek, & Neubauer, 2014; Lee & Therriault, 2013; Nusbaum & Silvia, 2011; Silvia, Beaty, & Nusbaum, 2013). According to this theory, cognitive control supports creativity via more effective memory retrieval and strategy implementation. Thus, these theories focus on processes operating upon memory that facilitate creativity, and not on how the structure of memory facilitates creativity. However, these theories maintain a role for semantic structure being the cognitive substrate upon which these executive functions operate. It is quite likely that both associative structure and executive functions interact in the process of creativity, an issue that has gained attention recently (Beaty et al., 2014; Forthmann et al., 2016; Kenett, Beaty, Silvia, Anaki, & Faust, 2016).

A third line of relevant theories includes the dual-process theories of creativity (Barr, Pennycook, Stolz, & Fugelsang, 2014; Simonton, 2013, 2015; Sowden, Pringle, & Gabora, 2014). These theories attempt to formalize the creative process based on its two main components – novelty and applicability (also claimed by Mednick's theory). Based on Campbell's (1960) evolutionary theory of creativity, Simonton has proposed that creativity is a result of Blind Variation and Selective Retention (BVSR; Simonton, 2013). The BVSR theory sees creativity from an evolutionary perspective, involving "blind" generation of exploratory ideas and a selection criterion that retains only relevant ideas (Simonton, 2010). Gabora et al. proposed that creativity involves a neurally plausible contextual shifting of focus between an associative mode of thought and an analytical mode of thought, contingent on task demands (Gabora, 2010; Sowden et al., 2014). In accordance with Mednick's theory, Gabora et al. proposed that an individual can shift into a "flatter" associative mode of thought, which in turn facilitates the connection between remote concepts. The main difference between this theory and the BVSR is that this process is context dependent and not "blind."

In sum, classic and current theories of the creative process acknowledge the role of semantic distance and memory structure in the creative process, either as an integral component (Mednick, 1962; Simonton, 2013; Sowden et al., 2014) or as the basis upon which executive functions operate (Benedek et al., 2014; Mendelsohn, 1976).

Neurocognitive Research on Creativity and Semantic Distance

Until recently, studies examining the contribution of semantic distance to the creative process mainly examined an indirect measure of semantic strength, based on frequency of responses. Mednick, Mednick, and Jung (1964) studied the number and latencies of associative responses generated by low, medium, and highly creative individuals over a two-minute period. This study found significant differences between association latencies of low and high creative individuals – high creative individuals were faster and more stable in generating associations than were low creative individuals. Thus, creative individuals may have more associative links in their semantic memory network and can activate associative relations faster than less creative individuals (Rossman & Fink, 2010). For example, Gruszka and Necka (2002) examined the priming of close and remote associations by low and high creative individuals. They showed that high creative individuals have a more complex semantic memory structure and activate a wider range of associations across their semantic memory network. However, other behavioral studies of Mednick's theory provided inconsistent results: while some studies found a positive relation between associative responses and creativity, others found a negative, null, or a nonlinear relation between them (reviewed in Benedek & Neubauer, 2013). These inconsistent results may be related to the behavioral measures used, mainly frequency of associative responses, indicating the need to use more sensitive measures of semantic distance in creativity research.

A more current neurocognitive research program on semantic distance and creativity has been conducted by Abraham on conceptual expansion (Abraham, 2014). Conceptual expansion refers to the ability to expand acquired conceptual structures to include novel elements (Ward, 1994). The task developed by Abraham involves passive or active conceptual expansion while processing stimuli which were manipulated on two dimensions, unusualness and appropriateness, and implemented in both EEG (Kröger et al., 2013; Rutter, Kröger, Hill, et al., 2012) and fMRI paradigms (Abraham et al., 2012; Kröger et al., 2012; Rutter, Kröger, Stark, et al., 2012). Their studies consistently show that creative conceptual expansion (stimuli judged as being highly unusual yet highly appropriate) is related to activation in brain areas that are associated with selection, controlled retrieval, combination and integration of semantic knowledge (inferior frontal gyrus; frontopolar cortex and the temporal poles). This paradigm only indirectly manipulates semantic distance (through the manipulation of unusualness and appropriateness). Still, it offers a neurocognitive approach to examine the effect of novel combinations at the conceptual level (see Faust, 2012 for a related approach).

The neural findings of the conceptual expansions approach converge with the growing field of creative neuroscience that studies the brain structures and dynamics implicated in creativity (Beaty, Benedek, Silvia, & Schacter, 2016; Gonen-Yaacovi et al., 2013; Jung, Mead, Carrasco, & Flores, 2013). Current research focuses on the relation of the default mode network (DMN) and creativity (Beaty, Benedek, Kaufman, & Silvia, 2015; Beaty, Benedek, et al., 2016; Beaty, Kaufman, et al., 2016; Mayseless, Eran, & Shamay-Tsoory, 2015). The DMN is a network comprised of midline and inferior parietal regions that are activated in the absence of external task demands, and is associated with cognitive processes that involve spontaneous, internally directed or self-generated thought (Andrews-Hanna, Smallwood, & Spreng, 2014). As such, it can be expected that processes related to semantic memory and conceptual combinations will be related to activation in the DMN. Recent studies have started to examine the role of the DMN in semantic memory (Kim, 2016; Shapira-Lichter, Oren, Jacob, Gruberger, & Hendler, 2013; Wirth et al., 2011). Kim (2016) conducted a meta-analysis to examine the role of the DMN in episodic (recollection compared to familiarity) and semantic (words compared to pseudo-words) memory. This analysis revealed that both episodic and semantic memory retrieval processes recruit extensive and largely overlapping DMN regions. Finally, Beaty et al. (2015) found a temporal interaction between DMN activity and activity in the executive control network (ECN) during performance in a creative task. Contrary to the DMN, the ECN has been related to task-related, goal-driven tasks. As such, Beaty et al. (2015) interpret their results as a neural basis for the two key components of the creative process – novel generation of ideas and their evaluation.

At the computational level, Olteţeanu and Falomir (2015) proposed a computational framework to model Mednick's theory on the relation of associative connections and creativity (see also Kajić, Gosmann, Stewart, Wennekers, & Eliasmith, 2016; Kajić & Wennekers, 2015, for a similar, more recent approach). This computational framework uses the corpus of contemporary American English (Davies, 2009) to construct a three-level knowledge base to model creative tasks (i.e., subsymbolic, conceptual, and structured representational; Olteţeanu & Falomir, 2015, 2016). The framework was used to develp a computional method – comRAT-C – that solves compound remote association stimuli, a task intially developed by Mednick to test his theory (Bowden & Jung-Beeman, 2003; Mednick, 1962). In this task a participant is presented with three target words (e.g., *cottage*, *swiss*, *cake*) and is required to find a solution (i.e., the fourth word) that is related to each of the three target words seperately (*cheese*; Mednick, 1962). The comRAT-C approach is based on examining the concepts that are activated by each of the initial target words and finding a solution concept that converges from these target word related activated concepts. The authors show that this approach successfully solves about 50% of the compund remote association stimuli (Olteţeanu & Falomir, 2015). However, the model is only a simple proof of concept and does not account for the main notion put forth by Mednick – connecting distant concepts.

In general, despite the intuitive role of semantic distance and semantic memory structure in creative theory, only a limited amount of research has been conducted on this issue. This is due to the challenge in measuring semantic distance. In this regard, a growing number of studies are being conducted applying computational measures of semantic distance in creativity research. Those studies will be reviewed next.

Measuring Semantic Distance

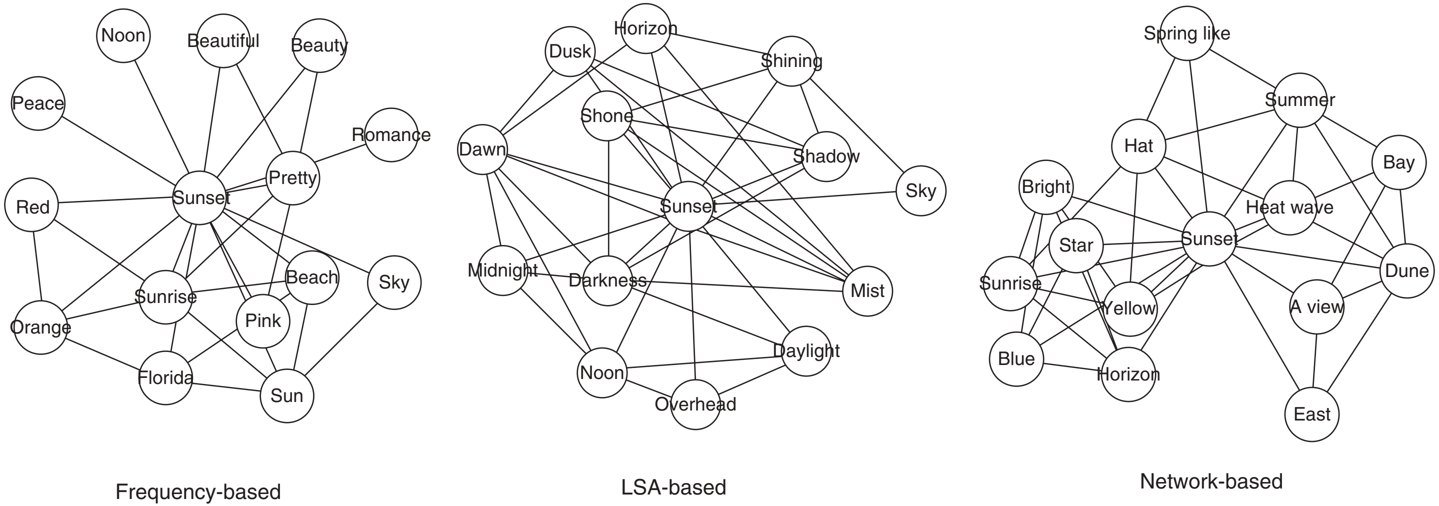
Semantic distance is a widely used notion in psycholinguistic research (Anaki & Henik, 2003; De Deyne, Navarro, & Storms, 2013; Nelson, McEvoy, & Dennis, 2000). It plays a major role in semantic memory structure, based on the notion that as two concepts become "closer" in a semantic space, the more similar they are to each other (Collins & Loftus, 1975; Den-Heyer & Briand, 1986). Semantic distance is the "shortest path [direct or indirect] between two nodes" (Collins & Loftus, 1975, p. 412, note 3). As such, it can be defined as the number of steps that intervene between two words in semantic memory. However, given the challenge to represent semantic memory (Jones et al., 2015), developing valid measures of semantic distance remains problematic. Such measures are needed to empirically manipulate semantic distance in creativity research. This section will cover three methods that are used for this purpose: frequency-based, LSA-based, and network-based approaches (Figure 13.1).

An empirical comparison of these three methods is outside the scope of this chapter (De Deyne, Verheyen, & Storms, 2016; Kenett, Levi, Anaki, & Faust, 2017; Mandera, Keuleers, & Brysbaert, 2017). Rather, the aim is to provide an overview for those interested in studying the role of semantic distance in creativity.

Frequency-based Approach

The conventional method to represent semantic distance is known as the frequency-based account. According to this method, semantic distance between a pair of words is measured through the frequency of participants in a sample that generate a target word in response to a cue word. The higher this frequency is, the shorter the semantic distance is between these words in semantic memory (Collins & Loftus, 1975; Nelson, McEvoy, & Schreiber, 2004). Traditionally, associative responses are collected via a discrete association paradigm, in which participants are required to respond with the first associative response that comes to mind in response to a cue word (Nelson et al., 2004; see also Chapter 15). These responses are then used to compute associative strength based on the frequency of the response. To determine response probability, the number of participants generating the target response in response to the cue is divided by the entire sample (Nelson et al., 2000). These responses are sorted based on their associative strengths – from strong responses (responses with a high frequency) to weak responses (responses with a low frequency). One of the main driving forces of this approach is the data set collected by Nelson et al. during several decades, known as the University of South Florida Free Association Norms (USFFAN, w3.usf.edu/FreeAssociation; Nelson et al., 2004). In this data set, a large sample of participants generated a large number of responses to 5019 cue words. This data set has served as a yardstick for stimuli construction in many behavioral and neurocognitive studies (McRae & Jones, 2013). For example, Figure 13.1 presents all the associative responses generated to the cue word *sunset* (left panel; retrieved from the USFFAN website), and whether these responses were also generated in response to each other. These responses are generally related to colors (*red*, *orange*, *pink*), beauty (*beauty*, *beautiful*, *pretty*) or to the beach (*sun*, *sky*, *beach*).

However, this method results in strong categorical differentiation of strength (strong versus weak; Hahn, 2008). Specifically, discrete associative responses to cue words usually consist of a small set of strong responses, or a larger set of weaker responses. For example, the cue word *dad* generates five associative responses, where *mom* is the strongest response (associative strength of .76). In comparison, the cue word *daily* generates 18 associative responses, where *news* is the strongest response (associative strength of .17; Nelson et al., 2004). As such, the experimental use of associative strength is usually dichotomized, strong versus weak associative strengths, and is not sensitive to more delicate and intermediate degrees of associative strength (Hahn, 2008; Van Petten, 2014). This challenge has led to the growing use of computational measures of semantic distance in neurocognitive research, especially via LSA.



Frequency-based

LSA-based

Network-based

Figure 13.1 First neighbors (directly connected concepts) for the word *sunset* according to the different approaches to measure semantic distance (frequency-based, LSA-based, and network-based). Frequency-based neighbors (left panel) were retrieved from the University of South Florida Free Association Norms website; LSA-based neighbors (central panel) were retrieved from the University of Colorado LSA website; network-based neighbors (right panel) were taken from Kenett et al. (2011). In all cases weights were binarized to equal one. Relations between neighbors were examined by whether responses to a neighbor word *x* elicited neighbor word *y*.

LSA-based Approach

A popular computational method to represent semantic distance is through LSA (Landauer & Dumais, 1997; Landauer, Foltz, & Laham, 1998). LSA quantifies the semantic similarity between words in a given high-dimensional semantic space by determining the probability of a given word co-occurring in a specific context (e.g., a paragraph of a document). In recent years a large number of corpus-based methods have been developed (Jones et al., 2015). These methods differ in terms of how they define a word's context (e.g., paragraph, document), the extent to which they use grammatical information (e.g., word order), and how the meaning is represented (e.g., latent spaces, mixture models).

A main resource for computing LSA-based semantic similarity is the University of Colorado LSA website (http://lsa.colorado.edu; Dennis, 2007). The website contains several computed semantic spaces and tools, such as near neighbors of a term (generating the nearest terms to a specific text/term), one to many comparisons (comparing the similarity of one text/term to many), and pairwise comparisons (comparing similarity of multiple pairs of texts/terms). For example, Figure 13.1 presents LSA-related concepts to the cue word *sunset* (central panel; retrieved from the Colorado LSA website). These responses relate to more physical properties related to *sunset*, such as *dusk*, *darkness*, *shadow*, *mist*, *dawn*, or *horizon*.

LSA has been empirically applied to examine semantic priming, memory and creativity (Beaty et al., 2014; Chwilla & Kolk, 2002; Coane & Balota, 2011; Griffiths, Steyvers, & Firl, 2007; Howard & Kahana, 2002; Prabhakaran, Green, & Gray, 2014; Steyvers, Shiffrin, & Nelson, 2004). For example, Beaty et al. (2014) used LSA to compute semantic distance values of responses generated by participants during verbal fluency tasks to specific cue words. Average semantic distance was computed as an indicator of variation in the organization of semantic memory structure. This measure, along with several other measures of cognitive ability, was used to examine the contribution of both semantic memory structure and executive function processes to creative ability (i.e., divergent thinking). The authors found joint effects of both semantic distance and executive abilities on the fluency and creativity of divergent thinking responses. These findings suggest the contribution of both associative structure and executive functions to the creative process. Prabhakaran et al. (2014) examined LSA semantic distances of responses in a modified verb generation task, where participants were required to produce verbs in response to a series of nouns, either a creative verb in a cued condition or a typical verb in an uncued condition (thus examining "Thin Slices of Creativity"). The authors found that semantic distance was higher only in the cued condition, which was also related to measures of fluid intelligence, divergent thinking, and creative achievement.

At the neurocognitive level, LSA has been used to examine neural activation of semantic integration in analogy mapping (Green, 2016). Studies of this type manipulate semantic distance based on LSA, which provides a continuous variable (unlike the frequency based approach). Green and colleagues conducted a series of fMRI studies to examine the effect of semantic distance on the neural processing of analogy mapping (Green, Cohen, Raab, Yedibalian, & Gray, 2015; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010, 2012). In these fMRI studies, semantic distance with LSA was manipulated to examine the process of semantic integration in analogical reasoning, showing how increased semantic distance was associated with increased activity in the frontopolar cortex. These studies implicate the frontal pole in semantic integration during analogical reasoning, and demonstrate that it is sensitive to the semantic distances between the concepts that need to be integrated. In a recent study, Green et al. (2017) conducted a transcranial Direct Current Simulation study with the "Thin Slices of Creativity" paradigm. The authors found that in the cued condition, anodal stimulation over the frontopolar cortex led to the integration of more distant concepts, as measured with LSA-based measures of semantic distance. No such effects were found for the uncued or sham conditions (Green et al., 2017). These studies demonstrate how computational measures of semantic distance can be used in neurocognitive research.

However, objections have been raised regarding the validity of this approach as a measure of semantic distance and in predicting semantic priming effects (Hutchison, Balota, Cortese, & Watson, 2008; Mandera, Keuleers, & Brysbaert, 2015; Recchia & Jones, 2009; Simmons & Estes, 2006). Hutchison et al. (2008) found that LSA does not predict semantic priming in a lexical decision or a naming task. Research has also indicated that performance of LSA models strongly depends on the choice and scope of the text corpus used, which can become the determining factor in how well the model captures human performance (Recchia & Jones, 2009). Finally, while more advanced computational models of semantic spaces are being developed (Mandera et al., 2017), the validity of estimating semantic distance based on analysis of textual corpora has yet to be determined (De Deyne et al., 2016). A different computational approach to represent semantic distances might be realized through path lengths in semantic networks.

Network-based Approach

Network science is based on mathematical graph theory, providing quantitative methods to investigate complex systems such as networks (Baronchelli, Ferrer-i-Cancho, Pastor-Satorras, Chater, & Christiansen, 2013; Boccaletti, Latora, Moreno, Chavez, & Hwang, 2006; Borge-Holthoefer & Arenas, 2010). A network is comprised of nodes, which represent the basic units of a system (e.g., semantic memory) and links, or edges, that signify the relations between them (e.g., semantic similarity). At the cognitive level, this approach is mainly applied to investigate complex systems of language and memory structure (Baronchelli et al., 2013; Borge-Holthoefer & Arenas, 2010; Chan & Vitevitch, 2010; De Deyne, Kenett, Anaki, Faust, & Navarro, 2016; De Deyne & Storms, 2008; Kenett, Anaki, & Faust, 2014; Kenett et al., 2011; Steyvers & Tenenbaum, 2005; Vitevitch, 2008; Vitevitch, Chan, & Goldstein, 2014; Vitevitch, Chan, & Roodenrys, 2012). Figure 13.1 represents the first neighbors (directly connected nodes) to the cue word *sunset* (right panel; based on a large-scale network analysis of Hebrew [Kenett et al., 2011]). These responses relate to more thematic, experience-based organization in the semantic network, such as *east*, *bay*, *summer*, *hat*, and *dune*. These responses also relate to physical properties related to *sunset*, such as *bright*, *yellow*, and *horizon*.

Kenett, Anaki, and Faust (2014) applied network science methods to directly investigate Mednick's (1962) notion of the structural difference between low and high creative individuals. The authors applied a novel computational method to extract the semantic memory network organization of 96 cue words in low and high creative individuals. This analysis showed that the semantic memory network of high creative individuals is less rigid than that of low creative individuals, which may allow for more efficient retrieval strategies when generating free associations. Kenett et al. (2016) examined the relation of fluid intelligence, creative ability, and semantic memory structure. Participants completed a semantic verbal fluency task (name as many animals as possible) and were divided into four groups based on their performance on intelligence and creativity measures. The semantic network of the animal category was represented and comparisons were made among all groups. Results revealed that intelligence and creativity were differentially related to semantic memory structure: intelligence was more related to structural properties and creativity was more related to flexible properties. Further, this study found that the semantic network of the high intelligence/high creative group has both properties.

A method to measure semantic distance, with network science tools, was recently developed (Kenett, Levi, Anaki, & Faust, 2017). The authors examined whether path length can be used as a measure of semantic distance. Path length in a semantic network represents the amount of steps needed to traverse from one word in the network to another, and thus may serve as a measure of semantic distance (Collins & Loftus, 1975). The authors developed a semantic relatedness judgment task, in which participants judged whether two words were related to each other. The word pairs constructed for this study varied in the path length between them, based on a large-scale network analysis of the Hebrew lexicon (Kenett et al., 2011). From this analysis a distance matrix was constructed, representing the shortest amount of steps connecting any pair of words. This distance matrix was used to operationalize semantic distance, from which the word-pairs were constructed. These word-pairs were used to examine how path length is related to behavioral performance in a semantic relatedness task (Kenett et al., 2017). This study found a differential effect of path length on participant's performance; when up to four steps separated between word-pairs, participants exhibited an increase in response time (RT) and decrease in the percentage of word-pairs judged as related. From four steps onwards, participants exhibited a significant decrease in RT and the word-pairs were dominantly judged as unrelated. Path length was also related with performance on a subsequent "surprise" free- and cued-recall tests – as distance grew, the amount of recalled words decreased. Path length was also significantly correlated with subjective ratings of the associative strength of the word-pairs, judged by an independent group of judges: as distance grew, the word-pairs were judged to have a weaker subjective rating of associative strength, based on a seven-point Likert scale. Finally, the authors show how path length outperforms LSA measures in predicting participant's performance on the semantic relatedness judgment task (Kenett et al., 2017).

Thus, while still at a very initial stage, these findings indicate that path length in a semantic network can be used as a measure of semantic distance. This measure, similar to LSA, can also be used to manipulate and examine more sensitively neurocognitive activation. Furthermore, measures derived from semantic networks based on behavioral data (such as free associations) might be more valid than those based on LSA data (De Deyne, Kenett et al., 2016; De Deyne et al., 2016). Thus, this measure, based on path length in semantic network, provides an alternative measure of semantic distance.

Measuring the Semantic Distance of Divergent Thinking Responses

Recent attempts have been made to examine the semantic distance of responses generated in divergent thinking tasks (Acar & Runco, 2014; Hass, 2016). A key feature of divergent thinking is moving away from conventional to more distant, weakly related responses (Runco & Acar, 2012). Acar and Runco (2014) examined the semantic distance of divergent thinking responses based on data collected from three different sources of semantic networks (such as WordNet; http://wordnet.princeton.edu). Each of the divergent thinking responses was classified as close, remote, or highly remote, depending on the amount of concepts in the responses that were found in a specific network. The authors show that this approach is more objective and reliable in assessing divergent thinking responses. Furthermore, the authors found that participants with higher tendency for creative attitudes and values generated weaker or more remote divergent thinking responses. Thus, this work demonstrates the feasibility of measuring semantic distance of divergent thinking, which is a key component in the creative process (Runco & Acar, 2012).

Concluding Remarks

This chapter provides an overview of the role of semantic distance in creativity. Classic and recent theories of creativity have perceived the role of semantic distance in the creative process. Until recently, this perception was not accompanied by direct empirical support (Benedek & Neubauer, 2013). More recently, neurocognitive research has started to examine neural activation related to creative manipulation of semantic distance, either through direct (analogical reasoning via LSA; Green, 2016) or indirect means (via manipulating unusualness and approporiateness related to conceptual expansion; Abraham, 2014). These studies have implicated neural activation related to manipulation of semantic distance to the DMN. Given the role of the DMN in spontaneous, internally directed thought processes (Andrews-Hanna, Saxe, & Yarkoni, 2014), it is not surprising that the initial component of the creative process – novel generation of new ideas – is supported by the DMN. Thus, the development of more sensitive, quantitative measures of semantic distance, such as via LSA or network science, has facilitated more direct examination of the role of semantic distance in creativity.

Neurocognitive studies of the creative process have been limited by lack of sensitive measures and tasks that can be related to neural activity (Abraham, 2013; Arden, Chavez, Grazioplene, & Jung, 2010). The growing popularity of textual-based models of semantic spaces (such as LSA) in creativity research facilitates direct manipulation of semantic distance in regard to creative tasks, such as analogical reasoning (Green, 2016). The developing research using network science in cognitive systems provides an alternative method to semantic distance (Kenett et al., 2017). Future work is needed to determine which of these two measures of semantic distance better predicts human behavior (De Deyne, Kenett et al., 2016; De Deyne et al., 2016; Mandera et al., 2017). However, these two computational measures provide a more sensitive measure of semantic distance than the frequency-based approach, and allow for the pursuit of exciting new research avenues, such as examining divergent thinking responses (Acar & Runco, 2014; Hass, 2016). This type of research can directly examine the role of semantic distance as proposed in different theories of creativity (Mednick, 1962; Simonton, 2013; Sowden et al., 2014).

A growing number of studies on the creative process focus on the involvement of top-down executive functions (Benedek et al., 2014). The top-down account of the creative process argues that semantic structure which facilitates connections of distant concepts is not related to creativity. Rather, what is important are the executive functions which allow more creative cognitive manipulation (Benedek & Neubauer, 2013). Recent studies consistently show the interaction of semantic memory structure and executive functions in the creative process (Beaty et al., 2014; Forthmann et al., 2016; Kenett et al., 2016). Accordingly, research on the roles of functional connectivity networks in creativity has identified an interaction between the DMN and the ECN networks (Beaty et al., 2015; Beaty, Benedek, et al., 2016). These findings provide a neural model wherein the two-process model of creativity can be situated: (1) novel generation of ideas and concepts, which involves the ability to reach more distant, weaker concepts in memory (DMN); and (2) evaluation of appropriateness and relevance of these new ideas or concepts.

Finally, the limitations of using LSA- or network-based measures of semantic distance must be acknowledged. The validity of these measures is still debated for LSA measures and only initially investigated for network measures. This is especially important as a complete model of semantic memory is still lacking (Jones et al., 2015). A second important limitation is that these measures are strongly dependent upon the data from which they are computed (Recchia & Jones, 2009). While these measures are derived from massive big linguistic datasets (De Deyne et al., 2016; Mandera et al., 2017; Nelson et al., 2004), they are still only as good as the data that they are drawn from. Finally, these data sets are collected slowly while language is dynamic and evolving. For example, the data that Kenett et al. (2017) used to manipulate network-based semantic distance were collected and published a decade ago (Rubinsten, Anaki, Henik, Drori, & Farn, 2005). Still, these measures provide a close approximation of the cognitive construct of semantic distance. As in any tool, these measures need to be constantly developed and updated to preserve their reliability and validity.

In conclusion, the increasing use of computational methods to measure semantic distance in creativity research advances the examination of the role of semantic memory structure, and distance, in the creative process. The creative process is multi-faceted, involving many cognitive processes, such as internal focused attention, openness to experience and working memory. Recent studies have started to identify the role of episodic memory in imagination and creativity (Addis, Pan, Musicaro, & Schacter, 2016; Madore et al., 2015). Given the development and advancement of computational measures of semantic distance in creative research, the time is ripe for directly addressing the intuitive role of semantic distance in the creative process, and to use these tools to go the "extra mile" in the semantic space of our memory.

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14 Episodic Memory and Cognitive Control: Contributions to Creative Idea Production

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Creative ideas have long been considered to result from the flexible combination of concepts stored in long-term memory (Mednick, 1962). Seminal creativity theories emphasized the contribution of semantic memory and the spreading activation of concepts within semantic networks as central to creative idea production. Recently, however, it has become clear that in addition to semantic memory, other cognitive systems make important contributions to the production of creative ideas. In this chapter, we highlight two such systems – episodic memory and cognitive control – with a focus on the brain networks thought to support these processes. We describe recent behavioral work on the contributions of episodic memory and cognitive control to creative thought. We also address neuroimaging evidence on brain mechanisms supporting episodic memory and cognitive control during creative idea production, with an emphasis on functional brain networks and their interactions. The chapter concludes by describing a framework that incorporates the multiple neurocognitive systems underlying creative ideation.

Cognitive Control and the Frontoparietal Control Network

An increasing body of behavioral evidence indicates that creative thought can benefit from cognitive control and executive functions. These core cognitive abilities allow people to monitor and direct mental activity in a goal-directed manner. Although executive functions have historically been studied in the context of cognitive tasks that require sustained external attention (e.g., complex working memory span tasks; Kane et al., 2004), recent work has begun to explore the role of executive cognition in tasks involving sustained internal attention, such as creative divergent thinking (Benedek et al., 2016). Several recent studies have examined individual differences in executive processes and creative cognitive ability using an individual differences approach. An emerging consensus from this work is that creative thought recruits higher-order processes associated with executive functions, including fluid intelligence, broad retrieval ability, and inhibitory control.

The Cattell–Horn–Carroll (CHC) model of human intelligence defines several lower-order cognitive abilities that underlie a higher-order general intelligence factor (McGrew, 2009). Individual variation in these abilities has been shown to predict aspects of creative cognition. For example, fluid intelligence – the ability to solve novel problems via visual–spatial and verbal reasoning – is associated with performance on a range of creative tasks, such as generating alternate uses for common objects (Beaty & Silvia, 2012; Benedek et al., 2014a; Forthmann et al., 2016; Vartanian, Martindale, & Kwiatkowski, 2003), solving insight problems (DeYoung, Flanders, & Peterson, 2008; Lee & Therriault, 2013), and producing novel metaphors (Beaty & Silvia, 2013; Silvia & Beaty, 2012). Because fluid intelligence is strongly correlated with working memory capacity (Kane et al., 2004), it may impact creative thought by providing attention control and the capacity to maintain and manipulate multiple items in active storage.

Another cognitive ability associated with divergent thinking performance is broad retrieval ability (McGrew, 2009) – the ability to strategically search memory, shift between conceptual categories, and select among competing exemplars (Badre & Wagner, 2007; McGrew, 2009; Troyer, Moscovitch, & Winocur, 1997). Broad retrieval ability is often measured with verbal fluency tasks that require retrieving items from a given category (e.g., animals), a process that involves the generation and maintenance of higher-order retrieval strategies that constrain semantic search processes (Unsworth, Spillers, & Brewer, 2010). The ability to strategically search memory may account for the association of broad retrieval ability with performance on the alternate uses divergent thinking task (Benedek, Könen, & Neubauer, 2012; Silvia, Baety, & Nusbaum, 2013) as well as tasks involving the production of novel metaphoric expressions (Beaty & Silvia, 2013; Silvia & Beaty, 2012).

The involvement of cognitive control in creativity is further supported by research on executive functions. In a recent study, Benedek et al. (2014b) examined the associations among divergent thinking ability, fluid intelligence, and three executive functions: *updating* (monitoring and replacing items in working memory), *shifting* (switching between task sets and demands), and *inhibition* (suppressing pre-potent response tendencies). Replicating past work, the authors found that fluid intelligence predicted increased originality of divergent thinking responses. They also found that originality was associated with updating and inhibition, and that updating statistically accounted for the relationship between fluid intelligence and originality. These findings suggest that divergent thinking involves the capacity to focus attention, manage the contents of working memory, and suppress pre-potent response tendencies.

The notion that divergent thinking taps cognitive control and executive functions is consistent with seminal theories on the cognitive basis of creative thought. Finke, Ward, and Smith (1992) conceptualized creativity as a two-stage, recursive process of idea generation and idea evaluation, with generation associated with spontaneous combinatory mechanisms and evaluation associated with controlled convergent mechanisms. Although this framework remains popular in contemporary research, it remains unclear whether idea generation and evaluation occur in isolation and whether both processes benefit from cognitive control. Because performance on creative idea generation tasks is associated with cognitive abilities (e.g., broad retrieval ability and pre-potent response inhibition), the notion that it solely arises from spontaneous processes seems problematic.

Further evidence for a role of executive cognition in creative thought processes comes from considerable neueroimaging evidence reporting activation of the brain's frontoparietal control network. Also referred to as the executive control network (ECN) or cognitive control network (CCN), the frontoparietal control network is comprised of lateral prefrontal and anterior inferior parietal cortices (Spreng, Sepulcre, Turner, Stevens, & Schacter, 2013; Vincent, Kahn, Snyder, Raichle, & Buckner, 2008). This brain system has shown reliable activation during experimental tasks requiring focused attention to and active manipulation of both external stimuli (e.g., working memory) and internal representations (e.g., autobiographical planning). Like other large-scale brain networks, the control network is spatially and temporally distinct during the resting-state (Vincent et al., 2008). However, as described below, the control network also interacts with other brain networks to support goal-directed task performance (Spreng et al., 2010).

The dorsolateral prefrontal cortex (DLPFC) is a core hub of the frontoparietal control network (Vincent et al., 2008). Meta-analyses have identified the DLFPC and other regions of lateral prefrontal cortex as among the most consistent cortical regions associated with creative task performance (Gonen-Yaacovi et al., 2013; Wu et al., 2015). The DLPFC has shown activation in studies of domain-general creative thinking, such as the classic alternate uses task (Abraham et al., 2012; Kleibeuker, Koolschijn, Jolles, De Dreu, & Crone, 2013). Studies of domain-specific artistic performance have also implicated the DLPFC, including musical improvisation (Beaty, 2015; Pinho, de Manzano, Fransson, Eriksson, & Ullén, 2014), poetry composition (Liu et al., 2015), and artistic drawing (Ellamil, Dobson, Beeman, & Chrsitoff, 2012; Kowatari et al., 2009). Notably, the DLPFC has shown preferential engagement during experimental paradigms that involve idea evaluation compared to idea generation (e.g., Ellamil et al., 2012; Liu et al., 2015). Together, these findings suggest that the DLPFC – a region involved in cognitive control and executive functions – plays an important role in certain aspects of creative cognition. In the context of the behavioral research described above, the DFLPC may support creative thought by inhibiting goal-incongruent conceptual knowledge, maintaining focused attention and higher-order task goals, and manipulating information in working memory.

Another prefrontal region consistently implicated in creativity studies is the left inferior frontal gyrus (IFG; Boccia, Piccardi, Palermo, Nori, & Palmiero, 2015; Gonen-Yaacovi et al., 2013). The left IFG is located in the ventrolateral prefrontal cortex, a region primarily involved in controlled memory retrieval processes often assessed with verbal fluency tasks (Badre & Wagner, 2004; Thompson-Schill, 2003). In the creativity literature, the left IFG has shown robust activity during performance on verbal divergent thinking tasks (Benedek et al., 2014a; Fink et al., 2009; Kleibeuker et al., 2013; Vartanian et al., 2013). For example, Benedek et al. (2014a) reported an association between the creative quality of divergent thinking responses and BOLD signal change in the left IFG during divergent thinking. The involvement of the left IFG during creative cognition is consistent with behavioral research on broad retrieval ability and divergent thinking (Beaty & Silvia, 2013; Benedek et al., 2012; Silvia et al., 2013), and may reflect neural activity related to the strategic search of memory and selection of concepts among competing alternatives.

Episodic Memory and the Default Network

Studies of cognitive control and divergent thinking have been complemented recently by an emerging area of research that has examined the possible contributions of episodic memory to creative cognition. Episodic memory was classically defined by Tulving (1983, 2002) as a neurocognitive system that supports the ability to recollect specific past personal experiences. That perspective has broadened during recent years, as it has become increasingly clear that episodic memory also contributes importantly to a range of cognitive functions, including imagining future experiences (Klein, 2013; Schacter et al., 2012; Szpunar, 2010), counterfactual thinking (De Brigard, Addis, Ford, Schacter, & Giovanello, 2013; Schacter, Benoit, De Brigard, & Szpunar, 2015), and means-end problem-solving (Jing, Madore, & Schacter, 2016; Madore & Schacter, 2014; Sheldon, McAndrews, & Moscovitch, 2011). There is now increasing evidence that episodic memory also contributes to divergent creative thinking. We will first review behavioral evidence on this point, and then consider relevant observations from neuroimaging studies concerning the neural underpinnings of such effects that have linked episodic memory and creative thinking with the interconnected set of brain regions known as the default network.

Behavioral Evidence Linking Episodic Memory and Divergent Creative Thinking

Perhaps the first evidence suggesting a link between episodic memory and divergent creative thinking comes from a study of young adults by Gilhooly, Fioratou, Anthony, and Wynn (2007). In their experiment, participants performed the well-studied Alternate Uses Task (AUT), where they are asked to generate novel and appropriate uses for a common object. Gilhooly et al. observed that people occasionally draw on episodic memories when performing the AUT, primarily during the early phases of task performance. In a study of healthy young and older adults, Addis, Pan, Musicaro, and Schacter (2016) administered the AUT to participants who were also required to remember past experiences, and to imagine experiences that might occur in their personal futures or might have (but did not) occur in their personal pasts. They reported that performance on the AUT is positively correlated with the number of episodic details that participants report when they imagine possible future experiences. However, this correlation with AUT performance was specific to imagined future events, and was not observed for imagined or recalled past events. In a neuropsychological study, Duff, Kurczek, Rubin, Cohen, and Tranel (2013) found that amnesic patients with severe impairments of episodic memory as a consequence of bilateral hippocampal damage are also impaired on the Torrance Tests of Creative Thinking, which provide a broad assessment of divergent thinking. However, because such patients also typically have problems in acquiring new semantic memories, it is unclear whether the observed divergent thinking deficit specifically implicates episodic memory in divergent thinking processes. Moreover, the creativity deficit in amnesic patients does not seem to be selective for divergent thinking. A recent study by Warren, Kurczek, and Duff (2016) provides evidence that amnesic patients also exhibit deficits in convergent thinking, i.e., the ability to generate the single best solution to a problem. They found that hippocampal amnesic patients performed poorly on the Remote Associates Test (RAT; Bowden & Jung-Beeman, 1998; Mednick, 1962), a widely used test of convergent thinking that requires participants to generate a solution word that forms a common word/phrase with each of the three main parts of a target word triad (e.g., for "Eight/Skate/Stick" the solution word is "Figure").

Madore, Addis, and Schacter (2015) recently provided evidence for a stronger link between episodic memory and AUT performance. In their experiments, participants received an *episodic specificity induction* – brief training in recollecting specific details of a recent experience – prior to performing the AUT. The specificity induction used in this study is based on the well-established Cognitive Interview (CI; Fisher & Geiselman, 1992), a protocol used primarily in forensic contexts to increase episodic retrieval from eyewitnesses. When receiving the CI-based specificity induction, participants are encouraged to focus on episodic details pertaining to people, objects, and actions in a recently viewed video of an everyday scene (i.e., people performing actions in a kitchen setting). Several previous studies have shown that this specificity induction, compared with a control induction where participants provide their general impressions of a recently viewed video, selectively increases the number of episodic details that participants provide on subsequent tasks that require remembering past experiences and imagining future experiences, while having no effect on the number of semantic details that participants provide on such tasks (Jing et al., 2016; Madore, Gaesser, & Schacter, 2014; Madore & Schacter, 2016; for review, see Schacter & Madore, 2016).

In the first experiment by Madore et al. (2015), specificity and control inductions were given prior to performance on two main tasks: the AUT, and an object association task that required participants to generate common associates of objects but did not require divergent thinking. Critically, the specificity induction resulted in a significant increase on several standard measure of AUT performance: the total number of uses generated, appropriate uses (i.e., total number of uses that are feasible), categories of uses (i.e., total number of unique categories that uses can be binned under for each cue) and categories of appropriate uses (i.e., appropriate uses that are clustered into categories, often referred to as flexibility). By contrast, the specificity induction had no effect on performance of the object association task. Note also that the effects of the specificity induction on AUT performance were limited to the generative outputs noted above: they did not impact ratings of elaboration (i.e., a rating of how detailed each generated use is) or creativity (i.e., a rating of how original/unusual each generated use is). A second experiment compared effects of the specificity induction on AUT performance with performance of a convergent thinking task, the RAT. Results revealed that, once again, the specificity induction significantly boosted performance on all measures of generative output on the AUT compared with a control induction, but failed to produce a significant effect on the RAT (note, however, that the Type of Induction × Type of Test interaction was only marginally significant, $p = .051$).

Madore, Jing, and Schacter (2016) have recently extended the foregoing results in two ways. In an initial experiment, they replicated the boosting effects of the episodic specificity induction in young adults on the AUT (but not on the object association test), and showed that the same pattern of results is observed in healthy older adults. In a second experiment, Madore et al. (2016) asked whether the effect of the episodic specificity induction could be observed on another divergent thinking test known as the Consequences Task (Guilford, 1967; Torrance, 1974), an index of divergent thinking that requires participants to generate the consequences of various improbable, novel scenarios (e.g., flying without mechanical aids). Results revealed that, just as observed previously on the AUT, after receiving an episodic specificity induction, participants generated significantly more consequences of improbable scenarios than after receiving a control induction.

Given the evidence that episodic memory contributes to performance on the AUT and the Consequences Task, a further question concerns the types of ideas that are impacted by the induction. Several researchers have distinguished between “old” ideas (i.e., ideas that participants experienced or knew about prior to the study) and “new” ideas (i.e., ideas that emerged for the first time during the study; see Benedek et al., 2014a; Gilhooly et al., 2007). In the experiments by Madore et al. (2015, 2016), after having completed all tasks, participants judged each idea they produced on the AUT and the Consequences Task as either “old” or “new.” Across tasks, there was some evidence that the episodic specificity induction increases the frequency of both “old” and “new” ideas, with the evidence for a boost in “old” ideas most robust for the AUT, and the evidence for a boost in “new” ideas most robust for the Consequences Task. However, these results must be interpreted with some caution, because labeling ideas as “old” and “new” is done retrospectively and could be subject to inaccuracies and biases (for discussion, see Madore et al., 2016).

Taken together, the findings from the foregoing studies suggest that episodic memory does make a contribution to creative cognition, but the contribution may be limited to divergent thinking. Schacter and Madore (2016) have argued that the specificity induction biases the way in which participants approach cognitive tasks by encouraging them to focus on episodic details related to places, people, objects, or actions. This focus on episodic details in turn impacts subsequent performance on those tasks that involve, at least to some extent, creating mental events or scenes that contain details like those emphasized during the specificity induction. By this view, a divergent thinking task such as the AUT or the Consequences Task involves the creation of mental events or scenes as participants attempt to imagine novel ways in which a familiar object could be used, and the specificity induction may help participants to create or retrieve more detailed mental events that support the generation of novel uses.

Neuroimaging Evidence Linking Episodic Memory and Divergent Thinking with the Default Network

The default network refers to an interconnected set of brain regions that includes medial parietal cortex, including posterior cingulate cortex (PCC) and retrosplenial cortex (RSC), the posterior inferior parietal lobule (IPL), medial prefrontal cortex (PFC), medial temporal lobes (MTLs), and lateral temporal cortex (for reviews, see Andrews-Hanna, Smallwood, & Spreng, 2014; Buckner, Andrews-Hanna, & Schacter, 2008; Raichle, 2015). Early neuroimaging studies often relied on a passive "resting-state" as a baseline condition, where participants simply rested in the scanner without a task to perform. Although this resting period was initially of little empirical interest, researchers began to notice a consistent pattern of brain activity that emerged across several experiments, raising questions about whether this pattern reflected some "default mode" of the brain. Since the initial discovery of the default network, it has become increasingly clear that this network contributes to core functions of the mind (Andrews-Hanna et al., 2014; Buckner et al., 2008; Raichle, 2015). Most critical for the present purposes, a growing number of studies have linked the default network with remembering past experiences and imagining future experiences, which as noted earlier are both thought to depend on episodic memory (Schacter et al., 2012). More specifically, a set of brain regions referred as the *core network* (Schacter, Addis, & Buckner, 2007), which largely overlaps with the default network, shows similarly increased activity when people remember past experiences or imagine future experiences (for a recent meta-analysis, see Benoit & Schacter, 2015). According to the constructive episodic simulation hypothesis (Schacter & Addis, 2007), these neural similarities, and corresponding cognitive similarities between remembering the past and imagining the future (Schacter et al., 2012; Szpunar, 2010), reflect to a large extent the influence of episodic memory on imagining future and other hypothetical experiences.

Several studies have also linked the default network with aspects of divergent creative thinking.

Ellamil, Dobson, Beeman, and Christoff (2012) examined brain activity during idea generation and evaluation in visual arts students. They found that idea generation was associated with default activity, whereas idea evaluation was associated with control network activity. Moreover, functional connectivity analysis revealed increased coupling of the default network with the control network, but only during the idea evaluation condition. Benedek et al. (2014a) reported that the hippocampus and MTL, which are strongly linked to episodic memory and are considered part of the default network, were among the regions that showed increased activation when participants performed the AUT during scanning. In a recent attempt to examine brain activity related to episodic memory, episodic simulation, and divergent thinking within the same individuals, Beaty et al. (2016) scanned participants while they remembered past experiences, imagined future experiences, or generated creative uses of objects. Results revealed that compared to a control condition, all three of these processes recruited core default network regions (i.e., posterior cingulate, bilateral angular gyrus) compared with the control condition, although episodic memory and episodic future simulation were associated with greater default network activity than was divergent creative thinking. An additional functional connectivity analysis that used the foregoing default network regions as seeds revealed that episodic memory and simulation were linked with increased coupling of the posterior cingulate with other default network regions. Divergent thinking, by contrast, was linked with increased coupling of the same posterior cingulate seed with default regions and also with regions involved in cognitive control, consistent with our earlier discussion. Taken together, an emerging body of neuroimaging evidence suggests that creative cognition recruits regions of the brain's default network, a pattern that may reflect the involvement of constructive episodic processes during the production of novel ideas.

Episodic Memory, Cognitive Control, and Brain Network Dynamics

We have thus far described research on the neurocognitive mechanisms underlying creative cognition, with a focus on episodic memory and cognitive control. The contribution of episodic memory and cognitive control to creative thought is supported by neuroimaging studies reporting consistent activation of brain regions underlying these cognitive processes. Here, we consider how these neurocognitive systems may interact to support creative cognitive processes. Several recent fMRI studies have sought to address this question by examining functional interactions between brain regions during creative thinking tasks. This work has shown remarkable consistency in terms of the patterns of functional connectivity reported across various creative tasks, largely implicating interactions of the default and frontoparietal control networks. We suspect that such interactions reflect the interplay of memory systems and cognitive control during creative idea production. In a previous review (Beaty, Benedek, Silvia, & Schacter, 2016), we characterized default activity as reflecting the bottom-up generation of candidate ideas from long-term memory, and control network activity as reflecting top-down oversight via executive functions and cognitive control (cf. Jung, Flores, & Hunter, 2016; Jung, Mead, Carrasco, & Flores, 2013). We further proposed that default and control network interactions may depend on the extent to which a creative task requires goal-directed processing. In the following section, we extend this framework by describing specific cognitive functions that may underlie default and control network dynamics during creative cognition.

As noted above, the default network shows robust activation during tasks that involve constructive cognitive processes, such as recalling episodic memories and imagining future experiences (Schacter et al., 2012). The constructive-episodic simulation hypothesis (Schacter & Addis, 2007) suggests that such processes involve the extraction and combination of mnemonic information to construct a mental representation. We propose that default activity similarly reflects the operation of constructive processes related to the extraction and combination of mnemonic information during various creative thinking tasks. This hypothesis is consistent with classic theories of creative thought that emphasize the flexible combination of acquired knowledge via bottom-up associative processes (e.g., Mednick, 1962). Notably, however, such theories have focused almost exclusively on semantic memory, with relatively little consideration of episodic memory. We suspect that both memory systems – each of which draws on the default network (Burianova, McIntosh, & Grady, 2010) – affect creative thought by activating and integrating declarative and episodic knowledge in a bottom-up fashion.

These constructive processes can be directed and constrained to meet task-specific demands by engaging cognitive control. The behavioral research described above highlights several control processes linked to creative cognition, including inhibition, updating, and controlled retrieval. Thus, the interaction of memory and cognitive control – reflected in functional coupling of the default and control networks – may correspond to *goal-directed idea production*. Although many creative tasks are often open-ended, they also typically require responses that conform to the creative goal at hand. In this context, cognitive control can support creative performance by implementing the task goal. As noted earlier, in the AUT participants are asked to generate novel and appropriate uses for a common object. Here, the task goals are to generate an object use that is both novel (i.e., it deviates from its common purpose) and appropriate (i.e., it could actually be implemented). Cognitive control can facilitate these goals by directing memory search processes, inhibiting goal-incongruent information, and evaluating candidate ideas.

The interaction of cognitive control and memory systems may account for patterns of functional connectivity reported in recent fMRI studies (for a review, see Beaty et al., 2016). Beaty, Benedek, Kaufman, & Silvia (2015) examined whole-brain functional connectivity associated with performance on the alternate uses task, and extracted regions of interest from the whole-brain network to identify patterns of connectivity among regions. Divergent thinking was related to functional connectivity among regions of the default (e.g., PCC) and frontoparietal control (e.g., DLPFC) networks. In a similar study using the alternate uses task, Mayseless, Eran, & Shamay-Tssory (2015) found that the creative quality of divergent thinking responses was positively correlated with the strength of functional connectivity between regions of the default network (i.e., left angular gyrus) and the anterior cingulate, a region associated with cognitive control. Moreover, a study using a noun–verb creative association task found that the creative quality of participants' responses – defined as the semantic distance between noun cues and verb responses – predicted increased functional connectivity between the mPFC and the ACC (Green, Cohen, Raab, Yedibalian, & Gray, 2015). Taken together, these findings provide support for the notion that verbal creative thinking involves cooperation among cognitive control and default network regions, a pattern that may reflect the interaction of executive cognition and memory systems.

Default and control network coupling has also been reported in studies of artistic performance (Ellamil et al., 2012; Liu et al., 2015; Pinho et al., 2016). In a study of professional pianists, Pinho and colleagues found that improvising melodies based on specific emotions elicited functional coupling of the right DLPFC with core regions of the default network. Other studies have sought to dissociate network interactions associated with idea generation and evaluation. As noted earlier, Ellamil et al. (2012) conducted a study with visual artists and reported greater functional connectivity between default and control network regions during idea evaluation compared to generation. In a similar vein, Liu et al. (2015) found that professional poets exhibited greater functional coupling of default and control regions during the evaluation and revision of self-generated poetry, compared to an initial idea generation period. The generation and evaluation of creative ideas within various artistic domains may therefore involve differential interactions of the default and frontoparietal control networks, providing further evidence for the interaction of memory systems and cognitive control.

Summary and Future Directions

In this chapter, we present evidence from recent behavioral and neuroimaging investigations that support the involvement of episodic memory and cognitive control during creative idea production. We suggest that episodic memory and cognitive control interact during creative cognitive processes, reflected in the activation of and functional connectivity among regions of the default and frontoparietal control networks. This interaction may reflect goal-directed idea production, with mnemonic functions of the default network related to generative processes that can be directed and constrained by the control network depending on creative task demands. The evidence suggests that default and control network coupling is central to both general creative thinking (e.g., divergent thinking) and aspects of artistic performance (e.g., musical improvisation). We believe this emerging literature provides important insights into how and when memory and cognitive control interact to support the production of new ideas.

An important direction for future research is to further clarify the default network's role in creative thought. We suggest that default activity reflects constructive processes linked to episodic memory (for further discussion, see Schacter, et al., 2007, 2012). Nevertheless, because the default network is associated with several cognitive processes with potential relevance to creative thought (e.g., semantic retrieval), a key direction for future research is to isolate default activity related to episodic processes during creative task performance, perhaps through the use of an episodic specificity induction along the lines discussed earlier in the chapter. In a similar vein, future research should clarify whether the default network contributes to creative thought via the operation of general constructive processes, activation of task-specific memory content, or both. We encourage neuroscience research to employ experimental manipulations that can further tease apart the specific cognitive processes underlying default and control network activity during creative idea production.

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15 Free Association, Divergent Thinking, and Creativity: Cognitive and Neural Perspectives

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Try to imagine your “train of thought” when you are not focused on a specific task, when it just wanders freely. You might think about past events, future plans, perceptions of the outside world, inner hopes and fears, significant thoughts, and many others that seem small and irrelevant. One thought arises after another, without necessarily a clear logical connection between them. This is a type of internally focused thinking that one might experience while daydreaming, or when the mind wanders off a goal-related task (Gruberger, Simon, Levkovitz, Zangen, & Hendler, 2011; Smallwood & Schooler, 2006). A main characteristic of cognition in general and of the spontaneous “train of thought” in particular is that it is associative. Each idea that arises is connected in some way to (i.e., associated with) other ideas that are currently active in the mind of the thinker (Collins & Loftus, 1975; Marupaka, Iyer, & Minai, 2012; Mednick, 1962).

Such associative processes have been linked to creative ideation in general, and specifically to divergent thinking, a critical component of creativity. In fact, associative abilities have been found to explain up to half of the interindividual variance in divergent thinking scores (Benedek, Könen, & Neubauer, 2012; Lee & Therriault, 2013). For example, conditions that facilitate associative thinking (e.g., probed mind-wandering, Baird et al., 2012; a period of unconscious thought referred to as an incubation, Dijksterhuis & Meurs, 2006) enhance performance on creativity tests. Moreover, associative thinking can lead to unusual combinations between ideas, which in some cases yield a creative idea or a creative solution to a problem (Schilling, 2005). Researchers have studied associative processes in individuals by using “free-association tasks” that entail nonconstricted verbalization of associative ideas. Past research has shown some connection between free-association tasks and creativity (e.g., Mednick, Mednick, & Jung, 1964; Riegel, Riegel, & Levine, 1966). In this chapter we review behavioral and neurological research providing insight into this connection. Specifically, we highlight the differences between three common types of free-association tasks (see below). Using behavioral and neurological findings, we conclude which aspects of creativity each free-association task is best suited to measure, and suggest that free-association tasks can serve as a valid, economic measure of some of the processes involved in creative thinking. We further suggest that protocols based on free association can enhance creative thinking.

Free-association tasks usually take one of three forms. The common factor of the three forms is that they reflect a verbalization of a spontaneous (i.e., “free”) thought that arises in the individual’s mind, not restricted by a specific task criterion (e.g., name a word that begins with a specific letter). The first type of free-association task is single-word associations: an individual is presented with a stimulus word, and he or she is required to verbalize the first word association that comes to mind in relation to that word (Nelson, McEvoy, & Dennis, 2000).

The second form is continuous association: the individual produces multiple associations, all of which relate to the stimulus word (Mednick et al., 1964). The third, less-researched form of free association is that of a chain: individuals are required to verbalize the first association that comes to mind, usually in relation to a stimulus word, and subsequently to verbalize additional associations, each of which relates to the previous associative response (Benedek et al., 2012).

In this chapter we will initially review different features of creative cognition and divergent thinking, specifically the ability to access remote concepts in memory, fluency of retrieval, cognitive flexibility, and originality, and their related brain networks (e.g., prefrontal areas, temporal areas in the right cerebral hemisphere and the default mode network; see below). We will then review how these creative features are explored through different free-association tasks in neurocognitive research. Based on behavioral data and brain network overlaps we conclude that continuous association and chain association are both effective, direct predictors of creative abilities. In particular, the former serves as a predictor of ideational fluency and originality and the latter of cognitive flexibility as well as originality. We also conclude that, while single-word association is less informative as a direct measure of creative abilities, it enables researchers to build association norms that serve to create diverse creativity tasks. We suggest that chain free association is most reflective of spontaneous associative thinking (i.e., the train of thought). Finally, we review research that shows that protocols built on each of three forms of free association can enhance creativity.

Cognitive Processes Underlying Creative Thinking

Some research models consider creative thinking to be different from "regular thinking," attributing the former mainly to creative geniuses and artists (e.g., Eysenck, 1995). A more prevalent school of thought, however, suggests that everyday thinking and creative cognition are part of the same continuum (e.g., Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Guilford, 1950; Marupaka et al., 2012). Ideas tend to be a combination of concepts from memory and/or new information that the individual receives (Marupaka et al., 2012; Nijstad & Stroebe, 2006; Schilling, 2005; Simonton, 2010). The associative flow of ideas in our mind can be very simple and very useful in everyday functioning. For example, we might look at a clock and see the time (i.e., new information), which reminds us that it is time for dinner. We will approach the table, and the concepts of silverware, plates, and glasses that need to be placed there arise from memory, enabling us to prepare the table for a meal.

Sometimes, the association of ideas can progress from these highly related elements (i.e., dinner, table, silverware) to further and more distant directions. This mind-wandering might cause distraction in some cases (e.g., thinking of traveling in the Far East while trying to prepare dinner; Gruberger et al., 2011). In other cases, the progression of association can enable *ideational combination* of remote concepts (Schilling, 2005). For example, thinking of India, and of its unique cuisine might elicit adding an Indian spice to a bland dish. When ideas that are associated and combined together produce an output that is original and novel, as well as useful (e.g., tasty in our example) – the output is considered to be *creative* (Marupaka et al., 2012; Mednick, 1962; Runco & Acar, 2012; Zhou, Xu, Zhao, Zhao, & Liao, 2011).

Mednick (1962) was one of the first to detect the importance of association of remote concepts for producing creative ideas. He defined the process of creative thinking as "the forming of associative elements into new combinations which either meet specific requirements or are in some way useful. The more mutually remote the elements of the new combination, the more creative the process or solution" (p. 221). In accordance with this conceptualization of creative cognition, Mednick defined individual creativity as the extent to which an individual is able to access associative elements that are distant from one another and combine them to form creative solutions (Mednick, 1962). Benedek and Neubauer (2013) recently tested the relationships proposed by Mednick (1962) and proposed several refinements to his theories, an important one being that the ability to retrieve distant associative elements might be more attributable to effective thought processes than to the organization of associative memory.

Jung-Beeman's (2005) fine–coarse theory on hemispheric differences in processing information is a prominent neurocognitive model capturing the brain underpinnings related to access the remote associations and their combination into ideas. According to the fine–coarse model, the left cerebral hemisphere is involved in the coding of highly related semantic associates, i.e., closely related word meanings or semantic features (e.g., dinner, table, plates, glasses), while inhibiting associations that are less strongly related (Jung-Beeman, 2005). The right cerebral hemisphere is involved in coarse semantic coding; it is more sensitive to distant associations (e.g., dinner, Far East, Indian spices) and is therefore useful for processing information relating to subtle, distant, peripheral and unusual semantic relations (Beeman, 1998; Jung-Beeman, 2005; Seger, Desmond, Glover, & Gabrieli, 2000). According to the fine–coarse theory, it should be expected that creative tasks that involve remote associations will activate the right hemisphere more than tasks that do not involve access to remote associations.

The latter hypothesis has been supported by several neuro-cognitive studies. In an fMRI and EEG study, Jung-Beeman and colleagues (2004) used a task very similar to that developed by Mednick, the Remote Associates Test (RAT; Mednick, 1968). In this task, the participant must find one word that serves as an associative link for three stimulus words (e.g., stimulus: "rat – blue – cottage"; answer: "cheese"). This task is supposed to test the ability to combine remote associations, because in order to answer correctly one must access remote semantic fields (Mednick, 1968). Jung-Beeman and colleagues (2004) found that when these problems were solved by simultaneously accessing remote semantic networks (i.e., an "A-ha" insight problem-solving experience) there was increased neural activation in the right hemispheric anterior superior temporal gyrus (aSTG).[1] Similar results were found in brain studies of a two-word novel metaphor comprehension task involving the ability to access and combine two remotely associated words (Comprehension of Metaphors task; CoM; see Faust, 2012; Faust & Mashal, 2007). Faust and colleagues found a unique role for the right hemisphere, specifically in the right STG, for accessing remote associations, as measured by comprehending novel metaphors in fMRI (Mashal, Faust, & Hendler, 2005; Mashal, Faust, Hendler, & Jung-Beeman, 2007), MEG (Zeev-Wolf, Goldstein, & Faust, 2010), and EEG (Arzouan, Goldstein, & Faust, 2007) studies. Bechtereva and colleagues (2004) tested brain underpinnings of connecting remote associations by instructing individuals to create a story by connecting remote semantic concepts. Although the authors did not find that the task elicited higher right cerebral activation, they did find that combining remote associations in this manner elicited brain activity in the left middle temporal gyrus (MTG), an area that is relevant for semantic memory processing (Binder, Desai, Graves, & Conant, 2009). This area can also be considered part of the default mode network (DMN), a network known to be highly involved in other cognitive abilities related to creativity, as will be explained in the following section.

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[1] Results of these studies must be interpreted with caution, as the RAT may reflect additional or even alternative cognitive process (e.g., verbal intelligence, attention, or working memory; Lee & Therriault, 2013; Mendelsohn, 1976).

Divergent Thinking: Fluency, Flexibility, and Originality

Three characteristics are often examined in studies of creative cognition: *fluency* of retrieval of associates from memory; *flexibility* in switching between broad semantic categories; and *originality* of ideas produced (Beaty, Silvia, Nusbaum, Jauk, & Benedek, 2014; Benedek et al., 2014; Nusbaum & Silvia, 2011). In particular, these characteristics are associated with divergent thinking, an important component of creativity. As mentioned before, a creative idea can be defined as a solution that is novel and unique, and that is also adequate and useful (e.g., Fink et al., 2009). To achieve this balance, the individual engages in a combination of divergent thinking and convergent thinking (Christoff, Gordon, & Smith, 2011). Divergent thinking entails drawing knowledge/ideas from diverse domains and combining them to generate multiple solutions to open-ended problems (Runco & Acar, 2012). This form of thinking is considered to be crucial for the novel idea generation component of creativity (Guilford, 1968). Convergent thinking, in contrast, is a more focused type of thought, used to find a single "correct" solution to a given problem (Benedek et al., 2012), and relates to the selection of useful and appropriate ideas. In divergent thinking, fluency enables the individual to generate multiple potential solutions; flexibility enables him or her to draw solutions from diverse domains; and originality leads to novel and unique solutions (and includes inhibition of mundane ideas) (Wei et al., 2014).

Although both convergent and divergent thinking are necessary to produce novel yet appropriate creative outputs, indicators of divergent thinking are more useful for evaluating creative potential (Benedek et al., 2012; Kaufman, Plucker, & Baer, 2008), and indeed many psychometric creativity tests essentially test divergent thinking (e.g., the Torrance Tests of Creative Thinking; Torrance, 1974). One common divergent thinking task is the Alternative Uses Task (AUT), also referred to as the Unusual Uses Test (Guilford, 1951), which requires thinking about creative uses for common objects (e.g. Benedek, Mühlmann, Jauk, & Neubauer, 2013; Runco & Acar, 2012). Similar divergent thinking tasks are the Instances Task (e.g., Beaty, Benedek, et al., 2014) in which participants are required to generate creative solutions to problems (e.g., "What can make noise?") and the Realistic Divergent Thinking Task (Chand & Runco, 1993) in which participants are required to read a described "everyday" problem, which may occur at school or work, and then try to write down as many solutions as they can for each problem. In these tests, fluency is measured according to the total number of ideas generated, flexibility is measured according to the number of categories or themes used by the participant, and originality/uniqueness is reflected in the extent to which responses are unique (e.g., ideas that appeared in 5% or less of the sample, or that are subjectively rated as original by judges). These three characteristics, which are usually studied together (e.g., the AUT checks for all three components), have been shown to activate specific areas of the brain. To put these observations in context, we will first provide a general overview of the areas in the brain with which divergent thinking has been associated, and will then discuss fluency, flexibility, and originality individually in relation to brain activation.

Brain networks Associated with Divergent Thinking. The brain networks most prominently associated with divergent thinking are the DMN and the executive network (Beaty, Benedek, Kaufman, & Silvia, 2015; Jung, Mead, Carrasco, & Flores, 2013). The DMN can be seen as an "inward-thinking" brain network: it has been consistently shown to be active in the absence of external task requirements (Buckner, Andrews-Hanna, & Schacter, 2008; Raichle et al., 2001) and is known to be related to internally based processes such as internal mentation and unconstrained thinking (Shapira-Lichter, Oren, Jacob, Gruberger, & Hendler, 2013). It has also been implicated in both semantic (Binder et al., 2009; Wirth et al., 2011) and episodic memory processes (Shapira-Lichter et al., 2013; Svoboda, McKinnon, & Levine, 2006). The core of the DMN comprises the posterior cingulate cortex (PCC) and the precuneus, the medial prefrontal cortex (mPFC), the bilateral inferior parietal lobes (IPL), and areas relevant for memory processes: the lateral temporal lobe (specifically the middle temporal gyrus (MTG; related to semantic memory) and the medial temporal lobe (MTL; e.g., hippocampus, which is activated during the formation and retrieval of semantic and episodic associations) (Binder et al., 2009; Buckner et al., 2008; Laird et al, 2009; Raichle et al., 2001). Brain imaging studies point to DMN activity and connectivity during divergent thinking tasks (e.g., Benedek et al., 2014; Ellamil, Dobson, Beeman, & Christoff, 2012; Fink & Neubauer, 2006; Takeuchi et al., 2012; Wei et al., 2014) as well as a relation between creativity and higher cortical thickness in DMN areas (Jung et al., 2010, 2013). We will elaborate below on the relevance of areas of the DMN for specific components of divergent thinking.

In addition to the DMN, prefrontal cortex areas which are considered to be related to executive functions have been shown to be related to divergent thinking. Such areas are the left inferior frontal gyrus (IFG; Benedek et al., 2014), the ventral and dorsal lateral prefrontal cortex (DLPFC; Beaty et al., 2015; Goel & Vartanian, 2005), and the middle frontal gyrus (MFG) (Goel & Vartanian, 2005). The executive functions related to these areas, which have been shown to be inherent in divergent thinking, are response inhibition, specifically, inhibition of common but uncreative responses, which facilitates access to more remotely associated concepts (e.g., Benedek & Neubauer, 2013; Gilhooly, Fioratou, Anthony, & Wynn, 2007; Pobric, Mashal, Faust, & Lavidor, 2008), and working memory activity necessary for combining and accessing ideas in divergent thinking tasks (Goel & Vartanian, 2005; Vartanian et al., 2013).

Ideational Fluency. Ideational fluency refers to the ability to fluently produce ideas, by retrieving concepts from memory (Benedek et al., 2012). Fluency is usually measured as the number of relevant responses generated in an open divergent thinking task (e.g., Takeuchi et al., 2012). Because fluency accounts for a large amount of the variance in divergent thinking tasks (Plucker & Renzulli, 1999), many studies have used fluency as the sole measure of creativity (e.g., Vartanian, Martindale, & Matthews, 2009).

High fluency abilities have been found to be related to several cognitive processes including (1) use of episodic memory and semantic knowledge to retrieve ideas (Gilhooly et al., 2007), (2) information processing speed in tasks involving no cognitive interference (Dorfman, Martindale, Gassimova, & Vartanian, 2008; Kwiatkowski, Vartanian, & Martindale, 1999), and (3) associative fluency (e.g., Benedek et al., 2012, 2014; Mednick et al., 1964; see "continuous free associations" below).

High fluency scores on divergent thinking tasks have been strongly correlated with activity in prefrontal areas and in prominent DMN hubs. Specifically, regarding prefrontal areas, high fluency scores correlate with high cerebral blood flow (CBF) in the left IFG, right MFG, and right orbitofrontal areas (Chávez-Eakle, Graff-Guerrero, García-Reyna, Vaugier, & Cruz-Fuentes, 2007). Regarding DMN, fluency scores have been positively related to resting state functional connectivity between the mPFC and the MTG (Wei et al., 2014), and to activity in the right IPL (Chávez-Eakle et al., 2007), and the MTL (Benedek et al., 2014).

Cognitive Flexibility. Two types of cognitive flexibility have been defined: adaptive flexibility, and spontaneous associative flexibility (Frick, Guilford, Christensen, & Merrifield, 1959). The former refers to the ability to change methods of thought in order to meet requirements imposed by a changing environment (e.g., change our normal route home if we see that a traffic jam is accumulating), whereas the latter refers to a tendency or ability to use a variety of categories and themes when producing ideas (Runco, 1986).

Both types of cognitive flexibility are necessary in everyday behavior and problem-solving. Flexibility is what enables us to change strategies to solve a problem more effectively or to see a problem from a new perspective (Thurston & Runco, 1999). The opposite of flexible thinking is rigidity, getting stuck on one part of a problem or on one method of solving it, even if it is not efficient (Frick et al., 1959; Georgsdottir, Lubart, & Getz, 2003).

Flexibility is widely considered to be a critical component in creativity and innovation (Benedek et al., 2012; Frick et al., 1959; Kühn et al., 2014). The more an individual is capable of changing strategies in problem-solving (adaptive flexibility) or in coming up with ideas from diverse semantic domains (spontaneous flexibility), the more creative she or he is considered to be (Frick et al., 1959; May & Metcalf, 1965).

Spontaneous flexibility is more relevant for our discussion, as we are attempting to use free association as an effective measure of the spontaneous thinking underlying creative cognition. Spontaneous flexibility is often measured by counting the number of categories or themes used by the individual in his or her responses on divergent thinking tasks (such as the AUT or the Instances Task; e.g., Kühn et al., 2014). Another more direct method of measuring spontaneous flexibility, initially suggested by Frick and colleagues (1959), involved counting the number of discriminable concepts that individuals produce on free word association chains. This has only recently emerged as a valid measure of flexibility (e.g., Benedek et al., 2012), as we will elaborate in this chapter in the section on chain free association.

Regarding brain findings, as in the case of fluency, both DMN and executive control prefrontal areas were found to be related to high spontaneous flexibility scores. High flexibility scores were related to high cerebral blood flow in the left IFG, right MFG, and right orbitofrontal areas (Chávez-Eakle et al., 2007), as well as the right superior frontal gyrus (SFG; Kühn et al., 2014). This might be in line with findings that creativity is related to a flexible cognitive control (Zabelina & Robinson, 2010). Yet, at the same time, success on cognitive flexibility tasks was found to be related to de-activation of the DLPFC (Nelson et al., 2007), which is related to inhibition. This observation is in line with findings that reduction of cognitive inhibition is associated with greater flexibility (Carson, Peterson, & Higgins, 2003).

Regarding DMN and semantic memory areas, high cognitive flexibility scores were positively correlated with gray matter volume in the mPFC, in the right temporoparietal junction, right inferior temporal gyrus, and the left insula (Kühn et al., 2014), and were negatively correlated with the presence of lesions in the mPFC (Shamay-Tsoory, Adler, Aharon-Peretz, Perry, & Mayseless, 2011). High scores on flexibility were also related to higher resting state functional connectivity between the mPFC and the MTG, central areas in the DMN (Wei et al., 2014). These findings support the hypothesis that the ability to flexibly draw from a large variety of categories when producing ideas is not only related to executive processes but is also associated with internal spontaneous thinking and the capacity to access areas related to semantic and episodic memory.

Originality. Originality refers to novelty and unusualness of responses (Chávez-Eakle et al., 2007), and is commonly associated with thinking “outside the box” (Wei et al., 2014). It can also reflect the ability to break away from habitual, normative responses (Torrance & Safter, 1999). Originality or novelty of responses has been found to be related to other aspects of creative thinking (i.e., ability to associate remote concepts, ideational fluency, and cognitive flexibility; Runco & Okuda, 1991), but nonetheless is referred to as a separate, crucial component of creative thinking and is scored separately in many studies (e.g., Kühn et al., 2014).

Originality of responses on divergent thinking tests is rated in several ways: (1) by judges on

Likert scales (e.g., highly original to not original at all; Fink et al., 2014; Wei et al., 2014); (2) by testing for unusualness (i.e., statistical infrequency) of response in comparison to the rest of the sample (e.g., original responses are those that appear in 5% or less of responses in the sample; Runco & Charles, 1993); (3) by using methods that aim to eliminate the confounding effect of fluency on originality scores, by means such as requiring participants to select their three top original answers, and then having a judge rate all answers for originality (Benedek et al., 2013).

Regarding behavioral and cognitive characteristics of original responses on divergent thinking tasks, original responses are more likely to be produced in the later stages of response production, and are characterized by more specific strategies such as disassembly (e.g., in the AUT, imagining disassembling the object and using parts or recombining parts) than by simple retrieval from memory. Additionally, high originality has been found to be related to other executive loading tasks such as letter fluency (Gilhooly et al., 2007).

High originality scores have also been correlated with brain areas that relate to executive actions, as well as inward thinking and memory networks. Specifically, high originality scores are related to prefrontal areas: right and left MFG, right orbitofrontal cortex (Chávez-Eakle et al., 2007), left IFG (Benedek et al., 2014), left frontal pole (Kühn et al., 2014) as well as DMN and memory areas: left STG (Chávez-Eakle et al., 2007), left IPL (Benedek et al., 2014), right IPL (Fink et al., 2014), ventral mPFC, and the precuneus (Fink et al., 2014; Kühn et al., 2014; Shamay-Tsoory et al., 2011). Enhanced originality scores following training were accompanied by an enhancement in resting state functional connectivity between the mPFC and the MTG (Wei et al., 2014) and by enhanced activity in the posterior cingulate gyrus, precuneus, right MTG, and right IPL (Fink et al., 2010).

These findings reflect the importance of different systems that apparently co-contribute to the process of coming up with an original idea. In particular, divergent thinking – i.e., vast memory search and unconstrained thinking (represented by enhanced activity and connectivity in DMN and memory areas) – coupled with the ability to inhibit habitual responses (related to the prefrontal areas) contribute to the production of unique, unusual ideas. Prefrontal activity might also represent the convergent aspects of choosing an appropriate idea among many original ideas that come to mind.

Free Associations as a "Window" into Spontaneous Creative Processes

So far, we have reviewed different cognitive processes crucial for creative thinking in general and specifically for divergent thinking: *ability to access remote concepts in memory*, *cognitive flexibility*, *ideational fluency*, and *originality*, and mentioned relevant brain networks underpinning these processes. The processes we described were mostly measured *indirectly* by different scoring techniques on divergent thinking tasks. We suggest that the following free-association tasks can serve as an effective, parsimonious, and more direct measure of these cognitive processes (specifically, the associative aspects of these cognitive processes). In the next sections we will review the three main types of free-association tasks, and will discuss which aspects of creative thinking can be measured most effectively by each type of association task.

Single-word Free Association

The classic approach to free associations is the "single-word" task (also referred to as "discrete free association"), in which an individual is presented with a single cue word and is required to verbalize the first word association that comes to mind in relation to the cue word (e.g., cue word: street; single-word response: car) (Nelson et al., 2000). In the past, such tasks were used to gain insight into the functioning of the psyche, and to assist in detecting psychotic states such as schizophrenia (Cattell et al., 1889; Eysenck, 1993; Galton, 1879; Jung, 1910). Today, the main contribution of single-word free association to the research of language and thought in general, and of semantic creativity specifically, is in the creation of free-association norms (Levin, 1978; e.g., Kent & Rosanoff, 1910; Palermo & Jenkins, 1964). Norms, based on free-association probabilities, index the accessibility of words in memory and the associative relations between them (Nelson, McEvoy, & Schreiber, 2004), and when performed on a large sample of people can be very useful in studies of individual semantic organization (e.g., Nelson et al., 2000; Kenett, Anaki, & Faust; 2014).

Single-word free association is not used much today to evaluate personality or to measure individual creativity, as it does not assist in characterizing individual differences in the different aspects of creativity. This observation is somewhat counterintuitive, as it might seem that it should be possible to test individual differences in various aspects of creative thinking by measuring the extent to which an individual's associations diverge from normative responses. Indeed, this notion has been studied before, but has produced contradicting results. For example, some findings showed that individuals with high creative abilities produce more uncommon single-word free associations (Gough 1976; Riegel et al., 1966; Merten & Fischer, 1999). However, Rothenberg (1973) found that unusual or uncommon word-association responses are not necessarily associated with creativity, although creative individuals have a tendency to answer more rapidly on free-association tasks compared with less-creative individuals. Benedek and Neubauer (2013) found that the probability of producing common associations does not differentiate between individuals with high versus low creativity. A potential explanation for these contradicting results is that most studies that found a significant relation between the uncommonness of single-word associations and creativity did not use divergent thinking tasks as a criterion for creativity. Rather, they used ratings by peers and supervisors (Gough, 1976; Creative Personality Scale: Riegel et al., 1966). In contrast, Benedek and Neubauer (2013) used a battery of divergent thinking tasks as a criterion of creativity, including a specific measure of originality and fluency on the AUT.

We reviewed brain research on single-word association to see if unusual associations elicit activation in areas that have been shown to be involved in remote and original idea production; however, little research has been done in this area. Two studies using a somewhat different task (i.e., instructing participants to produce an unusual verb versus a common verb in relation to an object) (Abdullaev & Posner, 1998; Seger et al., 2000) found that while producing unusual verbs (as opposed to common verbs) participants showed more activity in temporoparietal areas of both hemispheres (Abdullaev & Posner, 1998), in the left and right MFG, and in the right SFG (Seger et al., 2000). These data show a possible relation between unusual associations and the ability to access remote semantic networks (activation of temporoparietal areas), originality (bilateral MFG), and flexibility (right SFG, temporoparietal junction). Notably, these results might not be generalizable to "pure" free-association tasks; rather, the observed activation of executive areas might be attributable to the active search triggered by the instruction to identify an "unusual" verb. We conclude that in response to a cue word, healthy individuals will normally produce a common first association; thus, this method is less informative of individual differences in the tendency toward creative and divergent thinking (Benedek & Neubauer, 2013).

Although they are not specifically free-association tasks, it is important to also address semantic relatedness judgment tasks, which are constructed from free-association norms, and can be used to test for individual differences in access to remote associative concepts as well as to examine the underlying brain activity (Vartanian et al., 2009). These tasks usually involve presenting individuals with pairs of words, which they are required to decide (1) whether the words are related (e.g., Vartanian et al., 2009), or (2) to what extent they are related (e.g., Rossmann & Fink, 2010). The pairs of words have different types of semantic relations between them (e.g., close or remote) as calculated based on free association norms (see Kenett, 2016 for an overview on measuring semantic distance in creativity research). It has been shown that the more creative the individual, the more he or she rates remote words as related (e.g., Rossmann & Fink, 2010), and the faster he or she responds with a decision (e.g., Vartanian et al., 2009). Thus, although single-word free association on its own might not be helpful toward evaluating individual differences in creativity, the free-association norms derived from such tasks can assist in creativity research.

Continuous Free Association

Continuous free word association tests require the individual to provide a continuous sequence of association responses to one particular stimulus word (e.g., cue word: beach; continuous responses: sand, hot, sandals, ice cream, summer, fun, …) (Benedek et al., 2012). The individual may be restricted in the number of associations he or she is asked to produce, or in the time allotted for producing associations (Levin, 1978, Mednick et al., 1964). In creativity research, this free-association task is advantageous over single-word free association because it can be rated for fluency (number of associations produced) (Levin, 1978), allows for greater variability in associations that can be rated for unusualness (e.g., Benedek & Neubauer, 2013), and can be used to construct more complex free association norms (De Deyne & Storms, 2008; Kenett et al., 2014). However, this approach is subject to both response chaining and retrieval inhibition (McEvoy & Nelson, 1982). To avoid these effects, some studies have sought to generate free-association norms using only two or three first associates to a cue word (e.g., De Deyne & Storms, 2008; De Deyne, Navarro, & Storms, 2013).

Continuous free association can offer a "window" into the common as well as unique relationships between words, which are based on the individual's experiences, as well as his or her ability to fluently retrieve these words from memory (De Deyne & Storms, 2008). Specifically, associative fluency (i.e., number of associations produced) and unusualness of associations on continuous free-association tasks can be used in certain cases to predict and measure the different creativity abilities.

Associative Fluency. Associative fluency measured by continuous free word association tasks is related to high scores on ideational fluency scores as well as originality scores on the AUT (Benedek et al., 2012; Benedek & Neubauer, 2013; Kenett et al., 2014). It should be noted that, in one of these studies (Benedek et al., 2012), associative fluency scores (along with chain association flexibility scores – see section on *chain free association*) did not explain additional variance beyond other associative abilities (i.e., dissociative ability and associative combination). However, the strong intercorrelations between the different associative abilities suggest that dissociative ability and associative combination probably draw from fluency and flexibility abilities (Benedek et al., 2012).

The relation between performance in continuous free association tasks and ideational fluency and originality in divergent thinking tasks is supported by brain research. Specifically, continuous free association (as compared to baseline as well as a phonological fluency task) activates areas in the prefrontal cortex similar to those relevant for high fluency abilities and for high originality scores on AUT (Chávez-Eakle et al., 2007). These areas include the left MFG as well as the left IFG (Wende et al., 2012). Continuous free association also activates DMN and memory hubs, which are similar to those related to originality: left IPL (Benedek et al., 2014; Wende et al., 2012), precuneus, and MTG (Wende et al., 2012). Likewise, continuous free association activates the MTL (including the hippocampus; Wende et al., 2012), which is related to fluency.

Fluency scores on continuous free word association tasks are indicative of the ability to access remote semantic associates, as measured behaviorally by high scores on the RAT (Levin, 1978; Mednick et al., 1964; Kenett et al., 2014; Piers & Kirchner, 1971) and the CoM (Kenett et al., 2014). Brain research supports these behavioral findings as well, given that continuous free associations elicit activity in the right STG (an area that has been related to processing of remote associations) as well as the MTG (Wende et al., 2012). Notably, Levin (1978) explained that the relation of fluency on continuous associations to the ability to access remote semantic associates is due to the chaining effect that occurs in continuous associations (i.e., the tendency to produce associations that relate to previous responses rather than the actual stimulus; see section on *chain free association*). Brain research that compares continuous association with versus without signs of the chaining effect (e.g., as done behaviorally by Levin, 1978) can indicate whether chaining indeed explains the link between continuous association and the ability to access remote semantic associates.

Unusualness of Associations. In general, the unusualness of an individual's associations is expected to increase over time as the number of responses increases. Scores of unusualness in a continuous free association task have been shown to be correlated with originality scores as well as with ideational fluency scores on the AUT (Benedek & Neubauer, 2013). Interestingly, the strength of this relation significantly decreased when fluency in free association was controlled for, suggesting that individual differences in unusualness are largely due to differences in fluency (Benedek & Neubauer, 2013). The authors suggest that fluency affects unusualness, because as unusualness increases with the number of responses, people who are more fluent in retrieving associations will be able to retrieve more unusual associations sooner.

To the best of our knowledge, the relation between fluency or unusualness scores in continuous free word association tasks and flexibility scores on divergent thinking tasks is yet to be determined. We have found little behavioral research on this matter. One exception is the work of Benedek and colleagues (2012). Another study, which did not examine the relationship directly, showed that continuous free association elicits activation in the SFG and inferior temporal gyrus (Wende et al., 2012), areas that might be relevant for flexibility (Kühn et al., 2014). Nonetheless, a novel computational approach, mapping semantic networks of groups of people producing continuous free associations, has been shown to provide information regarding the structure and flexibility of these semantic networks. Specifically, the semantic memory network corresponding to a group characterized by low creative ability seems to be more rigid (i.e., less flexible) compared to the network of a group with high creative ability, in the sense that it is more spread out and breaks apart into more sub-parts (Kenett et al., 2014). Computational approaches to measure individual semantic networks using continuous associations are being developed, but they have not yet been used to study creativity (Morais, Olsson, & Schooler, 2013; Zemla, Kenett, Jun, & Austerweil, 2016).

To summarize, associative fluency scores derived from continuous free association tasks can serve as a more reliable measure of creative abilities than unusualness scores of the associations. Regarding specific creative aspects, these associative fluency scores can be indicative of ideational fluency and originality. They may also be indicative of cognitive flexibility and the ability to access remote concepts, although the relationship between fluency on continuous association tasks and the ability to access remote semantic associates could be due to chaining effects (Levin, 1978). More differential brain research to better characterize the nature of the relationship is thus needed.

Chain Free Association

Chain free association tasks require the individual to provide a sequence of associations, in which the first association should relate to a presented stimulus, and each subsequent association relates to the previous associative response (e.g., cue word: house; chain response: kitchen, food, dinner, family, love, hate, …) (Benedek et al., 2012). Chains of free association depict the spontaneous flow of thought and natural diversity of ideas, in the most direct manner, because when producing chain associations the individual is not required to constantly direct his or her thoughts to a given cue word (as in continuous associations).

The main measure derived from this type of free-association task is associational flexibility, which is assessed according to the number of discriminable concepts included in the generated word association chains (e.g., Beaty, Silvia, et al., 2014; Benedek et al., 2012; Frick et al., 1959). Fluency scores have also been used as a measure of flexibility, because the number of dissociable concepts tends to be highly correlated with the total number of generated responses (Benedek et al., 2012). Notably, Benedek and colleagues (2012) observed that associative flexibility was very relevant – even more so than divergent thinking ability – for predicting whether participants belonged to a creative group (i.e., design class) or to a less-creative group. This is in line with the notion that flexibility is a critical component of creativity and serves as a strong indicator of it (Ritter et al., 2012).

High associative flexibility scores measured by chain free associations have been related to high fluency and originality scores on the AUT (Benedek et al., 2012; Beaty, Silvia, et al., 2014; Frick et al., 1959; Silvia, Beaty, & Nusbaum, 2013). In one study, performance in a chain association task explained 26% of the variance in the originality of responses in the AUT, and 11% of the variance in fluency in this task (Beaty, Silvia, et al., 2014). In that study the participants received instructions to produce chains that were as diverse and as long as possible (Beaty, Silvia, et al., 2014). Perhaps this instruction elicited executive control over the free spontaneous task and could reflect adaptive flexibility in addition to spontaneous flexibility (see section on *flexibility*). The authors did not rate flexibility on responses of the AUT, which could have made for an interesting comparison to flexibility scores on chain associations. The observed relationships between flexibility in a chain association task and fluency/originality on the AUT are further supported by fMRI brain studies. Specifically, engagement in a chain association task elicits activity in areas of the brain that are relevant for high originality scores (the PCC, IPL, and precuneus: Kehyayan, Best, Schmeing, Axmacher & Kessler, 2013; and IFG: Spence et al., 2009). It also elicits activity in areas relevant for high fluency scores (MTL and hippocampus: Kehyayan et al., 2013; and IFG: Spence et al., 2009).

Regarding the ability of chain associations to predict access to remote concepts, Levin (1978), who administered a continuous free association task, showed that the reason that continuous association, as compared with single-word association, is more predictive of access to remote concepts (as measured by RAT) is that the former elicits chaining of associations. As noted above, this observation indirectly points to the ability of chain associations to predict access to remote concepts.

We have found little research attempting to connect associative flexibility to flexibility in divergent thinking tasks (e.g., Frick et al., 1959). Regarding brain findings, the only region that has shown activity in both chain free associations (Spence et al., 2009) and flexibility tasks

(Chávez-Eakle et al., 2007) is the left IFG. Spence also found that engagement in chain free associations elicits high activation of the left DLPFC. This activation supposedly contradicts the notion that chain free association reflects cognitive flexibility, as flexibility has been related to deactivation of the DLPFC in a cognitive flexibility task (Nelson et al., 2007). Spence and colleagues (2009) explained this finding by suggesting that DLPFC activation occurred as a result of internal censorship; subjects made selections among the words arising in their minds and apparently exercised inhibition of responses that might have caused embarrassment. Additional studies found that emotionally charged thoughts, especially those that are negative or cause internal conflict, might cause suppression (i.e., inhibition) of associations and memories, reflected in less activity in areas related to memory (e.g., hippocampus) and higher activity in prefrontal areas: right IFG and right MFG (Depue, Curran, & Banich 2007; Kehyayan et al., 2013), DLPFC (Anderson et al., 2004), and the anterior cingulate cortex (ACC), which is involved in emotion processing and conflict monitoring (Kehyayan et al., 2013). Indeed, it seems that negative internal reactions can inhibit vast memory search and inward thought, and in fact, studies have shown that a negative mood can narrow the individual's scope of associations (Baas, De Dreu, & Nijstad, 2008; Isen & Daubman, 1984), and that exposure to a broad scope of associations can improve one's mood (Mason & Bar, 2012).

In summary, it seems that flexibility in chain free association tasks is a promising measurement of flexibility and originality in divergent thinking tasks, but more brain and behavior research is necessary to understand this potential relationship. In this vein, our group (Marron et al., in preparation) has conducted an fMRI study comparing scores of flexibility, originality and fluency (measured by the AUT) as well as ability to access remote semantic networks (measured by the RAT and CoM) to the unique brain activations elicited during chain free association (as compared to semantic, letter, and episodic fluency). Initial findings show that chain free associations elicit activation in the DMN areas as well as the IFG. These observations may be useful toward defining brain networks that underpin spontaneous associative flexibility, i.e., the ability to produce ideas from diverse semantic domains with freedom from constraints on thought (Frick et al., 1959; May & Metcalf, 1965).

Using Free Association Techniques to Overcome Inhibition of Divergent/Creative Thinking

When trying to think of a creative solution for a problem, people sometimes get "stuck" on old or inappropriate ideas (Ritter & Dijksterhuis, 2014; Smith, 2003). Individuals may encounter this situation when presented with a creative task, or even with an everyday problem, and they may experience frustration as a result (Russ, 1993). Such thought rigidity can be caused by diverse factors (e.g., cognitive, cultural, or environmental conditions). In particular, emotional or intrapersonal blocks have been identified as profound barriers to creativity and idea generation. These blocks include the fear to fail or make a mistake, the inability to tolerate ambiguity, and the preference for judging ideas rather than generating them (Adams, 2001). A variety of interventions have been developed to overcome creative blocks and enhance creativity (e.g., Benedek, Fink, & Neubauer, 2006; Fink et al., 2010), many using free-associative techniques (e.g., probing mind-wandering: Baird et al., 2012; brainstorming: Osborn, 1963). Here we will discuss means of enhancing divergent thinking and overcoming mental blocks by free association.

Using an approach based on single-word associations, Maltzman and colleagues (1958, 1960) performed a series of experiments to determine whether a training technique can enhance unusual (original) single-word associations on a free-association task, and whether this training increases originality and fluency on the AUT. In the training technique, participants were presented with the same list of stimulus words a number of times. On each presentation they were required to produce a different response. This training improved originality of associations on a new set of words, and also translated into higher scores on the AUT (Maltzman, Simon, Raskin, & Licht, 1960). Notably, in an earlier experiment, the relationship between originality training and AUT scores was not decisive (Maltzman, Bogartz, &Breger, 1958). Interestingly, merely presenting participants with lists of pairs of associations that were unusual also enhanced original free association on the final list, but did not show any effect on performance on the AUT. This observation might suggest that the action of producing associations is what elicits the improvement in AUT scores, although the mere activation of unusual semantic networks seems to have an effect on originality (Maltzman, 1960). A recent study showed that inducing activity in the left frontopolar cortex by transcranial direct current stimulation (tDCS) increased the semantic distance of associations produced in a cued single-word free association task. However, this effect was apparent only for individuals with high RAT scores, producing associations to words that have been shown to normally produce a narrow set of strong associations. The authors suggested that the individual differences are due to highly creative persons' ability to avoid high-frequency responses (Brunyé et al., 2015).

Freedman (1965) found that generating continuous associations to stimulus words enhances creative performance on the RAT. He suggested that a similar study conducted by Caron, Unger, and Parloff (1963) did not produce similar results because the authors tested the effect of practicing single-word associations – rather than continuous associations – on RAT scores. Miller, Russ, Gibson, and Hall (1970) found similar results. An additional well-known free-association technique is brainstorming, an approach that is typically used to encourage groups or individuals to generate ideas relating to a problem at hand. This can be seen as continuous free association, as people are required to come up with as many associations as possible to a specific cue/ task. Specifically, people are asked to free-associate ideas, while following four basic rules: withholding criticism until a later stage, the wilder the idea the better, quantity is desirable, and combination and improvement of other ideas is sought (Osborn, 1963). These conditions enable individuals to overcome various barriers to creativity, including emotional blocks such as the fear to make a mistake (i.e., the wilder the better) and rushing to judgment (Russ, 1993).

Much more research is needed to test the capacity of chain free association to enhance creativity. In psychoanalysis and psychoanalytic psychotherapy, free association is a common technique used to overcome internal inhibitions (Freud, 1912/1958). Similar to chain free association discussed above, free association in psychotherapy refers to a means by which the patient verbalizes associative thoughts, feelings, and wishes that come to mind (Skelton, 2006). In therapy, however, free associations usually consist of sentences or phrases. The use of this technique is supposed to tap into thinking processes that are related to creativity (e.g., primary processes; Russ, 2001), facilitating more flexible forms of thinking and leading to new insights (which are a form of creative product). This, in turn, is hypothesized to enhance well-being (Bollas, 2013; Bordin, 1966; Kris, 1996; Winnicott, 1971).

In contrast to free association techniques in a therapeutic setting, brainstorming techniques are unlikely to be sufficient to enable individuals to overcome complex creative blocks, of which they might not even be consciously aware. Individuals are likely to be able to overcome or circumvent such inhibition only with the aid of professional psychological intervention (e.g., Busch, 1998; Gedo, 1990). Notably, very few studies have empirically tested the relationship between psychotherapy and enhancement of creativity (e.g., Berant, 2009). Neuropsychoanalysis studies using brain-imaging techniques have the potential to provide particularly useful insights in this regard (Solms & Turnbull, 2011). We are currently investigating this relationship in ongoing research.

Summary

Free-association tasks can provide useful measurements of participants' creative processes, particularly processes related to divergent thinking. In this vein, different associative tasks are effective as tools for different experimental purposes. *Single-word association* is useful for creating free-association norms that can be used in various methods to test for differences in creative abilities, but it does not assist in characterizing individual differences in fluency, originality, flexibility or the ability to access remote networks. *Continuous word association* can provide information about individual differences in the fluency and originality aspects of divergent thinking. It is also highly informative regarding mental semantic structures of memory and can enable researchers to test group differences and individual differences regarding semantic structures. *Chain free association* provides a good indication of originality and can effectively measure associative flexibility – both spontaneous and adaptive – depending on the instructions. It is possible that spontaneous flexibility as measured by chain free association actually reflects the natural associative flow of thought, by providing a verbalization of mind-wandering-like thinking. We suggest that, compared with flexibility scores derived from the AUT, this is a more direct measure of spontaneous associative flexibility because it reflects the natural ability to shift between diverse semantic networks, without strong external search criteria.

When researchers consider the extent to which free-association tasks can be used as a direct measure of aspects of creative thinking, they should note that while the tasks account for a significant amount of variance among the different creative abilities, they do not account for all of the variance. This is probably for two main reasons. The first is that measures of divergent thinking are less direct than free-associative measures and could be susceptible to more confounds (e.g., fluency on AUT is related to former knowledge and memory of uses for the object: Gilhooly et al., 2007; RAT tests also tap verbal intelligence: Kenett et al., 2014). The second is that free association reflects only the variance corresponding to associative, spontaneous thought, while additional cognitive abilities are most likely involved in each creative process as well (Beaty, Silvia, et al., 2014).

We suggest that the relationship between free association and creativity may be exploited to help individuals overcome creative blocks. Specifically, training that encourages free association, and that aims to help the individual to engage in more flexible associations, may assist in overcoming internal inhibition and thought rigidity, ultimately enhancing creative thinking.

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Figurative Language Comprehension and Laterality in Autism Spectrum Disorder

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Figurative Language in ASD Population

Figurative language serves various pragmatic goals (Roberts & Kreuz, 1994). Indeed, it is commonly used in everyday communication (Gibbs, 2000; Levorato & Cacciari, 2002). The comprehension and production of figurative meanings primarily derive from the ability to go beyond local processing to search for a global, coherent meaning in order to identify the meaning intended by the speaker (Levorato & Cacciari, 1999). Thus, comprehensions and production of figurative utterances integrate both the surface meaning and the pragmatic intent of the communicative partner (MacKay & Shaw, 2004).

Autistic Spectrum Disorder (ASD) is a neurodevelopmental disorder that reflects a continuum of abilities and difficulties. The essence of the disability is reflected in the social-communicative area. Five criteria are required for this diagnosis: (1) persistent deficits in social communication and social interaction across multiple contexts; (2) restricted, repetitive patterns of behavior, interests, or activities; (3) symptoms must be present in early developmental period; (4) symptoms cause clinically significant impairment in social, occupational, or other important areas of current functioning; and (5) these disturbances are not better explained by intellectual disability or global developmental delay (American Psychiatric Association [APA], 2013: DSM V).

Difficulties in linguistics and communication represent a central domain in autism (APA, 2000). Pragmatic skills that impair the understanding of the social function of language are affected in ASD. In particular, research suggests that individuals with ASD experience difficulty in comprehending figurative language and tend to interpret such language literally. Studies that examined comprehension of figurative language in children and adolescents with ASD have focused on idioms (Mashal & Kasirer, 2011; Norbury, 2004; Whyte, Nelson, & Scherf, 2014), metaphors (Mashal & Kasirer, 2011; Rundblad & Annaz, 2010), and irony (Colich et al., 2012; Pexman et al., 2011). MacKay and Shaw (2004) examined the ability of children with ASD to comprehend the meaning and the intentionality of a figurative utterance as compared to children with typical development (TD). Comprehension was examined in six different categories of figurative language, including hyperbole, indirect requests, irony, metonymy, rhetorical questions, and understatement. Each story ended with a character using a figurative utterance, followed by two questions, one regarding the surface meaning of the utterance and one regarding the intent. In all six categories TD children outperformed children with ASD. Comprehension of the speaker's intent was more difficult as compared to understanding the figurative meaning for children with ASD. Most of the studies that examined figurative language in ASD have examined children and adolescents (MacKay & Shaw, 2004; Olofson et al., 2014; Rundblad & Annaz, 2010), and only a few included adults with ASD (Gold & Faust, 2010; Kasirer & Mashal, 2014; Saban-Bezalel & Mashal, 2015a, 2015b; Williams et al., 2013). Nevertheless, there is evidence suggesting that some comprehension difficulties persist into adulthood (Thoma & Daum, 2006). The current chapter focuses on three subcategories of figurative language: idioms, metaphors, and irony, which have been mostly examined in ASD.

Idioms

Idioms are defined as strings of two or more words (e.g., "*kick the bucket*") whose meaning is not necessarily derived directly from their literal interpretation (*to die*), but rather each idiom stores unique figurative meaning (Roberts & Kreuz, 1994; Swinney & Cutler, 1979). They are characterized by a significant gap between what the speaker said (the literal meaning) and what he meant to say (the idiomatic meaning) (Iakimova et al., 2010). Idioms differ in their degree of transparency (i.e., the degree of comparison that can be made between the literal and the idiomatic meaning of the idiom) and familiarity. It is easier to identify transparent and familiar idioms as compared to opaque and less familiar ones (Nippold & Taylor, 2002; Vulchanova, Saladana, Chahboun, & Vulchanov, 2015).

The few studies that have tested idiom comprehension in ASD focused on adolescents and children (Mashal & Kasirer, 2011; Norbury, 2004; Whyte et al., 2014). Mashal and Kasirer (2011) examined comprehension of idioms among adolescents with ASD through a multiple-choice questionnaire. The results indicated that adolescents with ASD (ages 12–15) understood fewer correct idiomatic meanings as compared to TD adolescents (ages 12–13). In a study that explored comprehension of idioms within context, Norbury (2004) compared four groups: children with autistic features, children with language impairment, children with autistic features and language impairment, and TD children. The results showed that all children benefited from context. However, the two clinical groups with language impairment did not benefit from context as much as their TD peers or the group of children with autistic features without additional language difficulties. Regression analyses found that age, memory for story context, and language abilities were significant predictors of idiom comprehension in context. Recently, it has been shown that theory of mind (ToM) and syntactic abilities also contribute to idiom comprehension among children and adolescents with ASD (aged 5–12) (Whyte et al., 2014). With regard to adults with ASD, Saban-Bezalel and Mashal (2015a) examined idiom comprehension through a lexical decision task and measured accuracy and reaction times. ASD participants were matched to TD participants by expressive vocabulary abilities. Participants performed a lexical decision task to literally and idiomatically related target words. Results showed that although the ASD group performed less accurately than did the TD group, the ASD participants were relatively unimpaired in understanding idioms. However, after careful matching in terms of vocabulary knowledge, the group difference disappeared. Thus, studies that examined comprehension of idioms among individuals with ASD indicate that difficulties may originate from a broader language difficulty rather than the nature of the disability per se. Indeed, according to the "high intelligence imbalance" hypothesis, some intelligence components in ASD population are increased (i.e., perceptual domains) while others are preserved or reduced (i.e., verbal and rotational skills) (Crespi, 2016). The imbalance leads to a decrease in general performance as compared to the general population. Thus, it is possible that the reduced performance in ASD reflects a decrease in general performance.

Metaphors

Metaphors (e.g., "*family is a cradle*") are statements that communicate something about a target concept (family) by inviting a comparison to a familiar source concept (cradle) (Olofson et al., 2014). To understand a metaphor one must see the point of similarity between the two concepts. The more points of similarity the hearer or reader understands, the fuller he or she understands the metaphor. Thus, understanding metaphor is primarily a logical-analytic task in which the hearer must recognize a match between two divergent aspects of experience (Winner, Levy, Kaplan, & Rosenblatt, 1998). Metaphors do not constitute a homogenous class as they differ in their degree of familiarity. According to the Career of Metaphor model (Bowdle & Gentner, 2005), novel metaphors are comprehended via a comparison process unlike conventional metaphors that are processed by a categorization process. The meaning of a conventional metaphor is stored in the mental lexicon and thus its comprehension relies mainly on meaning retrieval of stored knowledge. In contrast, understanding a novel metaphor is a more demanding task that may exert cognitive demands (Mashal, 2013). Kasirer and Mashal (2014) found that whereas vocabulary and picture-naming contributed to conventional metaphor comprehension, executive functions such as mental flexibility (as assessed by the *The Trail Making test* (TMT-B, Reitan & Davison, 1974) predicted novel metaphor comprehension. Furthermore, evidence indicates that the generation of conventional and novel metaphors relies on different cognitive abilities (Bowdle & Gentner, 2005; Mashal, 2013). Silvia and Beaty (2012) suggested that the generation of conventional metaphors is influenced by general knowledge or vocabulary, whereas generation of novel metaphors is affected by fluid intelligence and executive processes. Indeed, it has been shown that nonverbal intelligence (as assessed by the Test of Non-Verbal intelligence) predicted novel metaphor generation (Kasirer & Mashal, 2014).

Research on metaphorical language use in ASD is relatively limited (e.g., Melogno, D'Ardia, Pinto, & Levi, 2012; Rundblad & Annaz, 2010). For instance, one study examined comprehension of metaphors and metonyms in ASD participants (5–11 years) as compared to age- and mentally matched TD controls (Rundblad & Annaz, 2010). Participants were presented with 20 stories accompanied by colored pictures in order to limit memory demands. The stories ended with a target metaphor/metonym along with a picture showing one of the characters. The child was asked to report what the character sees. Results indicated that children with ASD were impaired on metaphor comprehension and delayed on metonymy comprehension. Different results were observed in a study that tested conceptual metaphor comprehension (Olofson et al., 2014). In accordance with the "Conceptual Metaphor Theory," conceptual verbal metaphors are understood by accessing the metaphorically structured concept rather than relying on pragmatics. Participants were 13 individuals with ASD (age 7:03–22:03) and 13 age-matched TD controls. Although the TD sample outperformed the ASD sample, both TD and ASD individuals understood lexicalized and novel formulations of conceptual metaphors. Using "sensorial" metaphors, Melogno et al. (2012) investigated metaphor comprehension in a group of 24 ASD children (6.6–11.6 years) as compared to two TD control groups, children aged 5 and TD children aged 6. The authors used a test that elicits an analysis of meaning in explicit linguistic form. The assessment was based on a qualitative scale of processing levels, which included three levels, rather than on a yes/no or right/wrong scoring system. The ASD group showed some capabilities in metaphor processing as they significantly differed from the 6-year-old control group, but did not differ from the 5-year-old control group. While most 6-year-old TD participants produced qualitative elaborated responses, most 5-year-old TD participants and participants with ASD produced elementary- and intermediate-level responses and only a few produced elaborated ones. The authors indicated that that children with ASD processed metaphors in an atypical manner and attributed these findings to an objective delay.

With regard to adults with ASD, Kasirer and Mashal (2014) investigated metaphor comprehension and generation. Adults with high-functioning ASD were compared to TD adults. A multiple-choice questionnaire consisting of conventional and novel metaphors was used to test comprehension, and a sentence completion questionnaire was used to test generation of creative metaphoric language. For example, participants were asked to complete the sentence: "Feeling successful is like … ." The results show that the groups did not differ in the comprehension of conventional and novel metaphors. Surprisingly, adults with ASD generated more original and creative metaphors ("Feeling successful is like seeing the view from the mountaintop") as compared to more conventional figurative expressions produces by TD adults ("Feeling sad is to get the blues"). The authors concluded that the accumulated verbal knowledge that comes with age leads to greater familiarity with conventional metaphors within the ASD group. Furthermore, adults with ASD demonstrated a unique verbal creativity that had not been shown before. These results suggest that adults with ASD can create unique verbal associations that are not restricted to previous knowledge.

Another possible reason that explains the more original metaphors generated by adults with ASD might be related to difficulty in ToM. Mind-blindness may affect one's own thoughts, ignoring the addressee (Happé & Vital, 2009), possibly leading to the generation of less-conventional expressions.

To summarize, studies that examined comprehension of metaphorical language indicate developmental differences in individuals with ASD. It seems that during childhood and adolescence TD outperforms ASD on metaphorical language abilities, although children with ASD show some capability of comprehending metaphorical language. There is evidence that over the years this ability improves in ASD as differences between the two populations during adulthood were not found. We also note that the type of stimuli (e.g., conceptual metaphors vs. nonconceptual metaphors) and task (e.g., open questions vs. multiple-choice questionnaires) may affect performance.

Irony

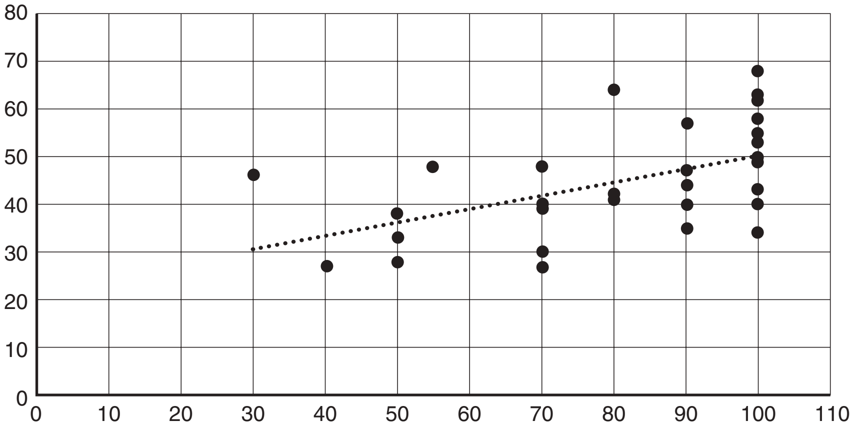
Irony is a linguistic mean that allows the speaker to express humor (Roberts & Kreuz, 1994) as well as criticism (Dews & Winner, 1995), and is important in creating social bonds (Clark & Gerrig, 1984). Irony often conveys the opposite message of the literal meaning (Gibbs, Bryant, & Colston, 2014) and the hearer must recognize the speaker's intentions (Winner et al., 1988). For example, a passage that ends with an ironic statement: *Exhausted after a long day at work, David planned to go to bed early. Just as he was ready for bed, he heard a knock on the front door. David opened the door and saw that some friends came by for a visit. David said: "The timing is perfect*" (Saban-Bezalel & Mashal, 2015b). Irony comprehension involves different skills, such as identifying the speaker's belief about what he or she said, identifying the communicative intent behind the ironic remark, and detection and identification of the speaker's motivation. These mentalizing capabilities develop at different time points and this is probably the reason for the prolonged acquisition (Filippova & Astington, 2010; Pexman & Glenwright, 2007). Evidence suggests that ToM (Baron-Cohen, Leslie, & Frith, 1985) and language ability of TD children contribute to their comprehension of irony beyond their age and memory capability (Filippova & Astington, 2008).

Several studies have examined irony comprehension in children with ASD. A recent study tested the comprehension of verbal irony through a task that minimized verbal and pragmatic demands (Pexman et al., 2011). Three groups participated in the study: children with high-functioning Autism Spectrum Disorder (HFASD), typically developing children matched to the HFASD for verbal ability, and typically developing children matched to the HFASD group for chronological age. The findings showed no group difference in accuracy rate in judging the speaker intent for ironic criticisms. Nevertheless, the groups differed in judgment latencies, eye gaze, and humor evaluations. That is, HFASD were able to recognize that the ironic statements do not mean to convey the literal meaning of their words, but they struggled to appreciate the broader social functions of the irony, such as the speaker's intent to be funny. Another study examined the roles of prosody and context in inferring a speaker's communicative intent (Wang, Lee, Sigman, & Dapretto, 2006) in children and adolescents with ASD (age 7.4–16.9) and TD children (age 8.1–15.7). Participants listened to short scenarios that included context and prosodic cues, prosodic cues only, and context cues only. Participants were asked to decide whether the speaker was sincere or ironic (i.e., interpreting the speaker's communicative intent). Children with ASD performed well above chance. However, they were less accurate as compared to TD children, specifically when they had to utilize context. In contrast, Colich et al. (2012) found that both ASD and TD groups performed equally well when asked to determine whether a speaker's remark was sincere or ironic, although the response times for the ironic remarks were longer in the ASD group.

Only a few studies have assessed comprehension of irony in adults with ASD. For instance, Martin and McDonald (2004) examined the ability of adults with Asperger's syndrome (AS) (mean age 19.64 years) to interpret an ironic joke. Participants were presented with a scenario and were asked to interpret the final statement. Individuals with AS demonstrated difficulty with the pragmatic interpretations of the ironic jokes. Specifically, they were more likely to judge that the protagonist was lying than being ironic (see also Au Yeung, Kaakinen, Liversedge, & Benson, 2015).

Recently, we examined irony comprehension in 34 adults with ASD (mean age = 25.80, *SD* = 5.45) and 22 TD adults (mean age = 27.45, *SD* = 3.94). As part of a larger study, participants completed a questionnaire that tested their irony comprehension (Saban-Bezalel & Mashal, 2015b). The questionnaire included 10 ironic passages and five literal passages. Each participant read the passage that ended with an ironic or literal utterance said by one of the protagonists in the passage. Participants answered a comprehension question that related to the speaker's thought. Participants also completed several background tests that included vocabulary (Wechsler, 2001), *Test of Nonverbal Intelligence: TONI-3* (3rd ed.) (Brown, Sherbenou, & Johnsen, 1997), phonemic and semantic fluency tests (Kavé, 2005), analogical thinking as assessed by the similarities test (Wechsler, 2001), and the Homophone Meaning Generation Task (HMGT; Kavé, Avraham, Kukulansky-Segal, & Herzberg, 2007). The results showed that whereas TD performance in the irony questionnaire was at ceiling, adults with ASD performed less accurately. Specifically, they were less accurate in comprehending the ironic than the literal passages. To further expand our understanding of the variables that are associated with irony comprehension, we computed Pearson correlations between irony comprehension and vocabulary, nonverbal cognitive ability, verbal fluency, analogical thinking, and HMGT. A strong positive correlation was found between irony comprehension and vocabulary, $r(32) = .53$, $p < .01$, and between irony comprehension and HMGT, $r(34) = .54$, $p < .01$ (see Figure 16.1), but not with the nonverbal intelligence test, fluency tests, or analogical thinking. The HMGT (Kavé et al., 2007) is a verbal executive function tool. The test is constructed of 24 homophones where the participant is required to evoke as many different meanings for each homophone. Performing the task requires mental control (i.e., suppress irrelevant meanings) and flexibility – both of which are considered to tap intact executive functioning. Participants are required to switch between different meanings of the same word. Mental control and flexibility are also both required during the processing of irony. One

(a) Irony comprehension and HMGT



(b) Irony comprehension and vocabulary

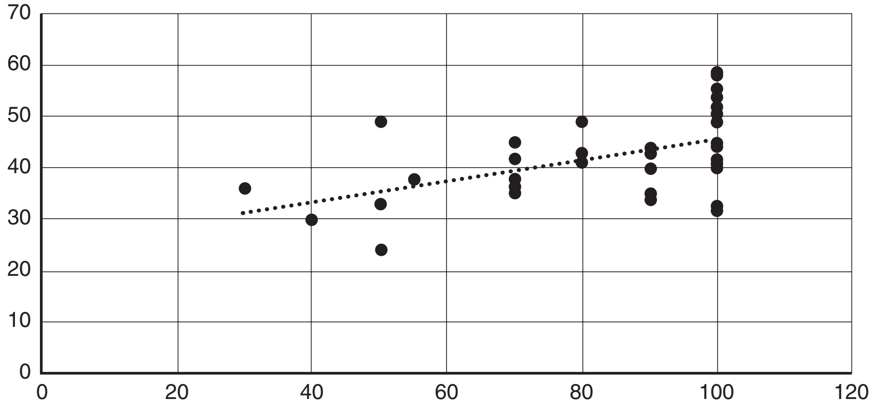


Figure 16.1 The correlations between ironic comprehension and scores on the HMGT (a) and the vocabulary test (b) in ASD.

must switch between the literal interpretation and the contextual interpretation of the utterance and favor the contextual one in order to interpret the speaker's intention. Our findings thus indicate that irony comprehension in ASD relies on some executive function abilities in addition to linguistic abilities.

To summarize, findings of studies that examined irony comprehension in ASD are not conclusive. Most of the studies show some difficulty in irony comprehension that persists into adulthood. Irony comprehension in this population is influenced by several factors such as ToM, language, and executive function abilities. Future studies that simulate everyday ironic situations in ASD are required.

In light of the inherent characteristics of figurative language as described above, it may be that the comprehension of figurative language may rely to some extent on one's creative ability, as they both engage in novel and significant information. Indeed, Gold, Faust, and Ben-Artzi (2012) reported negative correlation between the creative ability of the individuals and their response times when processing metaphorical expressions. Jung

(2014) considers creativity and intelligence as dichotomous ends of the cognitive mechanisms. While intelligence is characterized by deductive rule-based reasoning for cause and effect problems, creativity involves divergent thinking that solves unforeseen and abstract problems in a novel and adaptive manner. ASD thinking is known to be more deductive and explicit (Crespi, 2016; Jung, 2014). Studies have shown that people with ASD are challenged by tasks that involve creativity (Craig & Baron-Cohen, 1999), and generativity deficits in ASD have been suggested to reflect communication deficits (Dichter, Lam, Turner-Brown, Holtzclaw & Bodfish, 2009). Yet, as mentioned above, Kasirer and Mashal (2014) found that adults with ASD generated more creative metaphors relative to typically developed adults. We argue that further studies are needed to address the relationship between figurative language and creativity to establish the line of thought that argues that ASD's difficulty to comprehend figurative language originated in their thinking style.

Theories that Explain the Source of Difficulty in Comprehension of Figurative Language in Individuals with ASD

Comprehension of figurative language unlike literal language involves inferring the communicative intentions of the speaker and attributing mental states to him or her. Thus, impaired mentalizing process can explain the deficient figurative language comprehension in ASD (Happé, 1993) as framed by the ToM (Baron-Cohen et al., 1985). However, a later study (Norbury, 2004) demonstrated that ToM ability is a necessary but not sufficient condition for the comprehension of figurative language, and that semantic knowledge predicts metaphoric competence more than ToM abilities.

A different approach argues that individuals with ASD have no specific deficit in figurative language but rather a broader comprehension deficit (Gernsbacher & Pripas-Kapit, 2012). Indeed, in a study that compared irony and idiom comprehension following a strict linguistic matching between adults with ASD and TD, the group differences disappeared in the idiomatic task solely but not in the ironic task (Saban-Bezalel & Mashal, 2015a). In the ironic task participants had to read texts and perform a semantic judgment task, whereas in the idiomatic task participants performed a lexical decision task to a target word. It is possible that the ironic task was more demanding and relied more heavily on linguistic abilities, and therefore strict vocabulary-matching did not compensate for the group differences.

An alternative approach suggests that the processing of figurative language in ASD may be associated with the novelty of the stimuli rather than its non-literality (Kasirer & Mashal, 2014; Giora, Gazal, Goldstein, Fein, & Stringaris, 2012; Gold & Faust, 2012). Indeed, Hermann et al. (2013) found that processing of novel metaphors in adults with AS was similar to performance of age-matched TD individuals. The experiment included a semantic judgment task in which participants were asked to make rapid decisions about the literal truth of a given sentence. Consistent with Hermann et al. (2013), Mashal and Kasirer (2011) found that adolescents with ASD understood less-conventional metaphors as compared to TD children, but the group did not differ in the comprehension of novel metaphors. It might be the case that the ability to create novel semantic connections between apparently unrelated concepts is not impaired in ASD. Unlike conventional metaphors which are coded in the mental lexicon, novel metaphors require the computation of on-line interpretation and this ability may not be impaired in ASD (see Giora et al., 2012 for opposite results). Taken together, there is no clear conclusion regarding how novelty affects metaphor comprehension in ASD. Some of these inconsistent findings can be explained by the different testing modalities (e.g., multiple-choice questionnaire vs. verbal explanation) or types of metaphors (e.g., physico-psychologic vs. sensorial metaphors). Others may be explained by the heterogeneity of participants with ASD in terms of age, IQ, and diagnosis. As pointed before, inappropriate group matching may also contribute to the inconsistent findings.

Finally, we present a different perspective which attributes ASD's difficulty to comprehend figurative language to a broader cognitive deficit that characterizes ASD, namely the difficulty of integrating semantic information that originates in poor executive functions and weak central coherence (Vulchanova et al., 2015). Semantic integration refers to the ability to form associations, analogies, and other top-down skills. Processing of figurative language is demanding, because it requires one to refer to different aspects of information (linguistic, contextual, world knowledge) and integrate them into one coherent message. In light of the difficulties that accompany the ASD population in comprehension of figurative language, Vulchanova et al. (2015) infer that individuals with ASD are challenged when they encounter figurative language because they have difficulty integrating different aspects of the necessary information in order to build appropriate situation models. Alternatively, they build incomplete situation models or fail to use them in order to infer the meaning of the utterances and the speaker's intent.

In sum, different approaches attempt to explain the source of difficulty in figurative language comprehension in ASD. The explanations attribute this difficulty to broader language deficits, the novelty of the stimuli, ToM ability, deficient integration ability, or executive dysfunction. It is possible that more complex and demanding tasks (as observed in the ironic task in Saban-Bezalel & Mashal, 2015a) uncover the genuine difficulty in figurative language in ASD.

Psycho-linguistic Theories that Explain the Process of Figurative Language

In studies of brain lateralization it is known that the left hemisphere is a primary language processor among right-handed individuals. Nonetheless, a growing body of research shows that there are significant linguistic capabilities that are processed in the right hemisphere, such as processing of pragmatic interpretations that accompany the verbal message through processing of pre-linguistic and prosodic aspects (Lindell, 2006; Mitchell & Crow, 2005) and figurative language processing (Eviatar & Just, 2006; Mashal, Faust, & Hendler 2005; Mashal, Faust, Hendler, & Jung-Beeman, 2007). The involvement of the right hemisphere during processing of figurative language depends on several factors such as the types of figurative language, the task demands, and the linguistic features of figurative expression (Mitchell, & Crow, 2005; Rapp, 2009).

The differences between the left and the right hemispheres are embedded in fine versus coarse semantic coding theory (Beeman, 1998). According to this theory, semantic processing by the two cerebral hemispheres is qualitatively different. The theory posits that the left hemisphere (LH) engages in fine semantic coding whereas the right hemisphere (RH) engages in coarse semantic coding. During fine semantic coding (i.e., LH) the dominant interpretation of a word or several of its close associates are activated. This targeted activation along with suppressing of nonrelevant interpretations is what allows the LH to quickly select the most relevant interpretation to the word and the context. This fine semantic coding is what makes the LH an expert in most language tasks. In contrast, during coarse semantic coding (i.e., RH), weakly broad semantic fields including distant extensive semantic associative that encompass less-conventional information are evoked. This RH diffuse activation evokes distinct semantic relations of a word or multiple interpretations of ambiguous words, and thus new secondary meaning may be activated when the distant semantic fields come to overlap. Hence, the RH is more sensitive to distant semantic information and thus may be more efficient in decoding discourse or figurative language which requires integration of distant semantic information. Furthermore, the RH may be particularly adept at using mutually remote elements of new linguistic combinations, a process that may lead to the more-creative process or solution.

Consistent with Beeman's fine versus coarse semantic coding theory is the graded salience hypothesis (GSH) (Giora, 1997, 1999, 2003). According to the GSH, salient meanings are the foremost meanings on our mind, i.e., they are coded in the mental lexicon and can easily be accessed. What makes a meaning most salient is its conventionality, frequency, familiarity and/or prototypically. Giora (1997, 2003) claims that the degree of meaning salience, rather than the literal or metaphorical meaning of an utterance, determines the time course of meaning processing. According to the GSH, salient meanings will be processed in the LH whereas the RH will engage in processing of novel, nonsalient meanings and interpretations. Taken together, the two theories posit that salient meanings will be processed in the LH whereas the RH will engage in processing of novel, nonsalient meanings and interpretations. As the figurative meaning of an unfamiliar novel utterance (e.g., irony or novel metaphors) is usually more semantically distant than its literal interpretation, the two theories predict that the RH will be more apt for the interpretation of nonsalient figurative language. Indeed, neuroimaging evidence has shown that the RH specializes in processing of non-salient interpretations of figurative language (Eviatar & Just, 2006; Mashal et al., 2007).

Right-hemisphere Brain and Hemispheric Lateralization in ASD

Given the difficulties that characterize ASD population and the unique characteristics of the RH in respect to language abilities, several studies examined the possibility of RH dysfunction as a possible explanation for the pragmatic impairments in ASD. Rinehart, Bradshaw, Brereto, and Tonge (2002) administered a series of lateralization tests to individuals with autism and those with Asperger syndrome. They found that individuals with autism but not individuals with Asperger's syndrome showed similar characteristics of RH-damaged patients, but only in tasks that involved executive functions. In another study, Ozonoff and Miller (1996) tested the performance of different pragmatic tasks (understanding humor, measures of humor, inference, and indirect request comprehension). Individuals with autism performed below TD individuals on all tasks. The authors concluded that individuals with autism performed similarly to patients after right hemisphere stroke. In support of this conclusion, Dawson, Finley, Phillips, and Galpert (1986) showed that, whereas TD subjects demonstrated left asymmetry during speech processing, participants with autism showed a reversed asymmetry.

Atypical right hemispheric lateralization for language in ASD population has also been found in neuroimaging studies (Cardinale, Shih, Fishman, Ford, & Muller, 2013; Gage et al., 2009). For example, Kleinhans, Muller, Cohen, and Courchesne (2008) found that adults and adolescents with ASD show greater activity in the right frontal and right superior temporal lobes during a letter retrieval task as compared to TD adults and adolescents. Reversed language dominance was also found in participants with ASD when examining auditory perception using PET (Muller et al., 1999). The atypical right brain lateralization in language was found early on in toddlers later diagnosed with autism. The researchers suggested that the atypical lateralization pattern may reflect a fundamental early neural developmental pathology in this population (Eyler, Pierce, & Courchesne 2012). Other researchers have argued that the right asymmetry may be an indication of general organization of the brain in ASD that affects different brain systems that do not specialize specifically in language (Cardinale et al., 2013; Gage et al., 2009).

In contrast, lateralization studies that focused on figurative language did not find the rightward asymmetry. Instead, a bilateral pattern of hemispheric involvement in irony (Colich et al., 2012), metaphors (Gold & Faust, 2010), and idioms (Saban-Bezalel & Mashal, 2015a) was documented. With regard to irony, Wang et al. (2006) asked participants to listen to short scenarios with context and prosodic cues and decided whether the speaker was sincere or ironic. Although ASD children performed above chance level, they were less accurate compared to TD children in detecting the communicative intent behind a speaker's remark. While the TD and ASD groups recruited in general similar neural networks, the ASD group showed increased activation in the right inferior frontal gyrus (IFG) and bilateral temporal regions whereas the TD group showed greater recruitment of the medial prefrontal cortex (mPFC) when processing potentially ironic remarks. Colich et al. (2012) compared children and adolescents with ASD to TD controls when processing sincere versus ironic remarks. Although no differences between the two groups were observed at the behavioral level, differences were found at a neural level. The ASD group showed a more bilateral activation profile, and activated both language and "theory of mind" areas (i.e., ventromedial prefrontal cortex) (see also Williams et al., 2013).

Using the divided visual field paradigm, Saban-Bezalel and Mashal (2015a) examined the hemispheric processing of idioms and irony in adults with ASD in comparison to TD adults. At the behavioral level, ASD performed above chance on both tasks. However, ASD participants showed atypical bilateral processing for idioms and irony in contrast to TD adults. In accordance with the fine versus coarse semantic coding theory (Jung-Beeman, 2005) and the GSH (Giora 1997, 1999, 2003), TD adults demonstrated a RH advantage in processing both the nonsalient literal interpretations of idioms and ironic texts. Moreover, a reanalysis after the two groups were perfectly matched by vocabulary scores confirmed that participants with ASD rely on bilateral hemispheric processing for figurative language as this atypical brain lateralization was maintained. We further examined whether higher vocabulary abilities were related to increased lateralization in individuals with ASD by calculating an index of hemispheric lateralization (subtracting RH performance from LH performance, separately for accuracy and reaction times). Then, Pearson correlations were calculated between vocabulary scores and this hemispheric lateralization index. Within the ASD group vocabulary was not associated with hemispheric lateralization in the idiomatic task. However, a significant negative correlation was found in the ASD group between vocabulary scores and reaction times to literal passages. Thus, in the ASD group better vocabulary knowledge was associated with faster processing of literal passages in the LH. In other words, greater vocabulary scores are associated with decreased RH lateralization during processing of literal passages in the ASD group.

Interestingly, the decreased brain lateralization in ASD may be affected by a cognitive intervention. The effects of a short-term intervention designed to enhance irony comprehension in adults with ASD was tested in a follow-up study (Saban-Bezalel & Mashal, 2015b). Fifty-one individuals participated in the study, 29 adults with ASD and 22 TD adults. Participants in the

ASD group were randomly divided into a study group and a control group. Participants in the ASD study group participated in a short-term intervention, while participants in the ASD control group and in the TD group participated in a passive intervention. During the intervention participants in the study group engaged in analyzing verbal irony in short movies, stories, and comic strips in addition to production of irony. Irony comprehension was examined pre- and post-intervention via irony questionnaire in addition to a divided visual field experiment which examined hemispheric processing of ironic texts. The intervention improved irony comprehension in the ASD study group solely. Moreover, hemispheric processing in the ASD study group altered as a result of the short-term intervention. Whereas responses to ironic and literal targets were similar within each hemisphere prior to the intervention within the ASD study group and the ASD control group, after the intervention responses were lateralized to the RH in the ASD study group but not in the ASD control group. Thus, following the intervention, participants with ASD demonstrated a similar pattern of hemispheric processing of ironic texts as TD group prior to the intervention.

In sum, unlike the reverse asymmetry that was observed in ASD during language comprehension tasks, studies that examined figurative language found atypical bilateral processing. Moreover, vocabulary knowledge was associated with faster processing of literal passages in the LH. In some cases, similar behavioral performance as seen in TD, is accompanied with atypical bilateral processing in ASD (Colich et al., 2012; Saban-Bezalel & Mashal 2015a). The bilateral processing along intact behavioral performance may indicate of compensation processes in ASD.

Future Studies

We wish to raise some insights for directing future research. It appears that individuals with ASD have some ability to comprehend figurative language and by doing so they utilize atypical bilateral hemispheric processing as opposed to the TD population. The atypical bilateral hemispheric processing along with inferior performance compared to TD may in some cases indicate a compensatory mechanism in individuals with ASD. Future studies should test how different complex tasks affect the use of compensation strategies in ASD and the recruitment of the contralateral hemisphere. Recently, a surprising finding was documented in a study that tested the correlation between creative cognition and structural magnetic resonance imaging (sMRI) involving the relationship between divergent thinking and cortical thickness (Jung et al., 2010). The findings indicated that whereas increased cortical thickness in right posterior cingulate and right angular gyrus was associated with higher creative performance, decreased cortical thickness in several brain regions including the left frontal lobe, lingual, cuneus, angular, inferior parietal and fusiform gyri, was associated with higher creative cognitive abilities. Given the link between creativity and figurative language, future studies may examine the relationship between cortical thickness and figurative language processing in neurotypical as well as atypical individuals. In addition, different approaches attempt to explain the source of difficulty to comprehend figurative language in individuals with ASD, yet a unified conclusion has not yet emerged. We suggest that future research could examine this issue by not referring to figurative language as one unit but rather examine each subcategory with regard to its specific characteristics. Furthermore, it is important to consider the cognitive demands associated with various tasks so that the differences that might arise will not be influenced by their burden per se. Another line of future research is associated with the ASD/psychosis dichotomy (i.e., psychotic-affective conditions such as schizophrenia) that has been applied to the "social brain" (Crespi & Badcock, 2008). Jung (2014) described ASD as characterized by deductive and convergent thinking that favors intelligence-mediated solving of useful problems, whereas psychosis is associated with abstracted, metaphorical, and divergent thinking that mediates the resolution of implicit, novel, and creativity-based problems. Given that figurative language is associated with some aspects of creative thinking, it will be interesting to study the cognitive mechanisms that underlie the processing of figurative language of individuals that reside on the extreme ends of the ASD/psychosis continua.

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Part V

Cognitive Control and Executive Functions

00:18:24

17 The Costs and Benefits of Cognitive Control for Creativity

Evangelia G. Chrysikou

Introduction

At first glance, the experimental study of a topic as complex as creativity would seem like a formidable task for a cognitive neuroscientist. For one, the methods of cognitive neuroscience are best suited for cognitive processes we can clearly isolate in space and time and which can be reliably elicited with simple experimental manipulations in the laboratory. Although creativity falls far from satisfying these methodological constraints, the status of creative thought as a hallmark of the human mind has invited numerous investigations on the neural bases of creativity for nearly two decades. Cognitive neuroscience research on creativity has provided an extensive body of work highlighting the neural underpinnings of concepts key to creativity, such as divergent thinking and insight, that are theorized to underlie our ability to generate ideas deemed novel and appropriate to satisfy current goals. On the other hand, it has also become apparent that a lack of consensus on the operationalization of these concepts and their measurement, as well as the substantial variability in the use of definitions, creativity tasks, and experimental paradigms across studies, have brought issues of interpretation of the ensuing data for our understanding of the neural mechanisms of creativity to the fore (Abraham, 2013; Chrysikou, in press). To address these concerns, modern experimental and neuroscience research on creativity has recently begun to transition from the study of hard-to-define concepts, such as divergent thinking, to investigations of specific cognitive and neural processes (e.g., attention, memory, executive function) hypothesized to underlie creative thought (Abraham, 2014; Dietrich, 2007a,2007b; Smith, Ward, & Finke, 1995; Ward, 2007; see also Kounios & Beeman, 2014; Weisberg, 2006).

Cognitive neuroscience studies have revealed that creative thinking is associated with the involvement of an extensive network of regions that are widely distributed across the brain, and which reflect the complex set of diverse cognitive processes involved in creative cognition. A key question for this research pertains to the importance of executive functions or *cognitive control* processes for creativity and the attendant involvement of prefrontal cortical structures during creative ideation. Indeed, a point of convergence across the majority of recent work on the neural bases of creative thinking is the significance of the prefrontal cortex (PFC) for creative thought (e.g., Gonen-Yaacovi et al., 2013; see Dietrich & Kanso, 2010 for a review). Yet, the results of studies employing a range of cognitive neuroscience methods – including functional neuroimaging, electrophysiology, and patient lesion studies – have shown that the PFC can be both reliably engaged and disengaged during different creative thinking tasks. One interpretation of these seemingly paradoxical results is that the generation of novel and context-appropriate ideas may involve a combination of spontaneous, bottom-up processes that can result in unanticipated conceptual associations and controlled, top-down processes that can support the evaluation of the relevance, viability, and efficacy of these associations for the problem at hand. An optimal balance between such spontaneous and controlled processing is essential for creative thinking and likely relies on the flexible regulation of cognition at different points during the creative process (see Hélie & Sun, 2010; Zabelina & Robinson, 2010). Thus, if creative thinking involves switching between these different neurocognitive states, it is suitable to propose that a key mechanism in the creative process entails the dynamic modulation of cognitive control as supported by PFC networks (Chrysikou, Weber, & Thompson-Schill, 2014; Dietrich, 2004).

In line with these suggestions, recent proposals on the role of cognitive control processes for creativity have underscored the potential importance of trade-offs between spontaneous and regulatory mechanisms for different aspects of the creative process (e.g., Chrysikou et al., 2014; Jung, Mead, Carrasco, & Flores, 2013; Thompson-Schill, Ramscar, & Chrysikou, 2009). Here, I will review some of the evidence for these accounts, with an emphasis on the costs and benefits of cognitive control for creativity. I will relate these findings to recent work on the contributions of different brain networks to creative thought and discuss some key challenges on understanding the neural mechanisms involved in creativity stemming from this research. I will then present a proposal outlining how communication across these neural networks may support different aspects of creative thought. I will conclude with a discussion of ways through which research on cognitive control flexibility can foster creative thinking outside of the laboratory.

Hypofrontality and Creative Thought

Cognitive control pertains to the set of top-down regulatory mechanisms supported by the PFC that are thought to bias competitive interactions among bottom-up, sensory information from either the environment or the internal state of the organism toward context-appropriate responses. As cognitive control processes sculpt the representational space by prioritizing the attentional salience of goal-relevant information, bottom-up, sensory input that is deemed irrelevant to one's current goals is inhibited or discarded (Miller & Cohen, 2001; Shimamura, 2000). Although cognitive control is critical for most aspects of higher-order cognition, not all complex behaviors benefit similarly from this kind of regulatory monitoring. Indeed, how much cognitive control is necessary for optimal performance may vary substantially depending on individual differences, one's goals, and the characteristics of a given task. We and others (e.g., Chrysikou, 2014; Chrysikou et al., 2014; Dietrich, 2004; Thompson-Schill et al., 2009) have hypothesized that cognitive control mechanisms are critical to optimize performance on close-ended tasks that hinge on regulatory, top-down filtering (e.g., cued semantic retrieval), whereas the same mechanisms may constrain or impede performance on those open-ended tasks that rely on spontaneous, bottom-up thought (e.g., aspects of everyday problem-solving). With regards to creativity, the generation of novel ideas in the context of open-ended tasks with no obvious single correct solution (e.g., composing a piece of music, coming up with a new recipe, or repairing a broken heel on the fly before an important presentation) is not guided by the implementation of an explicit rule. Rather, performance on such tasks may benefit from the temporary availability of low-level data (e.g., perceptual, sensory, or emotional information) that can facilitate remote semantic associations that are typically inhibited or rejected during standard rule-based thinking.

Evidence from developmental and cognitive neuroscience studies offers support for the potential importance of a *hypofrontal* (or unregulated) neurocognitive state for certain aspects of creative thought that rely on the availability of bottom-up, sensory input. For example, the propensity for functional fixedness in the use of everyday objects is significantly reduced in children younger than the age of 5 relative to older children (Defeyter & German, 2003; German & Defeyter, 2000), a finding compatible with the protracted development of PFC throughout childhood and into young adulthood (Shaw et al., 2008). Additional evidence in favor of the potential benefits of hypofrontality for bottom-up processing comes from reports of patients with neurodegenerative disorders or brain lesions selectively affecting PFC. The temporal variant of primary progressive aphasia (i.e., frontotemporal dementia) that predominantly affects left ventral prefrontal and temporal cortex (see Gorno-Tempini et al., 2011), for example, has been associated with a paradoxical functional facilitation of visual accuracy in the patients' spontaneous drawing output, which was not present prior to their diagnosis (e.g., Seeley et al., 2008; Shamay-Tsoory, Adler, Aharon-Peretz, Perry, & Mayseless, 2011). Similarly, patients with focal strokes to the left PFC scored better than healthy participants on certain matchstick arithmetic problems, performance on which relies on violations of rule-based thinking (Reverberi, Toraldo, D'Agostini, & Skrap, 2005). In line with these findings, the abnormal acceleration of PFC development in autism has been associated with increased access to bottom-up, sensory information in this population, which is thought to underlie the musical, mathematical, or artistic skills of certain autistic savants (Snyder, 2009; see also Snyder et al., 2003; Snyder, Mar, & Kim, 2006). For instance, consistent with an increased availability of low-level perceptual input, children with autism outperform neurotypical children in their memory for unlabeled color stimuli, despite showing impaired sensitivity when discriminating between color categories (e.g., Heaton, Ludlow, & Roberson, 2008). The potential benefits of lower PFC engagement for perceptual processing can also be experimentally induced in healthy adult participants using noninvasive brain stimulation: disruptions in left ventrolateral PFC function using repetitive transcranial magnetic stimulation (rTMS), for example, lead to measurable improvements in absolute pitch perception and number estimation (Snyder et al., 2003, 2006). Although these data do not provide evidence for changes in creativity *per se*, they suggest that diminished lateral PFC function – especially in the left hemisphere – can increase availability of unfiltered perceptual input, which has been hypothesized to lead to improvements in certain aspects of creative production tasks (Dietrich, 2004).

A number of recent studies directly tested this prediction. A state of decreased PFC involvement characterized the neural profiles of musicians when engaging in jazz improvisation relative to the reproduction of well-learned musical sequences during functional magnetic resonance imaging (fMRI; Limb & Braun, 2008). An extension of this work has similarly shown a decoupling between executive control mechanisms and a network of medial prefrontal and subcortical regions during freestyle rapping relative to a memorized lyrical performance (Liu et al., 2012). In line with these findings, using fMRI we have shown that generating an uncommon use in response to pictures of common objects (e.g., using a baseball bat as a rolling pin) was associated with limited engagement of ventrolateral PFC regions, but increased activity in posterior, visual object-processing regions (i.e., occipitotemporal cortex), bilaterally, in healthy normal adults. In contrast, generating the common use for the same objects (i.e., a close-ended task with a unique correct solution) elicited the reverse effect (Chrysikou & Thompson-Schill, 2011). These findings are consistent with electroencephalogram (EEG) patterns reflecting transient hypofrontality and increased alpha rhythm synchronization over posterior parietal regions during creative ideation (Fink, Grabner, Benedek, & Neubauer, 2006; Mölle, Marshall, Wolf, Fehm, & Born, 1999; see Fink & Benedek, 2014a, 2014b for reviews). Indeed, enhancing alpha power with 10 Hz transcranial alternating current stimulation (tACS, a noninvasive stimulation technique involving the application of small electric currents on the scalp) over frontal cortex significantly improved performance on the Torrance Tests of Creative Thinking (Lustenberger, Boyle, Foulser, Mellin, & Fröhlich, 2015). These findings suggest an integral role of alpha oscillations for creativity, which are theorized to reflect top-down inhibition of response execution (Klimesch, Sauseng, & Hanslmayr, 2007).

Overall, the results of these investigations suggest a trade-off between perceptually based and rule-based thought for optimal performance during creative idea generation, by which reduced PFC activity is associated with limited filtering of low-level perceptual information (e.g., pure tones; the shape, size, or materials of common objects) that might prove useful or relevant in the context of forming broad associations during creative generation tasks (e.g., improvisation, impromptu problem-solving). Biasing response selection early on or inhibiting such information while working on new solutions to open-ended problems would, thus, be counterproductive. In fact, by inhibiting the left inferior lateral PFC using transcranial direct current stimulation (tDCS), a noninvasive neurostimulation method akin to tACS, we have elicited considerable increases in the speed in which participants generated uncommon (but not common) uses for everyday objects, as well as fluency in response generation. In contrast, inhibiting the right PFC or sham stimulation has not had any consequences for performance on either task (Chrysikou et al., 2013). These findings provide strong evidence for a causal relationship between hypofrontality and performance in data-driven, creative idea generation tasks for which regulatory filtering of perceptual, bottom-up information could impede performance. In addition, a recent behavioral investigation (Radel, Davranche, Fournier, & Dietrich, 2015) has demonstrated that the specific cognitive mechanism underlying this effect is a reduction in the capacity to exert inhibition, as exposure to high inhibitory demands was associated with fluency improvements in a subsequent open-ended, but not a close-ended, creativity task.

The potential benefits of limited cognitive control regulation for certain aspects of creative thinking may also be determined by trait variation that can operate independently of (or in conjunction with) the influence of particular task requirements. For example, decreased thalamic D2 receptor densities in normal adults have been associated with improved performance on data-driven creativity tasks, advantages that may be attributed to a reduction in thalamic gating thresholds and increased flow of information across corticothalamic circuits (De Manzano, Cervenka, Karabanov, Fanke, & Ullen, 2010). These results are compatible with positive relationships between increased regional gray matter volumes in corticostriatal dopaminergic regions as measured by voxel-based morphometry and performance in open-ended creative idea generation (Takeuchi et al., 2010). Moreover, participants' scores on similar bottom-up creativity tasks (e.g., the alternative uses task) show a nonlinear relationship with the subjects' spontaneous eyeblink rate (a clinical marker of striatal dopaminergic production) according to which medium levels of striatal dopamine may lead to optimal cognitive flexibility during this task (Chermahini & Hommel, 2010). On the other hand, performance on close-ended creativity tasks that typically have one correct answer (e.g., the Remote Associates Test) appears to benefit from decreased levels of striatal dopamine. These results are compatible with potential trade-offs in the involvement of cortical and subcortical brain regions depending on the specific nature of the creativity task or its components.

Accounting for these findings, we have recently put forth the Matched Filter Hypothesis (MFH) for cognitive control (Chrysikou et al., 2014), a potentially robust explanatory framework that can account for the neurocognitive processes involved in creative thinking. The MFH proposes potential competing interactions between prefrontal and posterior or subcortical brain systems, which determine the appropriate level of cognitive control filtering over bottom-up information (either endogenous or exogenous) for optimal task performance. According to this framework, PFC-mediated cognitive control is advantageous for explicit, rule-based tasks that rely on the manipulation of information that does not exceed the representational capacity of working memory. In contrast, cognitive control regulation is counterproductive for more spontaneous, automatic tasks that involve processing of information that exceeds working memory limitations. Decreased prefrontal regulatory filtering may optimize performance in these tasks via disinhibition of posterior, medial, or subcortical systems (e.g., sensorimotor cortex, medial PFC, basal ganglia; see Aron et al., 2007).

For the MFH, cognitive control can have both costs and benefits for creativity. Although the engagement of cognitive control systems can impede creative idea generation as discussed above, their contribution is imperative for maintaining task goals in working memory and in evaluating the novelty and appropriateness of the generated output. In addition, the potential consequences of the engagement of these networks likely differ depending on the task under investigation and the aspect of creative cognition assessed (e.g., fluency vs. originality; see Radel et al., 2015; cf. Chrysikou & Thompson-Schill, 2011). Thus, complex interactions between spontaneous and regulatory systems likely guide creative performance and are further determined by the developmental stage and intactness of these mechanisms, one's response to pharmacological agents affecting the central nervous system, as well as by individual differences due to genetics, neurophysiology, or psychopathology. For example, the quantity and quality of the creative output can be dramatically influenced by psychopathological disorders characterized by PFC hypofunction (e.g., depression, bipolar disorder; see Ramey & Chrysikou, 2014).

In light of the evidence on the potential importance of hypofrontality for access to bottom-up input during creative idea generation, iterative switching between spontaneous and controlled processing appears essential for creative thinking. A key question for future research in this context pertains to the precise cognitive control mechanisms – and, by extension, to the prefrontal executive and related brain networks – that determine the optimal balance and flexible transition between these different neurocognitive states at different points during the creative process. I will return to this issue in the sections that follow.

The Role of Cognitive Control in Creativity

A hasty reading of some of the literature reviewed above may lead to the conclusion that creativity, in general, necessitates reduced cognitive control that results from a hypofrontal neurocognitive profile. However, although certain aspects of idea production during open-ended tasks may, in fact, benefit from such lateral PFC disengagement, the potential for self-generated, creative thinking that is both novel and goal-appropriate in context requires the contribution of top-down, regulatory mechanisms as guided by these same lateral prefrontal cortical networks. For example, the emergence of paradoxical *de novo* artistic production in non-professional artists following brain injury (e.g., Chatterjee, 2006; Schott, 2012; Simis et al., 2014) or degenerative brain diseases typically affecting PFC (e.g., Chakravarty, 2011; Miller et al., 1998; Miller & Hou, 2004; Shamay-Tsoory, et al., 2011; Viscontas & Miller, 2013) as discussed earlier would suggest that, overall, the creative process is facilitated by the disinhibition of posterior and subcortical regions due to lateral PFC (especially left hemisphere) network impairment (Heilman & Acosta, 2013; Viscontas & Miller, 2013). On the other hand, other studies have shown limited or diminished creativity in the patients' artistic production (de Souza et al., 2010). Critically, a close inspection of the patient's artistic output has revealed that their work does not develop creatively with time as in healthy visual artists and is marked by obsessive–compulsive, ritualistic features (e.g., Chatterjee, 2006; Midorikawa & Kawamura, 2015; Rankin et al., 2007; Simis et al., 2014). Limited creativity has further been observed in cases of prolific artistic autistic savants who display unique drawing abilities for almost-photographic, realistic depictions of visual scenes, despite extensive neurocognitive dysfunction (e.g., Pring, Ryder, Crane, & Hermlin, 2012; Sacks, 2004; but see Treffert, 2013). These drawing and painting skills may, at first glance, resemble acquired visual artistic creative abilities; however, in the context of the patients' compromised language and semantic memory systems, such skills may be best viewed as substitute means of communication that reveal dormant innate artistic talent and not deliberate creative achievement (Zaidel, 2014).

These findings highlight an important role of the PFC for genuine creativity, that is, the generation of goal-directed new ideas that move beyond unconstrained conceptual associations or simple artistic expression. Intentionally novel combinatorial work that results in the generation of innovative and context-relevant conceptual spaces relies on healthy conceptual systems and intact evaluation mechanisms that can continuously assess the originality and relevance of the creative output. In line with this view, PFC regions have been implicated in the evaluation of the appropriateness of different novel ideas, and the selection of which among them are optimal for the task at hand. One study, for example, used a realistic creative drawing task under fMRI to examine different cortical networks implicated in the generation and evaluation of ideas produced (Ellamil, Dobson, Beeman, & Christoff, 2012). The results provided evidence for the involvement of medial temporal cortex during the generation of creative ideas, an area central to the brain's *default mode network*, a set of regions (including the medial PFC, lateral and medial parietal regions extending into the posterior cingulate and the retrosplenial cortex, and the medial temporal lobes) that show spontaneous structured activity patterns during passive task states, and are theorized to reflect memory consolidation and self-generated thought (Raichle et al., 2001); in contrast, activity in executive and default network regions in addition to rostrolateral PFC, insula, and temporopolar cortex was associated with creative idea evaluation. Importantly, positive functional connectivity characterized the relationship between executive and default network areas. This finding suggests that the assessment of the appropriateness of creative ideas in context involves PFC, but may also extend beyond executive networks to involve brain regions that are typically engaged in affective or visceroceptive processes (e.g., medial temporal and posterior parietal regions and the limbic system).

Studies showing rostrolateral PFC involvement during the combination of novel ideas are consistent with work on relational reasoning through analogies. Analogical thinking is hypothesized to leverage past knowledge toward establishing new idea associations that are relevant within a given problem context and, as such, important for creative thought (see Weisberg, 2006). Neuroimaging studies of analogical reasoning have shown consistent recruitment of left ventral prefrontal and especially frontopolar cortex, which has been proposed to facilitate representational integration of information relevant to predicting future outcomes (e.g., Bunge, Wendelken, Badre, & Wagner, 2005; Green, 2016). In support of this view, increased activity in the left frontopolar cortex was coupled with anterior cingulate and right frontopolar cortex engagement when participants were successful in consciously augmenting the creativity of their responses in a verb generation task (Green, Cohen, Raab, Yedibalian, & Gray, 2015). In addition, boosting activity in left frontopolar cortex using noninvasive brain stimulation significantly enhanced participants' deliberate efforts to form remote relational associations (Green et al., 2016). These results are consistent with reports of anterior cingulate involvement and occipital cortex suppression during insight experiences (e.g., Kounios & Beeman, 2014; Kounios et al., 2006; Salvi, Bricolo, Franconeri, Kounios, & Beeman, 2015), under the assumption that insight entails the integration of information that results in the – typically abrupt – realization of the relevance of certain associations for the solution to a problem.

The important contribution of PFC regions to the establishment of novel conceptual combinations and their evaluation is further supported by a recent meta-analysis of 34 neuroimaging studies involving various creativity tasks (Gonen-Yaacovi et al., 2013) that employed Activation Likelihood Estimation (ALE), a coordinate-based meta-analysis method that uses published activation peaks across neuroimaging studies to determine convergence across them at levels statistically higher than what would be expected by chance (Laird et al., 2005; Turkeltaub et al., 2012). The results of this analysis revealed a set of regions across the caudal PFC that were associated with novel idea production; in contrast, a different set of regions within the rostral PFC were linked to creative idea combination. A similar meta-analysis employing the ALE procedure across 45 functional neuroimaging studies on musical, verbal, and visuo-spatial creativity (Boccia, Piccardi, Palermo, Nori, & Palmiero, 2015) showed that each creativity domain is associated with different multicomponential neural networks that are broadly distributed across the entire brain, but which – importantly – include several regions within the PFC.

This research supports the conclusion that cognitive control mechanisms are integral to creative thinking specifically with respect to the support of goal pursuit, deliberate novelty-seeking and evaluation, and assessment of the feasibility and appropriateness of a particular product or solution. Precisely which prefrontal regulatory mechanisms are responsible for these effects during creative cognition, however, and *when* and *how* they impose constraints on the salience of information produced by an extensive network of posterior, medial, and subcortical brain regions remains an open question. For example, the research discussed earlier would suggest differential contributions of prefrontal regions along the rostral–caudal axis (Badre & D'Esposito, 2009) during creative thinking, whereas the disengagement of lateral (e.g., relative to medial) PFC – the area typically associated with cognitive control – appears to produce benefits for creative idea generation, but not evaluation (Radel et al., 2015; see also Vartanian et al., 2014). Moreover, the extent and consequences of the engagement of each of these regions is likely determined, in part, by the specific requirements of a given creativity task (e.g., alternative use generation, remote associates, verb generation, etc.). Future research is required to clarify the exact relationship between these systems and the relative timing of their contribution during the creative process for different tasks, as well as to determine how they are influenced by individual differences attributed to developmental, genetic, and psychopathological factors (e.g., Chermahini & Hommel, 2010; de Manzano et al., 2010; Takeuchi et al., 2010; Vartanian, Martindale, & Kwiatkowski, 2007) or variability in the employment of flexible cognitive control (Zabelina & Robinson, 2010). As we have argued (Chrysikou et al., 2014), if creativity involves vacillating between spontaneous and controlled processing, the rapid shifts between a hypofrontal generative state and a prefrontally guided evaluative state should occur numerous times during a creative task and implicate several regions across spontaneous and regulatory processing systems. We turn to research that has examined some of these relationships next.

Executive, Salience, and Default Network Engagement in Creative Thought

Understanding creativity by focusing on the neurocognitive processes involved in fluent idea generation or originality evaluation can benefit from a focus on particular brain regions and their contribution to creative cognition. Such modular methodological and analytic approaches have shed light on the specific roles of different cognitive processes (e.g., cognitive control, attention, relational reasoning, episodic memory retrieval, etc.) in creative thought, and hold potential for situating creativity within more established areas of cognitive neuroscience research (see Chrysikou, in press). As discussed above, given that creative thinking relies on the interaction of multiple such processes, it is no surprise that it recruits multiple brain areas, the engagement of which is further determined by individual differences. Likewise, there is variability in the requirements of different creative thinking tasks with regards to the broadening or narrowing of one's conceptual scope, the demands imposed on working memory, the reliance on episodic retrieval, any deliberate effort to be creative, and other factors.

Building on this region-specific work, recent proposals (Beaty, Benedek, Silvia, & Schacter, 2016; Jung et al., 2013) have eloquently highlighted the importance of examining the complex interplay between spontaneous and regulatory brain systems for creative thought at the network level. A growing number of neuroimaging studies have further employed connectivity measures to examine the dynamic interactions between these networks (see Zabelina & Andrews-Hanna, 2016 for a review). Such functional connectivity analyses hold great potential for elucidating the neural bases of complex behavior by focusing on sets of distributed regions across the brain that show correlated patterns of activity either at rest or during cognitive tasks (Bressler & Menon, 2010). Using this method, one such experiment examined functional connectivity across the whole brain when participants generated either alternative uses or simple characteristics for common objects. The results revealed that executive or regulatory network areas (i.e., the dorsolateral PFC) and default or spontaneous network areas (i.e., posterior cingulate cortex, precuneus, inferior parietal lobe) – regions typically thought to function antagonistically – engaged cooperatively during the alternative uses task (Beaty, Benedek, Kaufman, & Silvia, 2015). Interestingly, components of the default network (i.e., the posterior cingulate cortex) were coupled with areas of the salience network (i.e., the right anterior insula) – a system that has been implicated in switching between neurocognitive states – earlier during creative generation trials, whereas the same default areas were coupled with executive network regions later in the trials. These findings are in line with the recruitment of temporal cortex for creative idea generation and PFC for creative idea evaluation, as well as the positive connectivity between these networks, discussed above in the context of a creative drawing task (Ellamil et al., 2012; see also Beaty et al., 2014; Green et al., 2015; Pinho, de Manzano, Fransson, Eriksson, & Ullén, 2014). Such dynamic and synergistic interactions between the default and executive control regions in creative cognition have been offered in support of the proposal that creative idea generation and evaluation largely rely on the respective contributions and well-orchestrated interactions between these two systems (e.g., Beaty et al., 2016; Jung et al., 2013). What's more, increased communication between them can be predictive of better performance on creativity tasks (Beaty et al., 2014; Mayseless, Eran, & Shamay-Tsoory, 2015).

But how does the reciprocal engagement of the default and executive networks relate to low (hypofrontal) and high (prefrontally guided) cognitive control states during creative cognition? If creativity is defined as the intentional pursuit of ideas that are both novel and appropriate in context, then all creative cognition is inevitably goal-directed and consequently relying on cognitive control for the strategic assessment of the generated output within the constraints of task-specific goals. The involvement of cognitive control networks in creativity has received generally strong empirical support as discussed above; the direct consequences of default network engagement for creative idea generation, however, are less clear. On the one hand, cooperation between executive and default network regions is characteristic of generative tasks that involve self-projection and internally directed or self-generated thought (e.g., mind-wandering, prospection, autobiographical memory retrieval, perspective taking, mental simulation; see Buckner & Carroll, 2007; Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Spreng, Mar, & Kim, 2009). As creative ideation is, by definition, generative, it stands to reason to anticipate parallels between such processes and creative generation tasks regarding default network engagement. Consistent with this hypothesis, recent behavioral evidence has shown that autobiographical memory recruitment can improve performance on certain creativity tasks (Madore, Addis, & Schacter, 2015), whereas damage to medial temporal lobe structures (e.g., the hippocampus) produces creativity impairments (Duff, Hengst, Tranel, & Cohen, 2009; Duff, Kurczek, Rubin, Cohen, & Tranel, 2013). In conjunction with evidence from functional and temporal connectivity studies (e.g., Beaty et al., 2014, 2015; Ellamil et al., 2012) these findings have been offered in support of a two-system model for creative cognition according to which creative idea generation is ascribed to default network contributions, whereas idea evaluation is supported by executive network activity.

Yet, whether default network engagement is tantamount or ancillary to a hypofrontal state of reduced cognitive control related to creative generation remains an open question. Although a focus on network dynamics is descriptively attractive, discussing creative idea generation in general as the output of default network activity presents certain explanatory challenges. For one, not all aspects of creative idea production are necessarily “self-generated,” that is, relying primarily or exclusively on internally focused mental activity that is mostly independent of external input. For example, using a tennis racket as a snow shoe is an alternative use for a common object that can be partially guided by perceptual object characteristics (i.e., the visual similarity between the two objects, see Chrysikou, Motyka, Nigro, Yang, & Thompson-Schill, 2016) – a process that has been associated with low prefrontal engagement and activity in lateral occipitotemporal object processing regions that typically fall outside of the default mode network (e.g., Chrysikou & Thompson-Schill, 2011). A possible account for such discrepancies in default network activation during creative ideation may be related to the types of stimuli used (e.g., words vs. pictures) or participant strategies during open-ended tasks. For instance, some participants may recruit episodic autobiographical information or self-project, that is, think of themselves as using (or having used) objects in a particular way, whereas others may employ more abstract semantic retrieval strategies stripped of particular episodic context. Although the former strategies are likely to engage default network contributions, the latter may be more associated with activity in semantic or somatosensory processing regions. Similar differences in default network engagement may rely on the specifics of the task used. For example, instructing pianists to improvise music that expresses particular emotions has been associated with reduced activity in right lateral PFC and increased functional connectivity between executive and default network regions (Pinho, Ullén, Castelo-Branco, Fransson, & de Manzano, 2016), whereas instructing jazz musicians to improvise relative to reproducing musical sequences without explicit reference to emotion has been linked to a hypofrontal cognitive state, but not default network engagement (Limb & Braun, 2008; for a discussion on the relationship between emotion, self-reference, and the default mode network see Andrews-Hanna, Reidler, Sepulcre, Poulin, & Buckner, 2010). These findings would suggest that creative idea generation – although often linked to hypofrontality – is not always associated with internally focused self-generated thought and the concomitant default network involvement but may, instead, implicate other brain regions depending on the nature of the creative task.

Additionally, although the functionality of the default network has been associated with mental states indicative of spontaneous cognition (Andrews-Hanna, Reidler, Hunag, & Buckner, 2010), certain findings would suggest some caution when interpreting the coordinated patterns of activity within this network as the primary outcome of self-generated and unconstrained conscious thought. Task-evoked activity is associated with only minimal changes in global measures of brain circulation and metabolism (~5%, see Raichle & Mintun, 2006), which would imply that the regions within the default mode network are continuously and comparably active regardless of immediate task goals and irrespective of the particular nature of the task. Furthermore, very similar coordinated patterns of activity across homologous default network regions have been reported in nonhuman animals such as monkeys (Vincent et al., 2007) and recently mice (Lu et al., 2012; Stafford et al., 2014), whereas default mode network engagement has also been observed in humans under anesthesia (Greicius et al., 2008). These results introduce the possibility of a more general function of default mode activity for the mammalian brain (Deco, Jirsa, & McIntosh, 2013; Raichle, 2015) and make it difficult to establish a precise role of default network engagement for spontaneous cognition in general, and creative thinking more specifically.

Based on the above, the contributions of particular brain networks to creative idea generation, especially within the default mode system, might reflect subtle changes in neural network balance largely determined by task parameters, rather than constitute a neural signature of creative ideation *per se*. Future research is necessary to specify the precise task conditions under which episodic future simulation, self-projection, mind-wandering, and other aspects of self-generated mental activity are implicated in creativity, and whether they affect – to similar degrees – ideational fluency, originality, flexibility, or other aspects of creative thought (e.g., Madore et al., 2015; Radel et al., 2015). Critically, much further work (e.g., through interference paradigms or noninvasive brain stimulation, see Chrysikou et al., 2013; Green et al., 2016) is needed to determine possible causal relationships between activity within certain subregions of the default mode network and performance on different creative generation tasks. The availability of detailed behavioral data that can be directly linked to brain-based measures (e.g., Chrysikou & Thompson-Schill, 2011; Ellamil et al., 2012; Limb & Braun, 2008) is imperative for meeting these objectives.

Nevertheless, the seminal work on the relationship between the default and executive networks for creativity (e.g., Beaty et al., 2014, 2015; Jung et al., 2013) introduces the intriguing possibility that the brain's "default mode" might also be a "creative ideation mode." Instead of solely describing creative idea generation and evaluation as the outcome of the dynamic and positive relationships between default and executive network activity, however, here, I propose that executive control regions strategically guide the delicate balance between cooperation and antagonism across the brain through their connections with regions dedicated to salience processing (cf. Bressler & Menon, 2010; Cocchi, Zalesky, Fornito, & Mattingley, 2013). As indicated above, intrinsic functional connectivity patterns reveal continuous activity across multiple brain networks in the absence of specific task demands. Which aspects of that activity (e.g., episodic future thought, semantic retrieval, mental imagery) are brought to the forefront of cognition during creative tasks relies on the engagement of the executive control network that comprises lateral prefrontal and lateral parietal neocortex. Along with the dorsal anterior cingulate cortex (dACC) and the orbital frontoinsula (FI), these regions form a neural ensemble that is consistently recruited by cognitively demanding tasks. The dACC and FI, however, anchor a discrete “salience network” exhibiting extensive and robust connectivity with subcortical and limbic structures. Although distinct, there is a temporal overlap between executive and salience systems that is restricted to a small cluster of nodes within the bilateral FI and right dorsolateral PFC that appear to be shared between the two networks (Seeley et al., 2007). In the early stages of creative idea generation, executive network activity is limited to working memory maintenance of task objectives; thus, the lack of lateral PFC involvement is reflective of the hypofrontal state reported in many studies of creative ideation. During this phase, the brain is continuously bombarded by internal and external stimuli (e.g., semantic, autobiographical, perceptual information) that exceed working memory limitations and which are, thus, not subject to cognitive regulation (see Chrysikou et al., 2014). Identifying the most relevant of these inputs relies on the engagement of the salience network that integrates highly processed sensory data with visceral, interoceptive-autonomic, and hedonic “markers” through its connections with subcortical emotion, homeostatic regulation, and reward-processing regions, including the dorsomedial nucleus of the thalamus (Seeley et al., 2007). In extension of past work (Chrysikou et al., 2014; Jung et al., 2013), I propose that nodes within the salience network, and particularly the right frontoinsular pole (the right ventral PFC and the anterior insula), highlight semantic, episodic, perceptual, and other information and their interactions from multiple regions across the brain; this information then becomes salient and available in working memory for subsequent executive control processing.[1] Executive control regions are later recruited to direct attention to salient stimuli and guide goal-directed behavior against a backdrop of shifting conditions and context. Such response flexibility in the control of low-level data is achieved through mechanisms for sustained attention and working memory (dorsolateral PFC), inhibition of prepotent responses (ventrolateral PFC), and response selection (dorsomedial PFC and supplemental motor area), whereas conscious deliberate attempts toward relational integration are likely to recruit frontopolar cortex (e.g., Green et al., 2015, 2016).

Therefore, frontoinsular nodes function as “relevance detectors” and are implicated both in the idea generation and evaluation process of creativity by modulating the relative balance among executive control and other brain networks through the integration of cognitive and affective information (e.g., Ellamil et al., 2012). Critically, shifts between executive network involvement or disengagement occur iteratively numerous times until the optimal solution to a task is achieved (Chrysikou et al., 2014; Hélie & Sun, 2010). Of note, beyond the default mode, intrinsic functional connectivity studies have identified resting-state networks across sensory, motor, and higher-order cognitive systems (De Luca et al., 2006) with temporal dynamics that vary among different systems depending on context. I argue that the executive control network plays a primary role in strategically navigating the relative competitive or cooperative relationships

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[1] The ACC and (particularly right) FI (as well as the dorsolateral PFC) of humans and great apes feature a special type of large bipolar projection cells known as spindle or von Economo neurons that may have evolved to support complex behavior in highly intelligent mammals (Nimchinsky et al., 1999). Although one may speculate about the function of these cells for the human brain, there is currently insufficient evidence to hypothesize that the salience network nodes proposed here comprise exclusively such cells.

across these systems in the guidance of goal-directed behavior. Indeed, cooperation rather than competition might be the organizing principle behind neural network interactions (see Popa, Popescu, & Pare, 2009; Raichle, 2015), as also reflected in the positive connectivity between default and executive systems observed in creativity studies.[2] Nevertheless, additional detail is necessary to determine whether this cooperative relationship holds across the entire duration of a creative thinking task. For example, it is possible that an antagonistic relationship between default and executive systems characterizes their involvement at the microscale level (i.e., in the order of milliseconds), whereas a synergistic relationship characterizes their involvement at the macroscale level (i.e., in the order of seconds) with connectivity patterns changing multiple times throughout the task. Given that traditional neuroimaging methods lack the capacity to capture neural events with millisecond temporal resolution, this limitation must be taken into account when discussing the potential relationship between these networks (see also Jung et al., 2009; Jung & Haier, 2013). Future research is invited to examine with more precision the dynamic interactions between the proposed generative and analytic brain systems in space and time, to determine the influence of individual differences in network engagement, and to delineate the specific contributions of particular network components to different aspects of creative thought.

Leveraging the Costs and Benefits of Cognitive Control to Enhance Creativity Outside of the Laboratory

The examination of the neurocognitive processes involved in creative cognition especially with regards to executive control has inspired numerous efforts toward improving creativity outside of the laboratory through behavioral, neurostimulation, and pharmacological interventions. Several of these manipulations have elicited measurable changes in performance on various creativity tasks, primarily through interventions targeting creative ideation. In the context of executive control network engagement or disengagement discussed in previous sections, these interventions aimed to either directly decrease cognitive control or increase the function of posterior or subcortical brain systems important for creative generation. For example, creativity enhancement has been observed through brief behavioral exercises including ad-hoc categorization for common objects (Chrysikou, 2006), object decomposition (McCaffrey, 2012), routine disruption (Ritter et al., 2012), autobiographical memory cueing (Madore et al., 2015), or the influence of perceptual factors (e.g., color; Mehta & Zhu, 2009). Benefits to creativity performance have been reported with noninvasive brain stimulation procedures, particularly inhibition of inferior frontal and temporal cortex (e.g., Chrysikou et al., 2013; Green et al., 2016; Snyder et al., 2003, 2006; Weinberger, Green, & Chrysikou, 2017). Drug-based interventions have largely focused on the influence of different pharmacological agents on the dopaminergic and noradrenergic systems and have revealed both facilitative and inhibitory effects to creativity (e.g., Battleday & Brem, 2015; Mohamed & Lewis, 2014; see Beversdorf, 2013, for a review). A common thread across these investigations is the prospect of different techniques to alter the balance between executive and other brain regions (e.g., through potentiating the salience of low-level information), thus

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[2] Although much past work has revealed anticorrelations among brain systems, these findings might be an artifact of whether the analyses excluded the global signal (i.e., the signal common to all areas of the brain). Notably, functional connectivity studies of creative thinking reporting cooperative network relationships did not remove global signal (e.g., Beaty et al., 2015; Ellamil et al., 2012), which might partially account for the positive correlation patterns between default and executive regions – but not necessarily serve as an indicator of unique network cooperation distinctive of creativity or other self-generative processes.

increasing the likelihood of that information being considered during creative ideation. On the other hand, the theoretical and methodological rationale across these investigations is not uniform and the substantial variability in perspectives has obstructed their integration to existing neurocognitive models of creative thought. Future research is required to overcome this fragmentation and unify this multidimensional data set under a concise model of creative thinking, which will support the development of new and systematic interventions for creativity enhancement.

Conclusion

Research on the role of cognitive control for creativity points to the potential importance of trade-offs between spontaneous and regulatory mechanisms for different aspects of creative cognition. Here, I presented some of this evidence underscoring the costs and benefits of cognitive control for creativity. Extending past work on the Matched Filter Hypothesis for cognitive control (Chrysikou et al., 2014), I proposed that during creative thinking executive control regions strategically guide the delicate balance between cooperation and antagonism across the brain through their connections with regions dedicated to salience processing and that these iterative shifts take place throughout the idea generation and evaluation phases of the creative process. To advance techniques for fostering creative thinking outside of the laboratory, future investigations will need to move beyond descriptive discussions of the involvement of these networks in creativity, and explain the specific and causal contributions of particular network components for different aspects of creative thought.

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18 Creativity and Cognitive Control in the Cognitive and Affective Domains

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Since Archimedes' legendary "Aha" experience, outstanding creative accomplishments have long been conceived as being the result of an external "higher power," caused by divine help, often occurring after spontaneous, sudden inspiration. This view ranked creativity as a difficult or even an intangible trait to study, and it has taken quite a long period of time until empirical studies have begun to elucidate the manifold societal, interpersonal, and not least individual characteristics implicated in this fascinating human ability. With Guilford's (1950) seminal address to the American Psychological Association (APA), the idea of creativity as a stable trait that is linked to several personality characteristics of an individual became more and more accepted in this field. Meanwhile, research from both the psychometric and the neuroscientific traditions revealed a consistent pattern of personality traits and neurocognitive mechanisms that may underlie different facets of creativity. For instance, relevant research in this field has shown that creativity is among others closely associated with intelligence (Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014; Jauk, Benedek, Dunst, & Neubauer, 2013), domain-specific knowledge/expertise (e.g., Weisberg, 1999), motivation (Collins & Amabile, 1999), or personality traits such as openness, broad interests or self-confidence (Barron & Harrington, 1981; Feist, 1998). In addition, the growing field of neuroscience studies dealing with different facets of creativity such as creative ideation or divergent thinking ability has revealed that this ability might be best characterized as being organized in widespread neural networks, including both regions associated with executive processes and cognitive control (e.g., Fink & Benedek, 2014; Gonen-Yaacovi et al., 2013) and regions closely linked with (at least a subset of) the default network of the brain (e.g., Beaty, Benedek, Kaufman, & Silvia, 2015; Beaty, Benedek, Silvia, & Schacter, 2016; Jung, Mead, Carrasco, & Flores, 2013). Such findings support the idea that both spontaneous, automatic processes (e.g., loose associations, "mind-wandering") and more controlled modes of information processing such as cognitive control are essential components of the creative thinking process (e.g., Beaty et al., 2016).

On a more general level, such findings also make an important contribution toward eliminating some of the myths and mysteries that have gathered around creativity, inasmuch as they clearly indicate that an important source of creativity must be located within the individual, rather than in intangible external sources. This chapter will highlight one important individual characteristic in this context, namely the role of efficient executive functions (i.e., cognitive control) in creative thought. In the course of this discussion, three different lines of research will be outlined, each of which involve research efforts from the psychometric and the neuroscientific research traditions: (a) studies highlighting the role of cognitive control processes in tasks involving creative ideation or divergent thinking demands; (b) research on the potential link between creativity and schizophrenia spectrum disorders; and (c) studies which take a fresh and novel approach by investigating creativity-related demands in an affective context, specifically in dealing with emotions.

Cognitive Control in Creative Ideation and Divergent Thinking

EEG studies on creative ideation have revealed a reliable and robust picture of some brain mechanisms underlying creativity, especially task-related changes in the alpha frequency band (approximately in the frequency range between 8 and 12 Hz), which have consistently been found to be sensitive to different creativity-related task demands. As summarized in Fink and Benedek (2014), EEG alpha power has been observed to vary as a function of the creativity-related demands of a task (more creative task demands are associated with higher alpha power), as a function of originality (more original ideas are associated with higher alpha power), and as a function of the creativity level of an individual (more-creative individuals are more likely to show higher alpha power). In addition, there is also some evidence that alpha power is sensitive to verbal creativity interventions (Fink, Grabner, Benedek, & Neubauer, 2006; Fink, Schwab, & Papousek, 2011). Intriguingly, Lustenberger, Boyle, Foulser, Mellin, and Fröhlich (2015) were even able to demonstrate increases in psychometrically determined creativity (assessed via the well-known Torrance Tests of Creative Thinking) as a result of 10 Hz transcranial alternating current stimulation (i.e., within the alpha range), while no significant changes in creativity were found in applying 40 Hz stimulation. In addition to the EEG studies on creative cognition, this finding provides direct evidence for the functional role of EEG alpha oscillations in creativity-related demands (Lustenberger et al., 2015).

Increases in alpha power appear to be especially relevant during internal processing demands (Klimesch, Sauseng, & Hanslmayr, 2007; Sauseng et al., 2005), and are thought to indicate the absence of stimulus-driven, external bottom-up stimulation and, thus, are thought to reflect a form of top-down activity (cf. von Stein & Sarnthein, 2000). More specifically, it has been suggested that enhanced alpha power, especially over prefrontal sites – as consistently seen in EEG alpha studies on verbal divergent thinking demands (cf. Fink & Benedek, 2014) – may be indicative of top-down control, facilitating the inhibition of task-irrelevant activity such as irrelevant sensory processing or the retrieval of interfering information (Klimesch et al., 2007). This may be especially important in the context of novel idea generation, which is thought to involve various executive task demands including the inhibition of dominant, typical associations and of pre-potent response tendencies (Beaty & Silvia, 2012; Benedek, Franz, Heene, & Neubauer, 2012; Gilhooly, Fioratou, Anthony, & Wynn, 2007). This line of reasoning is further supported by brain-imaging studies, which have also revealed that regions of the prefrontal cortex, shared by various creativity-related task demands, may support executive processes inherent to creativity such as fluency, flexibility, or the inhibition of pre-potent responses (Gonen-Yaacovi et al., 2013).

The particular role of cognitive control processes in creative thought has also been highlighted in the psychometric research tradition, which suggests that divergent thinking ability is significantly and positively associated with cognitive control as assessed by the Stroop task or the random motor generation task (see, e.g., Benedek, Franz, et al., 2012; Edl, Benedek, Papousek, Weiss, & Fink, 2014; Golden, 1975; Groborz & Necka, 2003; Zabelina & Robinson, 2010; Zabelina, Robinson, Council, & Bresin, 2012). Edl et al. (2014), for instance, examined the relationship between creativity and cognitive control in a sample of design students with high creativity-related demands in their field of study, in relation to a control group of students with putatively lower creativity-related occupational demands. Cognitive control was assessed by a modified Stroop color-naming task, in which two color words and two font colors were used to generate congruent and incongruent conditions. Design students showed stronger cognitive control as indicated by the absence of a Stroop interference effect, while the control group exhibited a robust interference effect. In addition, the design students generally displayed better performance in the Stroop task than the control group. Moreover, additional correlational analyses revealed associations between stronger cognitive control and higher scores in several psychometric creativity measures such as originality and fluency in verbal and figural tasks, and self-assessed ideational behavior. Consistent with neuroscientific studies on creative ideation, these findings suggest that more-creative individuals may show stronger cognitive control, including the ability to effectively suppress competing and dominant but irrelevant response tendencies (see also Benedek & Neubauer, 2013; Gilhooly et al., 2007).

Creativity and Schizophrenia Spectrum Disorders

An additional line of evidence that substantiates the particular role of cognitive control processes during creative ideation stems from research on cognitive functions associated with schizophrenia spectrum disorders and particularly schizotypy, a personality trait closely related to a vulnerability toward developing schizophrenia (Chapman, Chapman, Kwapil, Eckblad, & Zinser, 1994; Lenzenweger & Korfine, 1992; Meehl, 1962). Both schizophrenia and schizotypy have been associated with creativity (Abraham & Windmann, 2008; Brod, 1997; Carson, 2011; Fink, Benedek, Unterrainer, Papousek, & Weiss, 2014; Fink, Slamar Halbedl, Unterrainer, & Weiss, 2012; Holt, 2015; Karlsson, 1970, 1984; Kyaga et al., 2011, 2013; Nelson & Rawlings, 2010; O'Reilly, Dunbar, & Bentall, 2001). Furthermore, a recent study supported a potential genetic link between schizophrenia and creativity (Power et al., 2015). At first sight, these findings seem to be puzzling, as there is broad consensus that creativity is associated with various highly adaptive traits such as intelligence, expertise, motivation, or openness (see, e.g., Barron & Harrington, 1981; Feist, 1998; Fink, Benedek, et al., 2014). In addition, a high level of creativity is commonly considered as a sign of mental health and emotional well-being (Dietrich, 2014; Simonton, 2000). Why, then, might a psychiatric disorder that is associated with severe maladaptive traits, including deficits in social interactions (Fletcher & Frith, 2009; Nitzburg, Burdick, Malhotra, & DeRosse, 2015), a breakdown of theory of mind (Chung, Barch, & Strube, 2014), and decreased executive functions (Kalkstein, Hurford, & Gur, 2010) be linked with higher creativity?

Some studies in this field found that specific facets of schizotypy or the schizophrenia spectrum, especially positive symptoms such as unusual hallucinatory experiences or magical ideation, may be linked to psychometrically determined creativity (e.g., Claridge & Blakey, 2009; see also Acar & Sen, 2013; Baas, Nijstad, Boot, & De Dreu, 2016; Crespi, Leach, Dinsdale, Mokkonen, & Hurd, 2016; Mohr & Claridge, 2015). Likewise, elevated levels of positive schizotypy were found in samples of artists (Nelson & Rawlings, 2010; Nettle, 2006). A possible interpretation of this finding could be that positive schizotypy and creativity may share some common cognitive processes that could be roughly summarized under the term disinhibition (i.e., more loose associations, over-inclusiveness of thinking, allusive thinking; Duchêne, Graves, & Brugger, 1998; Eysenck, 1993; McConaghy, 1989; Mohr, Graves, Gianotti, Pizzagalli, & Brugger, 2001; Rominger, Weiss, Fink, Schulter, & Papousek, 2011). Cognitive disinhibition may support the generation of novelty and originality, but as argued in Fink, Benedek et al. (2014) it may be especially conducive for creative thought if it occurs with the necessary cognitive control to guide evaluation and elaboration at the exploration stage of creative idea generation (see also Carson, 2011; Kaufman & Paul, 2014). Although speculative, this might also explain why only mild manifestations of disorders on the schizophrenia spectrum (e.g., schizophrenic patients in remission, people with schizotypal personality) are associated with heightened levels of creativity (Abraham, 2014; Barrantes-Vidal, 2004; Claridge & Blakey, 2009; Jung, 2014; Nelson & Rawlings, 2010), because the interplay between cognitive control processes and loose semantic networks needs to be in the right balance in order to generate something that is both novel and useful (cf. Holt, 2015).

As already indicated above, both cognitive control processes and disinhibition (e.g., loose associations, overinclusive thinking style) are considered to be core components of the creative thinking process in the psychometric research tradition (Beaty, Benedek, et al., 2014; Beaty, Silvia, Nusbaum, Jauk, & Benedek, 2014; Benedek et al., 2014; Benedek, Könen & Neubauer, 2012; Edl et al., 2014; Rossmann & Fink, 2010). Intriguingly, processes related to disinhibition and cognitive control have also been highlighted as integral components of creativity by recent EEG and brain-imaging studies. Specifically, both EEG and fMRI studies yield consistent evidence that creative ideation is organized in widespread neural networks, supporting processes such as attention, working memory, and semantic information processing (e.g., Fink & Benedek, 2014; Gonen-Yaacovi et al., 2013). Moreover, there appears to be emerging consensus that along with regions associated with executive processes and cognitive control, regions closely linked with (at least a subset of) the default network of the brain are implicated in creative thought processes as well (e.g., Beaty et al., 2015, 2016; Jung et al., 2013). Such findings provide strong evidence for the idea that creativity is the result of efficient cooperation between cognitive control processes and spontaneous thought processes such as imagination or mind-wandering (Beaty et al., 2015, 2016).

Whitfield-Gabrieli et al. (2009) reported an interesting study in this context. They found reduced task-related deactivation of the brain's default network in schizophrenics and their relatives, while controls exhibited the typical task-related suppression of default network regions. Deactivations of default-mode brain regions are typically seen when more controlled and goal-directed information processing is required (e.g., when successful task performance requires focused attention; cf. Cavanna, 2006; Raichle et al., 2001), thereby suppressing spontaneous and unsystematic thought processes. According to Whitfield-Gabrieli et al. (2009), the reduced deactivations of default regions may contribute to thought disturbances in schizophrenia and risk for illness. In a similar vein, Fink, Weber, et al. (2014) found that originality and schizotypy were associated with similar functional brain activity patterns during creative ideation, namely reduced deactivation of the right precuneus (see also Takeuchi et al., 2011), which is thought to be a part of the resting-state brain network (Cavanna, 2006). This finding may hint at heightened levels of spontaneous, unsystematic thought processes involved in schizotypy and in generating originality, and it strongly supports the contention that some facets of creativity and psychosis-proneness may share some common processes (see Carson, 2011; Fink, Benedek, et al., 2014; Rominger, Papousek, Fink, & Weiss, 2014).

Originally, the creative process was hypothesized to rely on two separable processes, or phases grossly overlapping with disinhibition (e.g., collection of ideas, associative, imaginative processes, loose associations, etc.) and cognitive control processes and inhibition (focus on the best solution, inhibition of irrelevant ideas; Finke, Ward, & Smith, 1996; Sowden, Pringle, & Gabora, 2014). People with higher scores on schizotypy measures or individuals suffering from disorders on the schizophrenia spectrum might have a higher affinity toward disinhibitory processes during creative ideation, due to their predisposition toward a more overinclusive thinking style (i.e., looser associations, allusive thinking; Eysenck, 1993; Mednick, 1962). However, for creative ideation to occur it is essential that there be a flexible switching and shifting between different thinking processes (Groborz & Necka, 2003; Sowden et al., 2014) depending on the respective task-demands (Chrysikou, Weber, & Thompson-Schill, 2014). Impairments in these cognitive skills might be assumed in people scoring high on schizotypy, and in individuals suffering from disorders on the schizophrenia spectrum, as nicely demonstrated in a study by Merten and Fischer (1999). They reported increased cognitive control and flexibility in creative people compared to patients suffering from schizophrenia. These results underline the particular role of intact executive functioning and volitional control in creativity, and suggest that impairments in these functions in patients suffering from schizophrenia might lead to rigid behavior. Interestingly, functional and structural abnormalities of frontal areas (e.g., inferior frontal gyrus) were reported for inpatients of schizophrenia with positive symptoms (Suga et al., 2010; Weiss et al., 2006), which may further underline the decoupling of cognitive control and disinhibition in this psychiatric disorder.

Creativity in an Affective Context

One type of creativity, which humans face almost every day, has largely been neglected in this field of research: Creativity in dealing with emotions. While there is plenty of research examining links between creativity and specific moods (see Baas, Dreu, & Nijstad, 2008 for a meta-analysis), creativity in an affective context such as creative behavior in emotion perception or in regulating an ongoing emotional state is largely unexplored. Research on creativity-related demands in the affective domain has been stimulated by concepts such as emotional creativity, defined as the experience and expression of original, appropriate and authentic combinations of emotions (Averill, 1999; Averill & Nunley, 1992). In fact, many classic constructs in the emotional research domain are thought to involve various demands that are likewise seen in classic cognitive creativity tasks. For instance, emotion regulation involves monitoring, influencing, and as such, transforming undesirable emotions in order to meet internal or external goals (Gross, 1998, 2013). Among many different emotion regulation strategies, cognitive reappraisal refers to the deliberate cognitive reinterpretation of an emotionally evocative event in order to modify its emotional impact (Gross & John, 2003; Lazarus & Folkman, 1984) and is labeled as more effective, healthy, and sustainable than other strategies like suppression or distraction (Augustine & Hemenover, 2009; Webb, Miles, & Sheeran, 2012).

Parallels between cognitive reappraisal and classic creative idea generation become most obvious in their shared divergent thinking demands. Both processes require the generation of manifold and alternative, preferably original but still useful and practicable solutions to an open problem. This certainly requires the overriding of dominant and context-inappropriate associations, or in a broader sense, intact executive functions, most prominently set-shifting, memory-updating and the inhibition of prepotent responses (e.g., Miyake et al., 2000), which can be subsumed under the term cognitive flexibility (e.g., Miller & Cohen, 2001; Zabelina & Robinson, 2010). It has been suggested that an individual's executive functioning determines the success of using cognitive reappraisal in terms of reducing negative affect (Joormann & Gotlib, 2010; Pe et al., 2013;

Schmeichel, Volokhov, & Demaree, 2008) and thus enabling cognitive control over affective arousal. Similar conclusions have been drawn for the generation of novel (creative) ideas, substantiating the view of top-down control of task-irrelevant activity as an important prerequisite of creative thought (e.g., Fink & Benedek, 2014; Klimesch et al., 2007). Indeed, various executive processes (flexibility, planning, working memory), which are thought to be basic components of the creative thinking process (e.g., Beaty & Silvia, 2012; Gilhooly et al., 2007; Runco, 2010; Ward, 2007), might play a major role in cognitive reappraisal as well.

Given that emotions need to be reappraised on a daily basis in order to ensure adequate intra- and interpersonal functioning, focusing on affective creativity in terms of cognitive reappraisal might be an innovative and promising approach to extend research on creativity toward more complex creative behavior or more real-world creativity, respectively. Fink et al. (2017) took a first step toward this direction by investigating functional patterns of EEG alpha activity while participants were engaged in conventional idea generation (i.e., Alternative Uses Task, AUT), and in the generation of reappraisals to self-relevant negative emotional events. The latter was assessed via a modified version of the Reappraisal Inventiveness Test (RIT; Weber, Loureiro de Assunção, Martin, Westmeyer, & Geisler, 2014), in which participants were instructed to empathize with anger-eliciting situations and to think of as many different ways as possible to reappraise these situations in a manner that reduces their anger. The RIT measures the capacity of an individual to generate different reappraisals for anger-eliciting situations, and provides scores for ideational fluency (the number of appropriate, nonidentical reappraisals) as well as flexibility (the number of different reappraisal categories). The generation of reappraisals hence appears to display a large overlap with concepts from the realms of creativity and divergent thinking (Weber et al., 2014). Especially the ability to think flexibly could be considered as a basic constituent of cognitive reappraisal in that it requires an individual to flexibly adopt and to generate new perspectives, solutions or strategies, accompanied by the inhibition and overriding of the typical and most obvious responses elicited by this situation (i.e., experience of anger). Such flexible idea production is likewise seen in many creativity-related task demands, and most interestingly, both the fluency and the flexibility scores of the RIT have been found to be significantly and positively associated with conventional divergent thinking measures and with the personality dimension of openness to experience that is closely linked to creativity (Weber et al., 2014).

The findings of the Fink et al. (2017) study suggest that cognitive reappraisal was generally associated with a quite similar pattern of alpha power to conventional verbal creative ideation. This was especially apparent in that both the AUT and the RIT yielded comparatively strong alpha power increases at prefrontal sites. Alpha power increases over the prefrontal cortex have been observed consistently during various verbal creative thinking demands (Fink & Benedek, 2014), and are thought to indicate top-down control by actively inhibiting task-irrelevant activity such as irrelevant sensory processing or the retrieval of interfering information (e.g., Klimesch et al., 2007; Sauseng et al., 2005). Such processes may be relevant in both the RIT and the AUT because they both involve high internal processing demands. However, there were also some important differences between cognitive reappraisal and conventional creative ideation. While cognitive reappraisal was associated with larger alpha power increases than performance of the AUT at frontopolar sites, the latter was associated with stronger alpha power increases at more posterior (i.e., central) cortical sites, possibly indicating higher cognitive control and less spontaneous imaginative thought processes in the generation of effective strategies to regulate an ongoing negative emotional state. Such a pattern of findings was to be expected, as in addition to the processes involved in conventional idea generation, cognitive reappraisal of emotion-eliciting situations or stressful events requires individuals to inhibit (disengage from) the negative emotional aspects of a situation. Such a regulation of an ongoing emotional response might strongly draw on cognitive control processes (e.g., Joormann & Gotlib, 2010; Pe et al., 2013; Rowland et al., 2013; Weber et al., 2014). Additionally, cognitive reappraisal involves switching (shifting attention) toward emotionally neutral aspects, and updating the affective value and motivational relevance of the situation (cf. Malooly, Genet, & Siemer, 2013).

The particular importance of cognitive control processes in the generation of reappraisals has been further substantiated using another EEG parameter, namely the assessment of hemispheric asymmetry of activation in the prefrontal cortex. This approach still constitutes a major research interest in affective neuroscience, with the general consensus being that a relatively greater left > right frontal activation facilitates adaptive emotional responding in terms of higher affective flexibility and more successful emotion regulation (e.g., Davidson, 2004; Papousek et al., 2013; Papousek & Schulter, 2006; Stewart, Coan, Towers, & Allen, 2014). Papousek et al. (2017) found that reappraisal inventiveness was significantly correlated with frontal EEG alpha asymmetry during reappraisal efforts, indicating that individuals higher on the capacity for reappraisal exhibited more left-lateralized activity in the lateral prefrontal cortex, particularly at frontopolar and ventrolateral frontal positions. Furthermore, this effect was independent from activation during the AUT, suggesting that specific processes were implicated when creativity operated in an affective context.

Major Challenges in the Neuroscientific Study of Creativity and Possible Ways Ahead

Without doubt, research from both the psychometric and the neuroscientific tradition has revealed an exciting body of evidence that facilitates valuable insights into potential neurocognitive mechanisms underlying different facets of creativity. As shown in this chapter, executive functions such as cognitive control, flexibility of thinking, or the inhibition of dominant, prevalent associations have been identified as core characteristics of the creative thinking process across different lines of research. Such executive processing demands are thought to closely interact with spontaneous, imaginative modes of information processing (Beaty et al., 2015, 2016); however, the specific mechanisms of how controlled versus more spontaneous, imaginative thought processes might interact during the creative thinking process, and at which stage of the creativity process they might occur, is still unclear. EEG studies on creative idea generation suggested that alpha power changes during the generation of novel ideas seem to follow a characteristic time course. At the beginning of the idea generation process a general increase of alpha power was found, followed by a significant decrease of alpha during the middle sections of the idea generation period, and finally a re-increase of power prior to responding (Jaarsveld et al., 2015; Schwab, Benedek, Papousek, Weiss, & Fink, 2014). Such time-related effects of alpha activity probably reflect different stages of the creative thinking process. Specifically, in light of the observed U-shaped function of alpha power changes during the creative thinking processes, one would expect cognitive control processes to be particularly apparent at the beginning of the creative thinking process, where the initial retrieval of common and typical ideas to a given problem takes place. This stage might increasingly merge into more spontaneous, imaginative thought processes, until the actual generation of novel and more creative ideas by overriding dominant and typical associations and selecting the most appropriate (i.e., creative) response (characterized by a re-increase of alpha power, cf. Jaarsveld et al., 2015; Schwab et al., 2014). This empirical example nicely illustrates that cognitive control versus more spontaneous modes of thinking might vary across specific stages of the creative thinking processes, a finding that needs to be elaborated in more sophisticated experimental paradigms specifically assessing different stages implicated in creative ideation.

Despite the considerable progress that has been made in creativity research over the last two decades, researchers are still struggling with some tenacious limitations and challenges in this field. EEG and brain-imaging research on creativity would benefit from conceptually and methodologically sound replication studies, and certainly also from more multimethod approaches, characterized by an intertwined treatment of data obtained with different brain imaging methods (e.g., resting state, task-related functional imaging, diffusion tensor imaging, voxel-based morphometry, etc.). Research findings are often based on a single neuronal parameter and surprisingly little is known about how structural and functional characteristics of the brain might interact to support creativity (e.g., how more vs. less gray matter in certain creativity-related brain regions coincides with activity patterns in functional creativity-related brain networks). This applies equally to EEG findings that often seem to live in a parallel universe to the brain-imaging literature. Another important challenge in creativity research, and more generally in the neurosciences, is the need to demonstrate causality in the brain–behavior relationship. This could be realized via longitudinal intervention designs, or with brain stimulation methods such as transcranial alternating current stimulation (tACS), which has revealed some evidence for a functional role of alpha oscillations in creative ideation (Lustenberger et al., 2015).

Among the most important limitations of neuroscientific studies on creativity is the fact that available evidence is largely based on a comparatively simple array of tasks, processes, or paradigms, which rely heavily on divergent thinking demands. Of course, studies are necessary to decompose the complex construct of creativity into quantifiable components and processes that could be assessed with sufficient psychometric quality (Arden, Chavez, Grazioplene, & Jung, 2010; Dietrich & Kanso, 2010), but future research is challenged to investigate neural and cognitive processes in more complex creative behavior, involving more real-life creativity demands. In extending research into the artistic creativity domain, including musical improvisation (Bengtsson, Csíkszentmihályi, & Ullén, 2007; Berkowitz & Ansari, 2010), visual art, or designing book covers (Ellamil, Dobson, Beeman, & Christoff, 2012) or new pens (Kowatari et al., 2009), some studies already have taken important steps in this direction.

As shown in this chapter, another novel step forward could be the study of creativity-related processes in the affective domain, which may entail important practical implications particularly in a therapeutic context. Previous studies have suggested a relationship between happiness (optimism, life satisfaction, personal control, well-being) and creative thinking (e.g., Gasper, 2004; Pannells & Claxton, 2008). However, regardless of whether one considers reappraisal inventiveness as affective creativity or strictly regard it as an ability approach linked with successful emotion regulation strategy, cognitive reappraisal has long been at the core of modern psychotherapeutic approaches. Teaching patients to exercise reappraisal in daily life may improve their handling of stress and negative moods, and can lead to significant attenuations of a prevalent affective disorder (e.g., Garnefski et al., 2002; Gross & John, 2003; Hertel, 2004).

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19 Associative and Controlled Cognition in Divergent Thinking: Theoretical, Experimental, Neuroimaging Evidence, and New Directions

Emmanuelle Volle

The divergent thinking (DT) approach is likely the most frequently used among theory-based approaches of creativity, at least in neuropsychology and neuroimaging studies (Lubart, Mouchiroud, Tordjman, & Zenasni, 2015; Runco, 2010; Runco & Acar, 2012). In contrast to theory-free approaches that aim to study creativity in ecological conditions, theory-based approaches make hypotheses on the cognitive processes or mental operations that allow for the production of something creative (Kozbelt, Beghetto, & Runco 2010; Ward & Kolomyts, 2010). DT explores the ability (or potential) to generate multiple solutions to an open-ended problem that does not have a right or wrong answer and to produce many ideas from a starting point (Guilford, 1950, 1967). DT tasks are idea generation tasks that require thinking away from pre-established ideas and generating various unusual (original) ideas in response to a given stimulus or situation. By examining several characteristics of the products of the task, the DT approach permits the exploration of creative processes. This cognitive approach of DT that will be developed in this chapter seeks to understand the mental representations and operations underlying creative thinking and to relate them to brain functioning.

Classical Divergent Thinking Approach

DT Tasks and Measures

The notion of DT was initiated by Guilford within his structure of intellect model, which describes the processes by which ideas are produced in divergent (searching for multiple possibilities) as opposed to convergent (looking for one correct solution) ways (Guilford, 1950, 1967). Building on this idea, Torrance developed the Torrance Test of Creative Thinking (TTCT), which may be the most employed and validated creativity assessment tool in various populations (Plucker & Makel, 2010; Torrance, 2004; Zeng, Proctor, & Salvendy, 2011). Other batteries including DT tests are also employed (non-exhaustively: Wallach–Kogan creativity tests [Silvia, 2008a]; S-A creativity test [Takeuchi et al., 2012], EPoC [2015]; Runco Creative Assessment Battery [http://creativitytestingservices.com/products/]). The TTCT consists of several verbal and figural activities that elicit divergent search and production. For instance, in some subtests of the TTCT participants are asked to (1) list all the questions they can think of when given a drawing of a scene; (2) expand incomplete figures to make drawings; and (3) generate as many interesting and unusual uses of a common object as possible, such as a cardboard box. This latter task, called the Alternate Uses Task (AUT), is frequently used by itself (using diverse common objects, for instance a brick or a newspaper) to assess creativity, especially in neuroimaging studies. Other DT tests include creative story or sentence generation tasks (the subjects are asked to generate a story or sentence based on a set of words; Bechtereva et al., 2004; Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005; Shah et al., 2013), the Remote Associates Test (RAT: three unrelated cue words are presented, and the subject has to provide a fourth word related to all three cue words; e.g., “rat, cottage, blue” leads to the solution word “cheese”; Mednick, 1962), and conceptual expansion (expand the concept of an object to generate novel and original ideas; Abraham, Pieritz, et al., 2012). The construct and predictive validities of DT tests are high, although the results from previous studies are not always consistent (Kim, 2006; Kim, 2008; Lee & Therriault, 2013; Mendelsohn, 1976; Plucker, Qian, & Schmalensee, 2014; Runco & Acar, 2012; Zeng et al., 2011).

In completing DT tasks, subjects should simultaneously explore different options and form distant and unusual associations between different semantic concepts. The psychometric approach of DT provides a procedure for administering and scoring creativity. Typically, DT tasks are scored for fluency (number of relevant productions), flexibility (number of different categories of productions), originality (number of unusual productions), and elaboration (the degree of enrichment of productions). Snyder, Mitchel, Bossomaier, and Pallier (2004) proposed a “creativity quotient” that takes into account the number of ideas (fluency) and the number of different categories the responses belong to (flexibility). This measure is based on the idea that responses that fall into different categories should be weighted more than those that fall into the same category. Potentially more closely theoretically tied to creativity than fluency, originality is a critical factor of DT but may be more difficult to measure. Originality has been operationalized and scored in a variety of ways, including the use of a panel of raters (Kaufman & Baer, 2012), the raters sometimes being the participants themselves (e.g., Silvia, Nusbaum, & Beaty, 2015). Silvia and colleagues (Silvia, 2008b) have proposed a subjective top-scoring method in which participants are asked to select their most creative ideas, which then are evaluated for creativity. This method elegantly dissociates the number from the quality of ideas and has been found to improve discriminant validity (Benedek, Muhlmann, Jauk, & Neubauer, 2013), although the procedure is also rater-dependent. Alternatively, an old/new scoring method has been recently proposed (Silvia et al., 2015) based on the fact that DT tasks engage the generation of novel and creative ideas (“new”) and the recall of ideas from memory (“old”) (Beaty & Silvia 2012; Benedek, Jauk et al., 2013; Gilhooly, Fioratou, Anthony, & Wynn, 2007; Silvia et al., 2015). This scoring procedure has shown correlations with predictors of creative ability and has the advantage of providing insight into how people generate their ideas. However, subjective scoring methods have the inconvenience of being dependent on the individual preferences and open-mindedness of the raters and to increase inter-rater variability, which may diminish the reliability of the originality scores (Forster & Dunbar, 2009). Objective measures of originality are scoring methods based on the frequency of responses from a normative sample (Torrance, 2004) or from the experimental sample (see Runco & Acar, 2012). This score reflects the rarity or uniqueness of responses of an individual compared with a group. It has been objected that the uniqueness measure reduces the measure of creativity to unique or rare responses specific to a given sample (Dumas & Dunbar, 2014; Nusbaum & Silvia, 2011), may be not sufficiently independent of the fluency and flexibility scores (Benedek, Muhlmann, et al., 2013; Plucker et al., 2014), and may miss explicit criteria for appropriateness (Lee & Therriault, 2013).

Nevertheless, the classical DT approach scoring system has provided the experimental basis for exploring its cerebral correlates. The aforementioned DT measures have been used in neuroimaging studies to explore the brain correlates of creativity, with valuable results informing us on how the brain allows new ideas to emerge, and how interindividual cerebral variability conveys higher creative abilities.

Brain Correlates of DT

Functional imaging studies have attempted to explore the cerebral bases of creativity using various experimental tasks (see Arden, Chavez, Grazioplene, & Jung, 2010; Dietrich & Kanso, 2010; Jung, Mead, Carrasco, & Flores, 2013, for reviews). Most of the tasks that were explored have drawn from theoretical cognitive models such as DT and insight, or explored artistic creativity. Previous reviews based on functional imaging studies of creativity have highlighted the heterogeneity of the results both within a task category (e.g., DT) and between task categories (Arden et al., 2010; Dietrich & Kanso, 2010; but see Fink & Benedek, 2013). However, recent meta-analyses and the growing number of neuroimaging results now offer a clearer picture of the brain correlates of distinct aspects of creative thinking and of DT.

In a recent meta-analysis summarizing the functional imaging findings on creativity (Gonen-Yaacovi et al., 2013), a set of brain regions involved in various creativity tasks was observed. Creativity-related regions were predominantly left-sided and included the caudal part of the lateral prefrontal cortex (PFC), both ventrally and dorsally, the medial and lateral portion of the rostral PFC, the inferior parietal lobule, the lateral temporal region, the inferotemporal cortex, and the cingulate cortex. In this meta-analysis, creativity tasks that involved an explicit request to freely generate an unusual response (as in DT tasks) were analyzed separately. Regions associated with idea generation tasks included a left lateral frontoparietal network, the posterior infero-temporal cortex and cerebellum bilaterally, the left parahippocampal region, the cingulate cortex and the left medial frontal pole. These findings were replicated and extended by another meta-analysis focused on DT tasks specifically (Wu et al., 2015) and by Boccia, Piccardi, Palermo, Nori, and Palmiero (2015). The left frontoparietal network and cingulate cortex appeared to be more strongly recruited by DT tasks than by other creativity tasks.

These results are in agreement with the small number of studies that have examined the cerebral bases of DT in neurological patients (Abraham, Beudt, Ott, & Yves von Cramon, 2012; de Souza et al., 2010; Miller & Tippett, 1996; Rankin et al., 2007; Shamay-Tsoory, Adler, Aharon-Peretz, Perry, & Mayseless, 2011). For instance, de Souza et al. (2010) used brain perfusion to examine patients with frontotemporal dementia, a neurodegenerative disease affecting the frontal and temporal cortices. The results showed a set of brain regions in which perfusion correlated with creativity performance on the TTCT, with several overlaps with functional imaging results in frontal and temporal regions (Figure 19.1).

Neuroimaging research on creativity also attempts to distinguish the brain correlates of distinct cognitive aspects of DT based on the classical scoring method. A pioneering study employing this approach is the one by Chavez-Eakle, Graff-Guerrero, García-Reyna, Vaugier, and Cruz-Fuentes (2007), which demonstrated separate neural correlates for fluency, flexibility, and originality DT scores in healthy subjects. Originality was associated with the rostral PFC, whereas fluency and flexibility were associated with a posterior PFC region. These results converged with those of a lesion study that demonstrated the critical role of the rostral PFC in producing original responses on

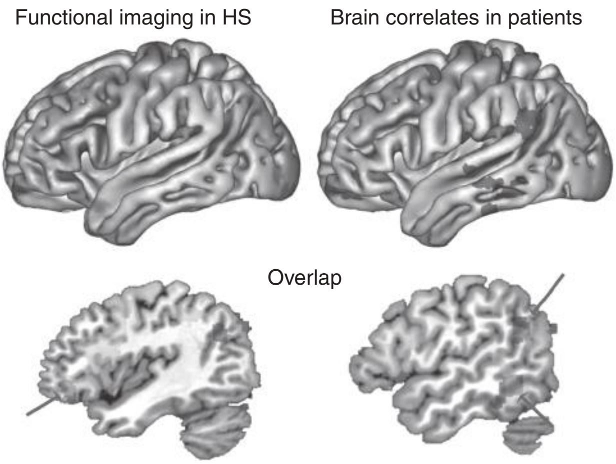

Figure 19.1 Comparative results of functional imaging studies in healthy subjects (meta-analysis from Gonen-Yaacovi et al., 2013) and a patient study in frontotemporal dementia patients (de Souza et al., 2010).

Notes. The significant network involved in creativity according to the functional MRI studies (in yellow) and the map showing the set of brain regions in which perfusion correlated significantly with creativity in frontotemporal dementia patients (in red) are superimposed on a template brain. Results from these two approaches show overlapping in particular in the left inferior frontal gyrus, the left posterior inferior and middle temporal gyri, the left inferior parietal lobule (bottom panel). For a color version of this figure, see the color plate section.

the TTCT (Shamay-Tsoory et al., 2011). Other studies have also found specific correlates of distinct aspects of DT based on different scoring methods (Benedek, Jauk, et al., 2013; Ellamil, Dobson, Beeman, & Christoff, 2011).

Overall, although recent meta-analyses have shown some consistencies in the brain correlates of creativity, a better characterization and measurement of the cognitive processes underlying DT is still needed to better understand how creativity emerges from brain functioning.

Cognitive Processes and their Brain Correlates

Existing theories and recent psychological and neuroimaging studies suggest a set of cognitive processes involved in DT that are distributed into two main axes: the cognitive control and the associative processing axes.

Cognitive Control Processes

Theory. Cognitive theories postulate that several executive functions (such as cognitive flexibility, fluency, selection, planning, working memory, or abstract thinking) are key cognitive processes of creativity (Changeux, Damasio, Singer, & Christen, 2005; Dietrich, 2004; Mendez, 2004; Ward, 2007). The fluency and flexibility aspects of DT tasks may be particularly related to these functions, although the use of similar terms in the executive functions and DT literatures does not necessarily mean identical cognitive processes. Inhibition is also a process that has been put forward. This is because DT tasks, as well as other creativity tasks, require one to break away from obvious responses and common mental sets to generate alternative unusual responses.

Psychology. Several recent studies have examined a range of controlled processes in creativity, such as fluency, cognitive inhibition, flexibility and switching, working memory, and broad retrieval abilities (Benedek, Franz, Heene, & Neubauer, 2012; De Dreu, Nijstad, Baas, Wolsink, & Roskes, 2012; Lee & Therriault, 2013; Nijstad, De Dreu & Rietzschel, 2010; Nusbaum & Silvia, 2011; Silvia, Beaty, & Nusbaum, 2013). Correlational studies have found a significant relation between DT tasks and verbal fluency tasks (Gilhooly et al., 2007; Lee & Therriault, 2013; Nusbaum & Silvia, 2011). However, fluency task performance depends on a complex set of cognitive processes, including self-initiation of action, semantic retrieval, switching between categories of responses, inhibition, updating and monitoring the content of working memory (Perret, 1974; Troyer, Moscovitch, & Winocur, 1997; Unsworth, Spillers, & Brewer, 2011). Thus the classical use of fluency tasks may not be sufficiently elementary to precisely identify the processes involved in DT. Higher capacities of cognitive flexibility or switching between categories of ideas have also been associated with better DT abilities (De Dreu et al., 2012; Nusbaum & Silvia, 2011). Nijstad, De Dreu and colleagues highlighted the importance of both flexibility (through switching abilities) and persistence (though working memory and focused attention) in their dual pathway to creativity model (Nijstad, De Dreu & Rietzschel, 2010). In this model, working memory influences creativity (both fluency and originality) by improving persistence (ability to focus and spend time on task, and take the most of a given category of ideas), whereas mental flexibility allows for switching between different categories of ideas.

Inhibition of prepotent responses is another cognitive process that has been associated with DT abilities (Benedek, Franz, et al., 2012; Edl, Benedek, Papousek, Weiss, & Fink, 2014). Cognitive inhibition has also been shown to be important in overcoming the mental fixation on prototypical responses that prevents the production of original responses (Cassotti, Agogué, Camarda, Houdé, & Borst, 2016), and may be a key process for solving the Remote Associates Test (RAT) (Gupta, Jang, Mednick, & Huber, 2012). However, a recent study that manipulated inhibition to explore a more causal link between inhibition processes and creativity (Radel, Davranche, Fournier, & Dietrich, 2015) obtained contradictory results. In this study, the inhibition efficiency of the participants was impaired by exhaustion through the intensive practice of nonverbal nonsemantic inhibition tasks (the Simon or Eriksen Flanker tasks). Altering inhibition resources led to an improvement in the number and originality of ideas in an AUT task, suggesting that inhibition is negatively related to DT. Impaired inhibition leading to paradoxical functional facilitation of artistic creative abilities has been described in neurological patients with frontal damage (De Souza et al., 2014; Schott, 2012 for reviews). A few noninvasive brain stimulation studies are consistent with this view, by demonstrating a facilitative effect of cathodal (inhibitory) transcranial direct current stimulation of the left PFC on performance in a DT task (Chrysikou et al., 2013; Mayseless & Shamay-Tsoory, 2015). However, other brain stimulation studies have reported converse results (Cerruti & Schlaug, 2009; Colombo, Bartesaghi, Simonelli, & Antonietti, 2015; Zmigrod, Zmigrod, & Hommel, 2015). The paradoxical link between inhibition and creativity may relate to the heterogeneity of the construct of "inhibition," i.e., distinct types of inhibition exist under the same term. There are in fact different conceptions about how inhibition is related to creativity. Creativity has been associated with lower inhibitory control (Radel et al., 2015), social or behavioral disinhibition (de Souza et al., 2010), higher abilities inhibiting prepotent responses (Edl et al., 2014), a decrease in latent inhibition (Carson, Peterson, & Higgins, 2003), or an adaptive engagement of inhibition (Dorfman, Martindale, Gassimova, & Vartanian, 2008; Vartanian, 2009). Gaining a better understanding of how these distinct types of inhibition are related to creative thinking and creative abilities is an important avenue for future research.

Neuroimaging. The importance of executive or controlled functions in creativity is also supported by studies demonstrating the involvement and/or the critical role of brain regions supporting executive and cognitive control. In functional imaging, the caudal and rostral lateral PFC, posterior parietal and cingulate cortex are some of the most reported regions associated with DT tasks (Gonen-Yaacovi et al., 2013). Studies that used other methods in creativity research, such as voxel-based morphometry, diffusion-weighted imaging, or cerebral blood flow (Bechtereva et al., 2004; Chavez-Eakle et al., 2007; Jung et al., 2013; Jung, Grazioplene, Caprihan, Chavez, & Haier, 2010; Jung, Segall, et al., 2010; Takeuchi et al., 2010a, 2010b) have also shown a link between creative performance and the lateral PFC or its connections. These regions are largely associated with executive functions, and are part of the "cognitive control," "frontoparietal," or "multi-demand" networks that involve PFC and parietal regions (Cole et al., 2013; Fedorenko, Duncan, & Kanwisher, 2013; Jung & Haier, 2007; Power & Peterson, 2013; Seeley et al., 2007; Smith et al., 2009; Sridharan, Levitin, & Menon, 2008; Vincent, Kahn, Snyder, Raichle, & Buckner, 2008; Woolgar et al., 2010). Several control-related networks have been described, but the precise role of each network and of the constitutive regions have not been elucidated (Power & Petersen, 2013). Control-related networks are recruited by diverse cognitive functions, including working memory, controlled retrieval in episodic or semantic memory, multitasking and prospective memory, relational reasoning and abstract thinking, cognitive inhibition and flexibility, and working memory (Badre, 2008; Burgess, Gonen-Yaacovi, & Volle, 2011; Duncan, 2010; Friedman & Miyake, 2017; Hobeika, Diard-Detoeuf, Garcin, Levy, & Volle, 2016; Jung & Haier, 2007, 2013; Koechlin, Ody, & Kouneiher, 2003; Konishi et al., 2010; Urbanski et al., 2016; Volle et al., 2008; Woolgar et al., 2010). A brain system specialized in semantic control and distinct from the multidemand network has also been described, encompassing the left inferior frontal gyrus and posterior middle temporal gyrus (Davey et al., 2016; Noonan et al., 2013). The left inferior frontal gyrus is involved in controlled retrieval and selection in semantic memory (Badre et al., 2005; Thompson-Schill & Botvinick, 2006).

More critically, patient studies have demonstrated that creative performance in DT tasks depends on the integrity of the PFC. Studies with frontal variant frontotemporal dementia patients have shown the impairment of all DT scores in these patients, correlated with executive dysfunctions in flexibility and fluency (de Souza et al., 2010; Rankin et al., 2007). To complement findings obtained for patients who have diffuse brain damage, studies on patients with focal lesions allow for more precise structure-function correlations (Volle, Levy, & Burgess, 2013). The few lesion studies that have explored creative ability confirm the critical role of the PFC. Shamay-Tsoory et al. (2011) analyzed 40 patients with focal frontal or parietal damage. The results revealed that damage to the rostral PFC resulted in lower DT abilities, and lower originality scores. Abraham and colleagues (Abraham, Beudt, et al., 2012) conducted a study with 74 patients with focal lesions affecting the lateral PFC, basal ganglia and temporo-parietal regions. The results indicated that patients with prefrontal or temporo-parietal damage had lower originality and fluency scores in DT tasks than other groups. However, patients with anterior but not posterior lateral PFC damage appeared to be better at overcoming the constraints of examples provided to them.

Overall patient and functional imaging studies indicate that the cognitive control regions, especially the PFC, are important for creativity, but a few findings challenge this idea by showing better performance after the alteration of inhibitory control mechanisms (Radel et al., 2015). The PFC is a large and heterogeneous region that is connected to different brain systems (Catani & Schotten, 2012; Vincent et al., 2008). It is thus likely that different frontal subregions are involved in distinct frontal networks and play distinct roles in DT. For instance, among the other processes involved in DT, the associative processes appear to rely on different brain networks than controlled processes, involving distinct frontal subregions.

Associative Processes

Theory. Associative thinking describes the process by which a given stimulus or thought automatically activates another stimulus or thought because they are associated in semantic memory. Unlike executive processes, associative processing is uncontrolled and spontaneous. The associative approach of creativity, based on the Collin and Loftus (1975) model, emphasizes the free activation of ideas or words by spreading from one to another, from the strongly associated ones to weaker associates. Thus, it is the preexisting association between words or concepts in semantic memory that determines their coactivation, with longer times being necessary for farther semantic distances. Mednick's theory has been the most influential in promoting associative abilities in creative thinking (Mednick, 1962; Mednick, Mednick, & Jung, 1964; Mednick, Mednick, & Mednick, 1964). According to this theory, creative individuals have a more flexible organization of associations between words or concepts in their semantic memory, characterized by flat associative hierarchies. These associative properties allow them to activate remote ideas and form associative elements into novel combinations. More flexible associations may explain why creative people appear to have more flexible barriers between semantic categories and to include more stimuli as belonging to a given category (i.e., overinclusiveness; Eysenck, 1993). For the same reason, creative people may be more capable of seeing similarities or analogies between dissimilar concepts or situations (Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010; Jones & Estes, 2015).

Psychology. Recently the role of associative thinking in DT and, more broadly, in creativity has been experimentally revisited. Using a free word association task, Merten and Fischer (1999) showed that more creative people (involved in the arts) provide more uncommon associative responses when uncommonness is asked for by the task. Recent studies have shown that highly creative persons give lower estimates of the remoteness of unrelated word pairs compared with less creative persons (Rossmann & Fink, 2010) and are faster in judging the relatedness of concepts (Vartanian, Martindale, & Matthews, 2009). These studies indicate that remote elements of knowledge/semantics may be highly interconnected in highly creative persons. Another set of recent studies used various fluency tasks as a measure of associative abilities and demonstrated their good predictive validity with respect to DT and creative abilities (Beaty & Silvia, 2014; Benedek, Könen, & Neubauer, 2012; Lee & Therriault, 2013). Association fluency tasks, for instance, consist of making free continuous associations with a cue word, listing synonyms, and generating lists of unrelated words. Beaty and Silvia (2014) showed that associational fluency predicted the creative quality (rather than the quantity) of DT responses in an AUT task, and Benedek and Neubauer (2013) found that higher DT abilities were associated with greater associative uncommonness in associative fluency. These findings indicate that associative abilities explored by associative fluency tasks explain a large portion of the variance of DT abilities. However, associative fluency tasks are multicomponent tasks that involve controlled processes in addition to associative processes (Perret, 1974; Silvia et al., 2013; Troyer, Moscovitch, Winocur, Alexander, & Stuss, 1998), and may allow only an impure exploration of the role of automatic associative processing in DT.

A more direct demonstration of the role of automatic associative processes in creativity is reported in priming studies (Faust & Lavidor, 2003). Priming may be a purer measure of associative processing by reflecting spontaneous and implicit spreading of activation. Gruszka and Neçka (2002) showed that creative people differed from less creative people in readiness to accept word associations and susceptibility to priming. Another study (Radel et al., 2015) showed that decreasing inhibitory control resources improved DT and increased the priming effect for weakly related primes, indicating that automatic associative processing is more efficient without control inhibition. Overall, these findings suggest that associative thinking represents a valid elementary cognitive process underlying creativity.

The associative approach and more specifically automatic associative spreading may have implications for the incubation effect (Sio & Ormerod, 2009; Yaniv & Meyer, 1987). An incubation phase refers to a period of task-unrelated activity after having attempted to solve a problem and before returning to it. The incubation effect refers to increased creative performance as a result of this incubation period. Studies on DT have showed a positive incubation effect on originality and on the constraints of examples, and some authors have proposed the role of unconscious thought in the incubation effect (Dijksterhuis & Meurs, 2006; Ritter & Dijksterhuis, 2014; Ritter, van Baaren, & Dijksterhuis, 2012; Zhong, Dijksterhuis, & Galinsky, 2008). Altogether these findings indicate a role for automatic associative thinking in original idea generation.

Neuroimaging. Although a series of functional imaging and patient studies have focused on the importance of the PFC and parieto-temporal regions in creative DT, recent neuroimaging studies based on interindividual variability, using brain morphometry approaches (Fink et al., 2013; Jauk, Neubauer, Dunst, Fink, & Benedek, 2015; Jung et al., 2013, 2015; Jung, Grazioplene, et al., 2010; Jung, Segall, et al., 2010; Kühn et al., 2014; Takeuchi et al., 2010a; Zhu, Zhang, & Qiu, 2013) or exploring functional connectivity (Beaty et al., 2014; Chen et al., 2015; Cousijn, Zanolie, Munsters, Kleibeuker, & Crone, 2014; Takeuchi et al., 2011, 2012; Wei et al., 2014) seem to converge on the role of the default mode network (DMN) in DT.

The DMN is a set of functionally connected brain regions in which activity is lower during tasks requiring focal attention, effort, or control and higher during rest (Buckner, Andrews-Hanna, & Schacter, 2008; Greicius, Supekar, Menon, & Dougherty, 2009; Raichle, 2015; Raichle et al., 2001). The DMN includes the medial rostral PFC, posterior cingulate and retrosplenial cortex, the precuneus, the medial temporal region (hippocampus and parahippocampal gyrus), and the temporo-parietal junction. The DMN can be distinguished from the set of regions functionally connected to the lateral PFC (Gilbert, Gonen-Yaacovi, Benoit, Volle, & Burgess, 2010) involved in cognitive control.

Existing findings indicate the involvement of this network in several cognitive functions: mentalizing (Frith & Frith, 2006), self-reference (Gusnard, Akbudak, Shulman, & Raichle, 2001; Northoff, 2011), future thinking and imagination (Demblon, Bahri, & D'Argembeau, 2016; Schacter, Addis, & Buckner, 2007), memory (Kim, 2016) and mind-wandering or daydreaming (Andrews-Hanna, Reidler, Huang, & Buckner, 2010; Andrews-Hanna, Smallwood, & Spreng, 2014; Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016; Fox, Spreng, Ellamil, Andrews-Hanna, & Christoff, 2015; Mason et al., 2007). Also called undirected/task-unrelated thoughts, mind-wandering refers to the stream of spontaneous thoughts, emotions, and memories that occur in everyday life and activities (Andrews-Hanna et al., 2010, 2014; Christoff et al., 2016; Fox et al., 2015; Singer, 1993; Smallwood & Schooler, 2015), and is thought to play a role in creative incubation (Baird et al., 2012). Recent evidence suggests that the DMN plays a role in semantic and episodic memory retrieval (Binder, Desai, Graves, & Conant, 2009; Buckner et al., 2008; Catani, Dell'Acqua, & Thiebaut de Schotten, 2013; Eustache, Viard, & Desgranges, 2016; Kim, 2010, 2016; McDonald, Crosson, Valenstein, & Bowers, 2001; Shallice et al., 1994; Shapira-Lichter, Oren, Jacob, Gruberger, & Hendler, 2013; Wirth et al., 2011). Some DMN regions may be shared between memory types (e.g., posterior cingulate), whereas others are specialized toward semantic memory (e.g., retrosplenial cortex and rostral PFC) or episodic memory (e.g., precuneus and posterior parietal cortex) (Shapira-Lichter et al., 2013). In addition, other semantic memory regions along the anterior and posterior lateral or inferior temporal cortex have been associated with creativity (Abraham, 2014; Gonen-Yaacovi et al., 2013).

The vast majority of the processes associated with the DMN depend on the activation of experience-based associations (Bar, Aminoff, Mason, & Fenske, 2007). For instance, episodic and semantic memory recalls elements that have been previously associated with a context or with another element, suggesting the role of an associative activation of semantic and episodic memory in DT. Mind-wandering may be described as thoughts that are recalled by a chain of associations (Andrews-Hanna et al., 2010, 2014; Fox et al., 2015; Mason et al., 2007). In other words, the DMN may support the associative processing that guides the progression of thought in a spontaneous mode of thinking, and favors creative thinking. The role of the DMN is likely not restricted to verbal associations as it may also play a role in spontaneous thinking in other modalities that also are important for DT. Indeed, Bar and his team described the "contextual association network" that supports the contextual associations facilitating the visual recognition of scenes and objects (Kveraga et al., 2011). This network largely overlaps with the DMN in the medial prefrontal, retrosplenial, and parahippocampal regions. Thus, the role of the DMN in creativity may be related to a mode of thoughts activation rather than to a domain-dependent cognitive process.

Overall, the dominant hypothesis recently strengthened by neuroimaging findings is that creativity involves both controlled and associative processes. However, the nature of these processes remains ill-defined. Although the classical scoring system has made and still makes a massive contribution to the assessment of creativity, the classical DT aspects of ideational fluency, originality and flexibility may not be sufficiently precise to distinguish between the different cognitive processes involved in creativity processes. The more fine-grained and objective measures of creativity that have been recently developed may be useful in clarifying these processes and their roles in different DT aspects, as presented in the following section.

Recent Advances in DT Measures

Semantic Distance as a Measure of Originality. An essential advancement in the evaluation of DT is the development of objective measures based on semantic associative distance (Acar & Runco, 2014; Beketayev & Runco, 2016). Semantic distance measures the probability (or the frequency) with which one concept or word is associated with another one, and reflects how ideas or concepts are usually associated together in individuals. The more semantically distant a generated idea is from a given starting point, the more original it is. Although the concept of rarity of ideas defines originality in DT theories, surprisingly, the distance between ideas is not taken into account in typical DT scoring. Because associative distance estimates the pre-established association between ideas, originality measures derived from this distance are more objective than classical measures, are not dependent on a given sample or on the subjectivity of the raters, and are more comparable across samples or studies.

Several methods have been used to measure the associative distance, either based on word co-occurrence or word free association (De

Deyne, Kenett, Anaki, Faust, & Navarro, 2016; De Deyne, Navarro, & Storms, 2013). The most frequently used measure of semantic distance in the field of creativity is likely the one based on Latent Semantic Analysis (LSA) (Beaty & Silvia, 2014; Dumas & Dunbar, 2014; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2012; Jones & Estes, 2015; Landauer, 1997; Prabhakaran, Green, & Gray, 2013). LSA is based on a large set of text corpuses and estimates the similarity (or distance) between words by examining word co-occurrences in texts. In creativity studies, this method has been used to manipulate the semantic distance in the task material (Green et al., 2012) or to measure the originality of individual responses (Beaty & Silvia, 2014; Green, Cohen, Raab, Yedibalian, & Gray, 2015; Prabhakaran et al., 2013). Other semantic databases have also been used to measure semantic distance in DT tasks. For instance, Acar and Runco (2014) derived the semantic distance between concepts from several word networks including Wordnet, IdeaFisher, and the Word Association Network and showed the correct validity of these measures for DT assessment (see also Beketayev & Runco, 2016).

An alternative measure of semantic distance that may be closer to creative idea generation is based on existing word association norms that quantify the semantic associations between words in a given language (Ferrand & Alario, 1998; Nelson, Dyrdal, & Goodmon, 2005) (http://dictaverf.nsu.ru/dict). These associative norms are computed from free word association tasks consisting of producing the first word that spontaneously comes to mind after reading a cue word. The associative strength (reflecting semantic distance) between words X and Y is based on the proportion of subjects who give the word Y in response to the word X. An important aspect of this task is that word generation is free and spontaneous with no other constraint than the cue word. For this reason, free associations tasks are thought to reflect the organization of semantic associations and are typically used in priming studies (Faust & Lavidor, 2003; Gruszka & Necka, 2002). Unlike LSA, free associative norms do not depend on the choice of a text corpus or grammar use, and take into account nonlinguistic processes that contribute to word meaning in the lexicon (De Deyne et al., 2016; Maki & Buchanan, 2008; Steyvers, Shiffrin, & Nelson, 2004). In addition, free associative norms are based on empirical data reflecting a process of word generation, and in this sense may be more comparable to creativity tasks than LSA-based measures are.

Although theoretically the free associative norms appear to be a better measure of associative thinking, they have rarely been used to measure the originality of responses in DT tasks. A recent voxel-based morphometry (VBM) study by our team (Bendetowicz, Urbanski, Aichelburg, Levy, & Volle, 2017) used associative norms to manipulate semantic distance in creativity tasks. We adapted the RAT by varying the semantic distance between the three cue words and the solution word. In healthy participants, there was a significant correlation between accuracy and the mean semantic distance between cue words and the solution word. The ability to solve more remote trials was correlated with DT abilities assessed by the short version of the Torrance test, and with creative achievement. A VBM analysis performed in this sample showed that the ability to combine more distant words was associated with structural variation in the left rostral PFC.

Altogether, these studies illustrate that the use of semantic distance helps improve creativity assessment by controlling the remoteness of ideas to be combined in task material or by improving originality measurements of the productions. Semantic distance may also be used to explore the associative hypothesis of creativity by allowing the estimation of association constraints in individuals. However, to fully test Mednick's hypothesis, and explore whether more creative subjects have a less-constrained organization of semantic associations, the whole semantic organization needs to be examined. Recent automated and computerized semantic network approaches using computational methods may better address this issue (Kenett, Kenett, Ben-Jacob, & Faust, 2011; Maki & Buchanan, 2008; Marupaka, Iyer, & Minai, 2012; Morais, Olsson, & Schooler, 2013; Steyvers et al., 2004), as highlighted by a few pioneering studies.

Semantic Network Approach. By considering not only pairs of words, but a large set of interrelated words as well, the semantic network approach allows for the study of individual or group semantic organization. The connective properties reflecting the organization of semantic networks can be examined using graphs or other computational tools, and linked with creative abilities.

In semantic networks, concepts or words are nodes that are connected to each other by edges. Based on the Collins and Loftus proposal, when a concept is activated (for instance, by presenting a word), its activation spreads to associated concepts through these links, from the closest associates to the more distant ones (Collin & Loftus 1975). According to several authors (De Deyne et al., 2016; Goñi et al., 2011), the most appropriate approach for exploring the link between the organization and activation of semantic knowledge and creativity is the use of free word association tasks to construct large-scale semantic networks. Semantic networks can be modeled and analyzed by using graph theoretic approaches, which allow for the extraction of various metrics and indices quantifying the topology of the connections between nodes (Baronchelli, Ferrer-i-Cancho, Pastor-Satorras, Chater, & Christiansen, 2013; Borge-Holthoefer & Arenas, 2010; De Vico Fallani, Richiardi, Chavez, & Achard, 2014; Kenett et al., 2011).

Few studies have used the graph approach in the field of creative thinking (Durso, Rea, & Dayton, 1994; Kenett, Anaki, & Faust, 2014; Kenett & Austerweil, 2016; Kenett, Beaty, Silvia, Anaki, & Faust, 2016; Schilling, 2005). A series of experiments by Kenett and colleagues provided empirical network support for Mednick's theory (Kenett & Austerweil, 2016; Kenett et al., 2014). These studies showed that the semantic network of persons with lower creative abilities is more rigid and less connected than that of highly creative persons, and that the properties of semantic networks can be differently affected by pathologies, with a continuum between chaos (disorganized) and rigid (too organized) semantic networks, and with implications in creative abilities (Faust & Kenett, 2014; Kenett, Gold, & Faust, 2016).

Other network approaches have been used to automatically analyze the productions of participants in fluency tasks (Goñi et al., 2010, 2011; Kenett & Austerweil, 2016; Kenett, Gold, et al., 2016; Lerner, Ogrocki, & Thomas, 2009) and in DT tasks (Bossomaier, Harré, Knittel, & Snyder, 2009; Beketayev & Runco, 2016). Bossomaier and colleagues (2009) used Wordnet to calculate commonalities between verbal responses in DT tasks and automatically compute a creativity quotient combining flexibility and fluency scores. Previous research on verbal fluency tasks has shown that successively produced words are semantically related and belong to the same subcategory, with occasional jumps to another semantic subcategory. This pattern of production has led to the hypothesis that word search in fluency tasks involves two processes: clustering (the search of words within the same semantic field or subcategory) and switching (flexible jump to another subcategory) (Troyer, 2000; Troyer et al., 1997). Troyer and colleagues showed that clustering relies on automatic semantic processing supported by the temporal lobe, whereas switching relies on strategic and controlled processes (flexibility, shifting) supported by the prefrontal cortex (Hirshorn & Thompson-Schill, 2006; Troyer et al., 1998). A network approach that allows for automatically analyzing clustering and switching may be particularly powerful when applied to DT tasks in allowing for a better understanding of the strategies and processes (associative and controlled) employed by participants. The network approach may also help explore the associative versus controlled creativity processing (Kenett & Austerweil, 2016; Kenett, Beaty, et al., 2016). A few studies based on semantic spaces or semantic networks have also attempted to clarify the possible semantic search mechanisms involved in RAT performance (Davelaar, 2015; Gupta et al., 2012; Smith, Huber, & Vul, 2013). Finally, it is important to note that the network approach may also be useful to better understand the "aha!" phenomenon explored in the insight problem-solving approach of creativity (Durso et al., 1994; Schilling, 2005).

Overall, new creativity measures based on associative norms and on semantic networks properties provide a useful assessment of DT and, more broadly, of creative capacity. The use of semantic distance and/or network measures is useful in controlling the requirements of remote thinking in creativity tasks (Bendetowicz et al., 2017; Green et al., 2012; Gruszka & Necka, 2002; Radel et al., 2015), in automatically and objectively measuring the originality of ideas (Acar & Runco, 2014; Dumas & Dunbar, 2014; Forster & Dunbar, 2009; Prabhakaran et al., 2013), in providing automatic metrics reflecting cognitive strategies (Bossomaier et al., 2009; Gupta et al., 2012; Kenett & Austerweil, 2016; Smith et al., 2013), and by allowing for a deeper exploration of the associative/controlled processes in creativity (Kenett et al., 2014; Kenett, Gold, et al., 2016). Such measures of creativity have the advantage of avoiding the pitfalls of subjective (e.g., influenced by creativity-unrelated factors and the open-mindedness of the judges) as well as psychometric (e.g., normative values) assessments. The computational approach based on semantic networks constitutes a real advance in understanding interindividual abilities in creative potential, and is a promising tool for identifying the processes involved in DT tasks, especially regarding associative and controlled processing.

Balance Between Associative and Controlled Cognition for Creativity and Implications

Scientific Implications: Toward a Two-processing-mode Hypothesis

Based on the existing literature reviewed above, it can be hypothesized that an original (distant) idea can result from two possible processing modes. Associative processing that relies on the spontaneous spreading of activation from close to distant associates can lead to original ideas by activating unusual associations, particularly in people with more flexible semantic networks. In turn, controlled processing that relies on cognitive processes that voluntarily constrain the stream of thought according to the goal can lead to the activation of original ideas by voluntary strategies or rules, orientation of attention, retrieval, mental manipulation in working memory, and response selection. This assumption may be met under the concept of a "distance-dependent representation activation mode" hypothesis (D-DRAM hypothesis; Figure 19.2). This hypothesis builds on previous theories and results suggesting a differentiation between two processing modes – spontaneous vs. deliberate – for creative cognition (Beaty, Benedek, Silvia, & Schacter, 2016; Dietrich, 2004; Gabora, 2010; Jung, 2014; Kenett & Austerweil, 2016; Kenett et al., 2014; Mok, 2014; Sowden, Pringle, & Gabora, 2015; Wiggins, & Bhattacharya, 2014; Zabelina, & Andrews-Hanna, 2016). However, in the D-DRAM hypothesis, the controlled mode is not only involved in the evaluation, elaboration, or selection of generated ideas to meet the constraints of the task (e.g., appropriateness), but it is also involved in generating original ideas using specific processes to constrain thinking, for instance, those underlying memory search strategies including focus on specific features or contexts in DT tasks or inhibition of common ideas. The relative involvement of these processing modes likely depends on the requirement of the tasks and of the phase of the creative process

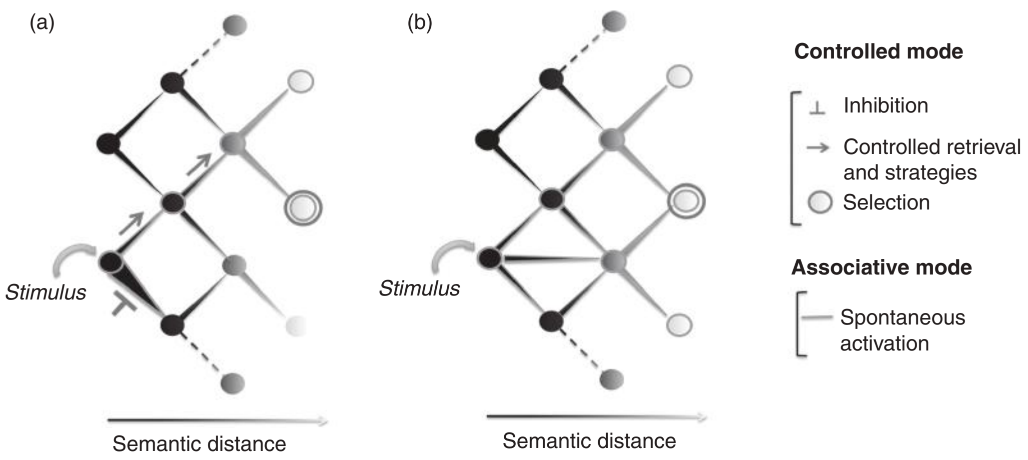

Figure 19.2 Schematic representation of spontaneous and controlled processing for idea generation.

Notes. Circles schematically represent ideas and arrows the link between them in a theoretical semantic network. Strongly related ideas are represented by a larger arrow.

(A) Starting from a given stimulus, a spontaneous activation of associated elements spreads by association from the closest associates to more distant ones (blue). The activation of a distant (original) idea combines spontaneous associative activation and controlled processes that enable the inhibition of steeply associated ideas, the orientation of semantic retrieval, and the selection of an element. Individuals with higher efficiency of the controlled mode (higher inhibition, selection, and controlled retrieval) may generate more distant ideas in ideation tasks, allowing higher creative abilities.

(B) Individuals with more flexible and densely connected semantic networks (or placed in situations favoring associative processing) may be able to spontaneously activate distant ideas. For a color version of this figure, see the color plate section.

(Allen & Thomas, 2011; Gilhooly et al., 2007; Silvia et al., 2015). Moreover, in addition to the two processing modes, the D-DRAM hypothesis relies on the notion of semantic distance that provides objective measures of originality and puts forward the semantic network approach and new neuro-computational tools that may be powerful in distinguishing associative and controlled modes. The balance and interaction between associative and controlled processing may be essential, but remains to be clarified and may depend on individual variability in semantic network properties, individual preferences or cognitive styles, personality, or emotional states.

The D-DRAM hypothesis is directly linked with classical dual-process theories that generally oppose an intuitive-heuristic system (typically effortless, automatic, rapid, global, or holistic) to a deliberate analytic system (slow, controlled, serial, effortful) (Allen & Thomas, 2011; Cassotti et al., 2016; De Neys, 2006; Evans, 2003, 2008; Evans & Stanovich, 2013; Kahneman, 2012; Sowden et al., 2015; Varga & Hamburger, 2014). The D-DRAM view may also be related to attention theories of creativity, based on the suggestion that associative thinking results from a defocused attentional state, whereas controlled analytic thinking requires focused attention (Dorfman et al., 2008; Gabora, 2010; Martindale & Mines, 1975; Mendelsohn, 1976; Vartanian, 2009; Vartanian, Martindale, & Kwiatkowski, 2007). The interaction of this view with the Blind Variation and Selective Retention theory remains to be clarified (Dietrich, 2015; Gabora & Kauffman, 2015; Jung, 2014; Simonton, 2015).

Finally, the D-DRAM hypothesis also relies on recent neuroimaging studies demonstrating the involvement of the DMN, semantic networks, control-related networks and attention networks in creativity tasks (Beaty et al., 2014, 2016; Beaty, Benedek, Kaufman, & Silvia, 2015; Benedek et al., 2016; Fink & Benedek, 2013; Jung et al., 2013; Mayseless, & Shamay-Tsoory, 2014; Takeuchi et al., 2012; Wei et al., 2012; Zabelina & Andrews-Hanna, 2016), and that control-related and default networks interact during creative performance (Beaty et al., 2015, 2016; Takeuchi et al., 2012). The coupling of the DMN and frontoparietal control networks has been shown to be important for semantic retrieval (Davey et al., 2016) and for other elaborate cognitive functions (Chen et al., 2013; Christoff et al., 2009; Spreng et al., 2014; Spreng, Stevens, Chamberlain, Gilmore, & Schacter, 2010; Vincent et al., 2008). This coupling may be mediated in some cases by the salience network (Beaty et al., 2016; Goulden et al., 2014; Jung et al., 2013; Sridharan et al., 2008) or the semantic control network (Davey et al., 2016). These data, combined with the D-DRAM hypothesis, suggest that creative thinking involves the interaction between distinct sets of networks, including control-related networks (lateral frontoparietal/cingulate), which underlie the control of thought, and the DMN, which underlies the spontaneous stream of thoughts. Recent findings have also shown that the rostral PFC, the posterior cingulate/precuneus, and the posterior temporal region may be important connective nodes between these systems with regard to creativity (Chen et al., 2014, 2015; Davey et al., 2016; Fink et al., 2013; Jauk et al., 2015; Jung et al., 2013; Kühn et al., 2014; Takeuchi et al., 2010a). These findings are in line with recent results obtained using the morphometry approach combined with white matter tractography (Bendetowicz et al., 2017), which indicated that the left rostrolateral prefrontal region is an essential relay station in the networks supporting creative combination of ideas. Overall, the D-DRAM hypothesis of combined controlled and spontaneous cognition for creative thinking takes into account existing theoretical, psychological, and neuroimaging findings that suggest that the connectivity within and between several networks enables both original and appropriate ideas to emerge.

Impact on Future Research

The D-DRAM hypothesis combined with neurocomputational approaches to creativity based on semantic networks is a powerful avenue for gaining a better understanding of creative neurocognitive mechanisms. Although this approach may not account for all the dimensions of creativity, it has the potential to make several important contributions. First, studies using semantic networks indicate that this approach can be useful in exploring creativity in different frameworks, including DT, insight, and artistic performance, and may be able to estimate both associative and controlled mechanisms thanks to several methodological graph tools. This scheme can constitute a theoretical and experimental basis for exploring the impact of other influential factors of creativity, such as the impact of emotions, attentional focus, task instructions, motivation, context of cooperation or competition, personality and cognitive styles. For instance, positive and negative emotions may have different or even opposite effects on the associative and controlled modes of creative thinking, which could explain the discrepancies between the results reporting the impact of emotional states on different creativity tasks (Chermahini & Hommel, 2012; Lubart et al., 2015). Understanding whether the task instruction effect reported in several recent studies (Forthmann et al., 2016; Green, Cohen, Raab, Yedibalian, & Gray, 2015; Howard-Jones et al., 2005; Zabelina & Robinson, 2010) operates on associative or executive thinking may also have important implications when searching for bases for creativity training programs. Importantly, examining how individual abilities vary in the relative use of associative and controlled modes may also inform us on the bases of creative potential and on the possible ways to improve it. Variability in individual creative capacities can be explored in terms of variable individual properties of associative/controlled processing, of individual preferences for a thinking mode, or of switching abilities between modes. Altogether, these studies would have both important scientific and societal implications.

Finally, the D-DRAM hypothesis may provide an interesting framework for investigating how some neurological and psychiatric pathologies impact creative abilities (De Souza et al., 2014; Jung, 2014). New findings suggesting the interaction between separate brain systems for associative and controlled modes of creative thinking provide important hypotheses to be tested in future patient studies or in future direct brain stimulation studies (Chen et al., 2013). It can be postulated that the DT process can be impaired by two potential interfering mechanisms: damage to the DMN may alter the associative mode of thinking, whereas damage to control-related networks would affect the controlled mode of thinking. Patients with different brain lesions (for instance, patients with a rostrolateral versus a ventromedial lesion in the frontal cortex) would be expected to show distinct profiles of performance. How each alteration would affect the whole DT performance and how one system can compensate for the other in the ability to produce creative ideas remain open questions. The results obtained in exploring these questions may help better explain the paradoxical observation of increased artistic creativity in patients (De Souza et al., 2014; Schott, 2012).

Conclusions

In an integrative attempt, existing theories, recent neurocognitive findings, and new measures of DT can be synthesized as the D-DRAM hypothesis as follows: to be creative, one needs to break from common ideas and make original (and appropriate) associations between concepts. There are two processing modes that interact to generate an original (remote) idea. First, there is an associative mode that activates remote ideas by the spontaneous spreading of semantic activation from close to distant associates, supported by the DMN. Semantic networks built on specific measures of semantic distance can be used as a simplified model of the organization of associations between concepts. Second, there is a controlled mode that relies on several cognitive processes that allow for the voluntary activation, elaboration, and selection of remote ideas. This mode is supported by control-related networks. These modes interact during creative thinking. Several regions or networks have been proposed to mediate this interaction.

Combined with this approach, recent neurocomputational methods based on semantic networks and drawing on specific measures of semantic distance represent an important advance in creativity research in several ways. First, semantic distance provides an objective measure of usual and unusual associations, i.e., of the originality of the productions in DT tasks. Second, semantic networks based on spontaneous associative productions can inform us on the organization of semantic concepts that contribute to better creativity. Third, semantic networks based on productions in DT tasks can be useful in identifying the associative versus controlled mode of activation used during these tasks. The methodological challenge is to determine the types of measures of semantic distance that are most relevant to each of these aims with regard to creativity. The scientific challenge faced by this field will be to better understand the nature and the dynamics of the interaction (or the shifting) between associative and controlled modes of creative thinking, and of their underlying brain networks. Altogether, in the field of cognitive neurosciences of creativity, these theoretical and methodological aspects provide interesting directions for future research and applications.

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Part VI

Reasoning and Intelligence

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Creativity in the Distance: The Neurocognition of Semantically Distant Relational Thinking and Reasoning

Adam Green

Creativity and intelligence are not the same thing, but intelligent solutions often require creative insights. Reasoning is more commonly associated with intelligence than creativity, but reasoning can be measurably creative when it reveals connections between ideas or experiences that seem different on the surface. This kind of creative relational reasoning, especially in the form of analogy, provides valuable insights that drive advances in science and industry (Holyoak & Thagard, 1995). While intelligence and creativity have both been primarily studied as static traits that vary between individuals, growing evidence indicates that creative relational reasoning is also subject to variations in state creativity within an individual across time.

Here I provide a brief review of recent advances in the neurocognition of creative relational thinking and reasoning, focusing in particular on analogical reasoning. I first seek to explicate characteristics that make reasoning creative and strategies that make studies of creative cognition practicable. I provide a brief review of insights about relational cognition achieved by the cognitive neuroscience of analogical reasoning. I then review work that is elucidating cognitive attributes and neural mechanisms of understanding and generating distant semantic relations in analogy and simpler forms of relational cognition. Next, I address the dynamism of creativity as a state, rather than a trait, in relational thinking and reasoning. Finally, I consider new efforts to enhance state creativity through exogenous modulation of electrical activity in the brain, and the potential implications of this work for creative reasoning.

Much of the research I review utilizes computational tools for measuring the distance between concepts as a means of quantifying the creativity of relational connections. Such work is largely situated in the verbal domain. It goes without saying that there are many important forms of creativity beyond those considered here; this brief review is not intended to be exhaustive. Relatively simple verbal stimuli and quantifiable characteristics are a good fit for the methods of cognitive neuroscience, and thus have been prominently represented in the first generation of the cognitive neuroscience of creativity. The reviewed literature describes an encouraging trajectory, with quantitative "semantic distance" approaches driving progress, and cognitive state manipulations and electrical neuromodulation showing promise for augmenting creative performance.

Phenotyping Creativity in Reasoning

It is not always obvious which sorts of reasoning are creative, and maybe even less so which sorts of reasoning are not creative. Like identifying cognitive, emotional, or disease phenotypes across the range of human variation, the endeavor is likely best considered along a spectrum. Reasoning is broadly divisible into deductive and inductive processes. Stipulating that division, deductive processes appear likely to populate the lower end of the creativity spectrum. Deduction leans heavily on the modal must – that is, it involves determining the conclusion that *must* follow from a given set of premises. Given the premises, "All fruits are delicious," and "Guava is a fruit," we *must* conclude that guava is delicious. Reaching this conclusion does not feel especially creative, likely in part because creativity feels like it ought to involve creating something new (at least in our mind) and nothing much in this example requires creating. All the information required to formulate the conclusion is given to us in the premises. If you imagine a person or a machine that had no knowledge other than these premises – a near complete lack of the raw materials that minds use for creating – that person or machine would nonetheless be fully able to deduce the valid conclusion.

In fairness, not all deduction is as drab as the above example. One way to enliven the deductive process is to point the premises toward a conclusion that contradicts the reasoner's intuitions or prior knowledge. For example, given the premises "Norbert is the youngest person in the room," and "Norbert's child is in the room," it is necessary to conclude that Norbert is younger than Norbert's child. As in the previous example, prior knowledge is not required to reach the valid conclusion. The difference is that in this case the presence of prior knowledge may actually make valid reasoning more difficult. Reaching the valid conclusion in this case requires a reasoner to inhibit the influence of prior knowledge (i.e., knowledge about the relative ages of parents and children). Inhibiting a prepotent representation or intuition in favor of the conclusion that must follow the premises might fairly be described as an instance of cognitive flexibility. It may even be fair to describe this process as drawing upon the same neurocognitive resources that support cognitive flexibility across a range of creative functions (Zabelina & Robinson, 2010). Consistent with this interpretation, reasoning to counterintuitive conclusions elicits anterior cingulate cortex activity that often marks flexible processing of alternative responses (De Neys, Vartanian, & Goel, 2008). Such findings may be taken as evidence that deduction can be creative, although it is also possible to argue that the creativity-related inhibition of biases and prior knowledge is distinct from the deductive process itself. In any case, closely adjudicating whether specific examples of deduction involve creativity, even in small measure, may be less fruitful than a broader spectrum-based approach comparing manifestly more and less creative sorts of reasoning.

Enter induction. In contrast to deduction, inductive reasoning leans far more heavily on could than on must. Induction involves generating a broad theory that *could* account for multiple specific instances, although the general validity of that theory cannot be known for certain. Induction is about abstracting out what appears to be shared between different pieces of information. There are many types of inductive reasoning, from simple surface-level observations (e.g., inferring that all swans are white because all the swans one has seen so far were white) to complex pattern detection (e.g., predicting the chance of rain today based on inferences from days in the past that had similar meteorological characteristics). Among the most powerful forms of induction for insightful inference is analogical reasoning. Analogies are similarities between relations – that is, similarities between the way one set of things are related to each other and the way another set of things are related to each other. Inferences based on analogical reasoning, e.g., developing a theory for how to adjust mirrors on the Hubble telescope based on the way the pieces of a showerhead adjustment mechanism work together (Ward, Finke, & Smith, 1995), are frequent drivers of learning and problem-solving. One aspect of analogies that suggests a creativity phenotype is that, unlike deduction, analogies require the reasoner to search through stored knowledge to formulate a theory about a similarity (e.g., finding a knowledge representation of how the pieces of a showerhead work together and developing a theory that the pieces of the Hubble can work together in a similar way). This process feels more creative because an inference that *could* solve a problem is generated (created) based on knowledge not provided in the problem itself. Put another way, the cognitive process of induction is open-ended whereas deduction is closed-ended, and open-ended processes leave more room for creativity.

It is worth noting that analogy can often be usefully classified under yet another reasoning type, abduction. Abduction is distinguishable from induction in that it requires the reasoner to look backwards for a possible common basis or root of multiple given instances, rather than using existing knowledge to make forward inferences about a new instance. Analogical reasoning may be considered to vacillate between induction and abduction depending on the goals and context of the analogy. Analogical inference to solve a new problem (e.g., fixing the Hubble) is more inductive. Pure analogical mapping without a clear inferential goal (e.g., determining the validity of a given statement like “helmet is to head as ozone is to Earth”) can be considered abductive because the reasoner seeks to identify a fundamental information structure or abstract relational principle that could underlie or antecede the individual exemplar analogs (Abe, 1999, 2000).

Both induction and abduction operate in the open-ended realm of *could*, which contributes to the creativity phenotype. However, neither induction nor abduction is always creative (e.g., the classic white swan induction does not move the creativity needle much), and there are plenty of tepid abductions (e.g., “helmet is to head as kneepad is to knee”). So the creativity phenotype in reasoning is richer than could-ness alone.

Beyond could-ness, a strong marker of the creativity phenotype in analogical reasoning is “semantic distance” (Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010, 2012). Analogies are similarities between sets of relations, but not all sets of relations seem similar on the surface. Roughly speaking, the more the pieces of an analogy seem different on the surface, the greater the semantic distance of the analogy that connects them. Take the foregoing comparison of creativity to a biological phenotype. This comparison boils down to an analogy that could be stated as “creativity is to reasoning as a phenotype is to humans,” or creativity : reasoning :: phenotype : humans. The distance between the two sides of the analogy in semantic space appears fairly substantial. Subjective judgments of semantic distance are quite useful and, interestingly, the intuitiveness of thinking about word meanings as near/distant is likely a product of the deep seating of analogy, or at least metaphor, within the core of human cognition (Hofstadter, 2001; Lakoff & Johnson, 1980), e.g., we naturally co-opt spatial cognitive resources to represent nonspatial differences in terms of spatial distances. However, subjective judgments are often less than an ideal measure for use in quantized psychometric and neuroimaging inquiry.

The study of semantic distance has been greatly advanced by the development of text-corpus analysis tools that calculate objective, quantitative values for semantic distance. A prominent tool is the Latent Semantic Analysis (LSA) calculator developed by Thomas Landauer and colleagues at the University of Colorado (Landauer & Dumais, 1997; Landauer, Foltz, & Laham, 1998). Using an extensive bank of English text corpora, LSA leverages regularities in the contexts in which words are/are not used to assign locations to terms within a high-dimensional semantic space where locations represent the context usage of each term. The semantic distances calculated by LSA represent the quantitative distances between these locations in semantic space. Given the input, “creativity : reasoning :: phenotype : humans,” LSA returns a semantic distance of .83, which is relatively large. If we instead input, “creativity : reasoning :: openness : attention,” LSA returns a semantic distance of .67, indicating that the terms reside closer together in semantic space. Computational text corpus analysis tools like LSA remain imperfect; important shortcomings include difficulty with distinguishing synonyms and representing subtle contextual sense meanings. Nonetheless, these tools appear to provide highly reliable measurement of semantic distance between words, low measurement error, and good construct validity with respect to subjective creativity ratings (Green et al., 2010; Green, Kraemer, et al., 2012; Landauer & Dumais, 1997; Prabhakaran, Green, & Gray, 2014; Wolfe & Goldman, 2003). In application, text-corpus analysis approaches are likely to provide greater precision for quantitative approaches to creativity at cognitive and neural levels. For example, quantified semantic distance has been used to objectively staircase increases and decreases in the creativity of stimuli used to study relational thinking (e.g., for parametric neuroimaging analysis) as reviewed below. Bolstering this kind of parametric approach is especially important for neuroimaging studies that seek to interrogate creativity with greater sensitivity than simple binary contrasts (e.g., creative vs. noncreative conditions) to test associations between quantitative changes in degree of creativity and quantitative changes in the distribution and intensity of neural activity.

Creativity Can Be Studied, Just Not All At Once

Although the most valuable analogies are generally the creative ones (Holyoak & Thagard, 1995), studies of creativity represent only a small subset of cognitive and brain-based studies of analogical reasoning and relational cognition broadly. An often-cited obstacle to the rigorous study of creativity is that it may be impossible to lasso all creative processes within a unifying, operationalized definition. In addition, given the emphasis on subjective valuation for many forms of creativity (e.g., in the visual and performance arts), reasonable objections can likely be made to any quantitative measure of creativity. The availability of text-corpus analysis tools such as LSA helps, and improved iterations of concept mapping (e.g., Pennington, Socher, & Manning, 2014) are likely to help more. However, even if these tools could perfectly achieve their intended purposes, they would not resolve many of the fundamental challenges of studying the broad and ambiguous construct of creativity.

While the absence of a complete definition of creativity limits the breadth of claims that can be made, it does not mean that nothing meaningful can be learned about creative cognition. Few, if any, higher cognitive constructs have thoroughgoing definitions. Nonetheless, cognitive science and cognitive neuroscience have made appreciable gains by focusing on specific exemplars that manifestly reflect constructs such as attention, memory, and even consciousness. In identifying good exemplars of creativity, researchers can refer to two broad-frame characteristics that creativity researchers generally agree creative processes should have: novelty and usefulness (Mayer, 1999; Runco & Jaeger, 2012). Novelty connotes the divergence of a creative product from what is standard or what is expected. Usefulness indicates the meaningfulness/sensibility of a creative product with respect to the context in which it is generated (e.g., the problem to be solved). As such, wild production of divergent thoughts that do not meaningfully fit any discernable contextual constraints, as can sometimes be observed in psychiatric disorders such as schizophrenia, does not have the usefulness characteristic of creativity.

Taking these characteristics as a frame, semantically distant analogical reasoning emerges as a good exemplar of creativity. In order to be semantically distant, an analogy must reveal a connection between concepts, situations, etc., that are not standardly considered to be similar. Thus, the novelty/divergence characteristic is evident (Green, Kraemer, et al., 2012). However, this divergence is tempered; unconstrained connections between concepts, situations, etc., that do not have meaningfully similar relational structures cannot fit sensible alignments and do not result in a valid analogical mapping. Fitting to the constraints of analogical alignment and mapping (Gentner, 1983; Gick & Holyoak, 1980; Sternberg, 1977) evince the usefulness/meaningfulness characteristic of creativity.

It is entirely fair to point out that semantically distant analogical reasoning differs in important ways from the sort of creativity that is required to design an evening gown or compose an aria. Indeed, semantic distance is not an exhaustive measure of creativity and can perhaps only be usefully applied to a circumscribed set of creative tasks. But that is not a damning assessment. As with other areas of higher cognition, what makes a rigorous neuroscientific inquiry into creativity practicable is to focus a lens on an individual creative process at the highest achievable resolution, rather than widening the lens out of focus in an attempt to capture the whole of creativity in one shot.

E pluribus unum: Neural Mechanisms of Relational Integration in Analogy

The moment when we understand the analogy, "helmet is to head as ozone is to Earth" is the moment when we succeed in integrating the first-order relation helmet : head with the first-order relation ozone : Earth to form an abstract second-order relation that unifies the two relations into a single relational representation – something like, "surrounds and protects." This bringing-it-all-together culmination of the analogical reasoning process is referred to as relational integration (Bunge, Helskog, & Wendelken, 2009; Christoff et al., 2001; Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006). The neuroscience of analogical reasoning, still in its early stages, has made some advances in characterizing the neural mechanisms supporting relational integration (Bunge et al., 2009; Bunge, Wendelken, Badre, & Wagner, 2005; Christoff et al., 2001; Green et al., 2006, 2010; Green, Kraemer, et al., 2012; Hampshire, Thompson, Duncan, & Owen, 2011). Fittingly, the search for relational integration in the brain has led, among other places, to a region at the anterior pole of left prefrontal cortex (frontopolar cortex) that appears to be ideally wired for integrating disparate representations (Bunge et al., 2005, 2009; Green et al., 2006, 2010, 2017).

A fruitful approach to identifying the neural signature of relational integration has been to contrast analogies with analogy-like stimuli, thereby manipulating the demand for relational integration. A study in our laboratory (Green et al., 2006) compared analogies made up of four words (e.g., Gun : Bullet :: Bow : Arrow) to four-word stimuli designed to mimic these analogies, except that a valid relational integration was not available. For example, the item Cow : Milk :: Duck : Water resembled analogy stimuli in that it involved two semantic relations that could be understood separately from each other (i.e., cow gives milk, and duck swims in water). Understanding conventional semantic relations of this sort is a necessary operation within the analogy process (e.g., Sternberg, 1977). In addition, the words could be aligned with each other based on category co-membership (e.g., cow and duck are both animals, and milk and water are both potable liquids). One-to-one alignment between corresponding elements on opposite sides of an analogy is a well-characterized component of the process of analogical reasoning (Gentner, 1983; Gick & Holyoak, 1980; Sternberg, 1977). Category co-membership was chosen as the basis for alignment in the control stimuli based on evidence that categorization subserves one-to-one alignment in analogy (Green, Fugelsang, Kraemer, & Dunbar, 2008). While both conventional semantic relations and category alignments were present in the control stimuli, valid analogical similarities were not, e.g.,

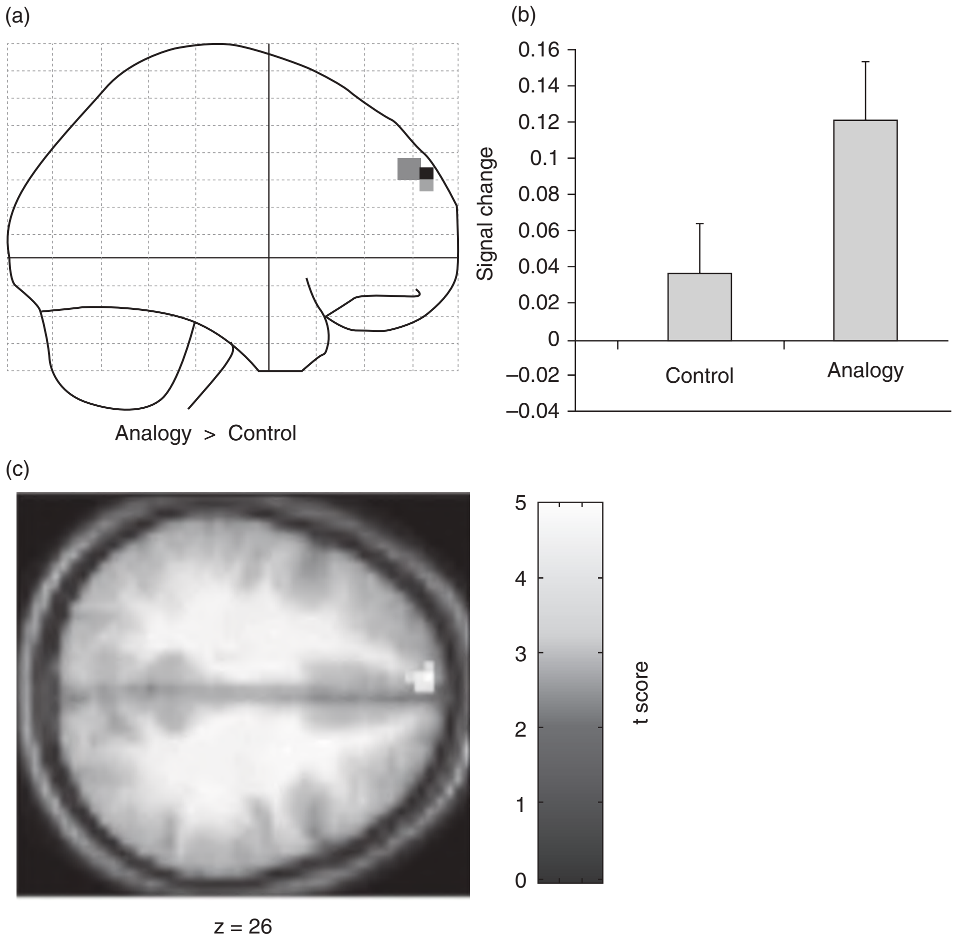

Figure 20.1 Frontopolar cortex activity during analogical reasoning. A region in the left frontopolar cortex showed significantly greater activity during a four-word analogical reasoning task than during a nonanalogical four-word control task. (A) A glass brain rendering at a stringent statistical threshold indicates that a cluster of voxels in frontopolar cortex was the locus of greatest activity across the whole brain for the Analogy > Control contrast. (B) Peak activity averaged across all voxels within a frontopolar region of interest differed significantly from resting baseline in the Analogy condition, but not the Control condition. (C) Location and activity of frontopolar voxels in an axial slice rendering ($z = 26$) of the Analogy > Control contrast. For a color version of this figure, see the color plate section.

there is not a valid analogical similarity between Cow : Duck and Milk : Water. Thus, relational integration could not be completed for these stimuli. In the control condition, participants evaluated the separate pieces of the stimuli (e.g., validity of conventional semantic relations, and category co-memberships). In comparison to this control condition, processing of valid analogies, which included relational integration, recruited stronger neural activation in left frontopolar cortex (Figure 20.1). This increased frontopolar activity was not related to task difficulty; the control condition was designed to be more difficult than the analogy condition, was rated as more difficult by participants, and elicited greater overall brain activation. This study was convergent with a study by Bunge and colleagues (2005) that dissociated relational integration from the retrieval of remembered information for verbal associations more generally. Comparing tasks in which participants recalled recently presented word pairs for the purposes of analogical relational integration vs. unconstrained semantic association revealed stronger frontopolar activity in the relational integration condition.

Further work on the neural basis of analogy over the last decade or so, has yielded a strengthening convergence on frontopolar cortex (Bunge et al., 2005, 2009; Green et al., 2010; Hampshire et al., 2011; Krawczyk, McClelland, Donovan, Tillman, & Maguire, 2010; Krawczyk, Michelle McClelland, & Donovan, 2011; Vartanian, 2012; Volle, Gilbert, Benoit, & Burgess, 2010; Wendelken, Nakhabenko, Donohue, Carter, & Bunge, 2008). A recent activation likelihood estimation (ALE) meta-analysis of neuroimaging data, considering a wide range of studies of analogy and associated forms of verbal and nonverbal relational cognition, identified the left frontopolar cortex as a reliable and domain general point of convergence among the extant evidence (Hobeika, Diard-Detoeuf, Garcin, Levy, & Volle, 2016). Analogy research implicating the frontopolar cortex has largely relied on functional neuroimaging, but work using electrical recording (Maguire, McClelland, Donovan, Tillman, & Krawczyk, 2012; Qiu, Li, Chen, & Zhang, 2008) and studies of clinical populations characterized by frontopolar degradation (Lagarde et al., 2015; Morrison et al., 2004; Waltz et al., 2004) has provided further support, as has recent evidence that analogical reasoning ability is associated with gray matter volume in frontopolar cortex (Aichelburg et al., 2016).

The evidence placing the frontopolar cortex at the integrative apex of the analogical reasoning process is also consistent with a general rostrocaudal hierarchy of prefrontal cortex organization, which is empirically indicated by a growing body of research (Badre & D'Esposito, 2007; Braver & Bongiolatti, 2002; Bunge, Kahn, Wallis, Miller, & Wagner, 2003; Christoff & Gabrieli, 2000; Koechlin, Ody, & Kouneiher, 2003). This work coheres with a set of hierarchical models of parieto-frontal brain function in which anterior prefrontal cortex mediates the most highly complex and/or abstract level of information representation (Badre & D'Esposito, 2007; Burgess, Dumontheil, & Gilbert, 2007; Christoff & Gabrieli, 2000; Gilbert, Spengler, Simons, Frith, & Burgess, 2006). With respect to analogical reasoning, these accounts suggest a hierarchy in which information that is directly derived from external stimuli (e.g., the words or images that are the components of an analogy) is represented at relatively caudal areas of the supramodal cortex, and internal representations generated from this information are integrated through more abstract cognitive operations (e.g., analogical mapping) mediated by the frontopolar cortex.

The convergence of neurocognitive data and computational accounts of analogical reasoning on frontopolar cortex as an integrator fits nicely with what has been learned about the structure and connectivity of frontopolar cortical neurons. These neurons exhibit a distinctive arborization profile in comparison to other frontal neurons; relatively less densely populated cell bodies account for high numbers of dendritic connection points due to high numbers of dendritic spines per cell and per neurite arbor (Jacobs et al., 2001). An influential account proposed by Ramnani and Owen (2004), which accommodates both brain imaging and histological data, suggests that the cellular wiring of frontopolar neurons is ideally suited for integrating information at an abstract level based on afferent connections from more caudal brain regions where to-be-integrated information is represented.

Imaging Analogical Creativity

Establishing neural mechanisms that support the analogical reasoning process, and especially relational integration, has set the stage for targeted investigations of how the brain manifests creativity through analogy. The availability of LSA has further enabled testing of quantitative predictions about the relationship between brain function and the creativity of analogical reasoning, as represented by semantic distance. Evidence implicating frontopolar neuronal integration circuitry in the relational integration of analogies suggests an intriguing hypothesis: as analogies integrate increasingly distant representations, this may increase the demand on frontopolar cortex. If so, then more creative (semantically distant) analogical reasoning should recruit stronger frontopolar activity.

Two studies in my laboratory have targeted the parameter of semantic distance in analogy. One of these studies (Green et al., 2010) investigated the effect of semantic distance on the neural process of evaluating whether proposed analogies are valid. In four-word analogy stimuli of the form "A is to B as C is to D," we parametrically varied semantic distance values, as derived quantitatively from latent semantic analysis (Landauer & Dumais, 1997; Landauer et al., 1998). That is, we varied the semantic distance from [A : B] to [C : D], over which the two halves of the analogy had to be integrated through analogical mapping. Consistent with our hypothesis, parametric analyses revealed that increasing semantic distance predicted increasing activity in frontopolar cortex, and this effect was independent of the effect of difficulty. Semantic distance predicted increasing activity in an area of frontopolar cortex overlapping with the area we had previously associated with relational integration in analogical reasoning (Green et al., 2006). These data provided a first empirical characterization of how the brain mediates semantic distance in analogical reasoning, indicating increasing frontopolar recruitment as a key mechanism.

When creative analogies are applied in the real world, they are often used as a means of generating solutions to problems (Dunbar & Blanchette, 2001). Given the findings of our study of analogy evaluation, we were interested in the hypothesis that activity in the frontopolar cortex might underlie not only evaluation of creative analogies but also the generation of creative analogical solutions across semantic distance. To test this hypothesis, we again varied the semantic distance of verbal analogy stimuli, but this time participants were required to generate a solution to an analogy problem of the form "A is to B as C is to?" Subjective ratings of our stimuli by a large group of independent raters confirmed that more semantically distant analogies were judged to be more creative. Consistent with our study of analogy evaluation, parametric analyses again revealed that activity within the predicted region of the frontopolar cortex increased as a function of increasing semantic distance in analogical solution generation, even after accounting for the effects of task difficulty.

Taken together, these data provide an initial delineation of a dose–response relationship between semantic distance in analogical reasoning and activity in the frontopolar cortex. Thought of another way, these findings point to frontopolar activity as a potential biomarker of creativity, at least with respect to analogical reasoning. Establishing a reliable biomarker for creative thinking through continued replication and convergence could have applied implications for brain-based adaptive creativity training. Such applications are likely still far off, but early indications of convergence toward frontopolar function as a marker of creativity are emerging in the literature. Taking a broad view of extant neuroimaging data, an ALE meta-analysis of the creativity neuroimaging literature (Gonen-Yaacovi et al., 2013) revealed the frontopolar cortex as a point of strong convergence across multiple creativity measures. In line with the neuroimaging findings, clinical research on frontotemporal dementia-related degradation of the frontopolar cortex has shown that the extent to which patients retain creative ability may depend on the degree to which frontopolar cortex integrity is preserved (de Souza et al., 2010).

It is important to note, even if it may strike most readers as obvious, that the frontopolar cortex is by no means a lone actor in analogy or other creative cognition. The frontopolar cortex appears to be important for analogical reasoning, but it acts as part of a broader collaboration of brain regions involved in the analogical reasoning process. Two such regions are the dorsolateral prefrontal cortex, which appears to be involved in storage and manipulation of informational bits that are ultimately integrated in analogy formation (Fincham, Carter, van Veen, Stenger, & Anderson, 2002; Green et al., 2006), and the inferior frontal gyrus, which likely contributes to semantic elaboration (Wagner et al., 1998; Wig, Miller, Kingstone, & Kelley, 2004), and increasing selection demand for ambiguous analogy problems (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Green, Cohen, Kim, & Gray, 2012; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). Given the complexity of creativity as a construct, or even the complexity of any individual creative task, no single region should be thought of as exclusively mediating creativity. Promising efforts to develop network-based models of creative neurocognition are well underway (Beaty, Benedek, Silvia, & Schacter, 2016; Jung & Haier, 2013). Work to understand network dynamics that support creativity is extremely valuable but is largely beyond the scope of this chapter.

It is also important to note that the frontopolar cortex is not an analogy- or creativity-specific brain region. The integration circuitry housed at the frontal pole appears to play a more general role in integrating mentally generated representations of information. Frontopolar activity is associated with a wide range of tasks that involve integrating information, including economic decision-making (e.g., Shamosh et al., 2008), branching/subgoaling (Koechlin & Hyafil, 2007), mathematical problem-solving (De Pisapia, Slomski, & Braver, 2007), matrix reasoning (Christoff et al., 2001), and episodic memory (Reynolds, McDermott, & Braver, 2006); for relevant reviews, see Gilbert et al. (2006), Knowlton, Morrison, Hummel, and Holyoak (2012), and Ramnani and Owen (2004).

The Interstate Travels of Relational Creativity

What does it mean to *be* creative? Traditionally, creativity research has treated this as a question of *who*; that is, who is more creative and who is less creative. Individual differences in creativity as a trait variable, like individual differences in IQ, are quite real and are a valuable target for cognitive and brain-based research (Guilford, 1950; Jung et al., 2010). However, being creative is also a question of *when*; perhaps unlike IQ, creativity exhibits dynamic changes in state level within a person and this dynamism can happen on a rapid timescale. Evidence for state augmentation of creative thinking has been found across multiple cognitive domains and stimulus modalities (Gilchrist & Taft, 1972; Green, Cohen, et al., 2012; O'Hara & Sternberg, 2001; Weinberger, Iyer, & Green, 2016); for review, see Nusbaum, Silvia, & Beaty (2014). However, state creativity has received surprisingly little attention in the cognitive neuroscience literature such that the neural mechanisms underlying changes in creative state remain virtually unexplored. Increasing recognition of the value of creativity – indeed, the potential to think creatively may be what is most valuable about the human mind in an age when the reach of artificial intelligence is extending to many other aspects of information processing (Brynjolfsson & McAfee, 2014) – is motivating institutions across sectors of education, science, and industry to orient toward encouraging creative innovation ("Global chief executive officer study," 2010; NSF, 2011). Understanding the mechanisms that enable the brain to become more creative will be pivotal in these efforts, so state creativity dynamics represent an area of neuroscience that is likely to receive considerably higher priority in the years ahead.

In an initial study of augmented state creativity in relational cognition, we tested the hypothesis that performance on a task of creative analogical reasoning would be improved through the deliberate effort to be creative. Specifically, we tested whether an explicit cue to "think creatively" would elicit better identification of creative analogies among participants performing a four-term verbal analogical reasoning task. We found that the explicit creativity cue led to improved performance in judging semantically distant (creative) analogies as valid, but only when those analogies actually were valid, i.e., without decreasing sensitivity to detect invalid analogies (Green, Cohen, et al., 2012).

Building on this work, we sought to more directly study the effects of state creativity on the kind of analogical reasoning that supports creative innovation. Real-world creative insights require finding analogical connections that others may have missed among a broad array of possible concept combinations, where most of the possible combinations do not lead to valid analogies. However, this broad search space is not reflected in traditional tests of analogical reasoning, including those we have used, which constrain the search space to "single-serving" analogies laid out in the classical "A is to B as C is to D" format. To begin moving toward more ecologically valid analogy finding, we developed an Analogy Finding Matrix (AFM; Weinberger et al., 2016). In the AFM (see Figure 20.2), participants seek analogical connections among a large matrix of word pairs while attempting to avoid far more frequent combinations of word pairs that yield invalid analogies.

Using the AFM in the context of an explicit creativity cue (Weinberger et al., 2016), we found that participants formulated analogies that were substantially more semantically distant when they were cued to think creatively. Given the extensive availability of invalid analogical mappings in the AFM, we were particularly interested to find out whether the creativity cue would lead participants to begin inappropriately formulating invalid analogies. Encouragingly, the data indicated that this was not the case – that is, the creativity cue appears to have increased signal in the search for creative analogies without appreciably increasing noise. Taken together, these studies help to establish that state creativity interventions yield enhancement of "real" creativity rather than simply provoking inappropriate divergence.

While these and other studies have established the dynamism of state creativity at the behavioral level (Nusbaum et al., 2014), the neural bases of this dynamism are, as noted above, almost completely unexplored. The first and, to our knowledge, only neuroimaging study of state change in relational creativity relied on a simplified form of relational cognition involving relations between two words (Green, Cohen, Raab, Yedibalian, & Gray, 2015). This task was modified from classic verb-generation tasks that are easily implemented in the fMRI environment (Petersen, Fox, Posner, Mintun, & Raichle, 1989) and has been validated in relation to standard creativity tests (Prabhakaran et al., 2014). Participants viewed a series of nouns onscreen and the color of the font was used to implement a creativity cue manipulation. The color cues successfully elicited repeated conscious engagement and disengagement of augmented state creativity in the scanner, indicated by large effect-size changes in the semantic distance between the noun prompt and the verb responses. We hypothesized that augmenting creative cognition would place greater demand on neural circuitry within thefrontopolar cortex that supports creative integration across semantic distance (Gonen-Yaacovi et al., 2013; Green et al., 2010; Green, Kraemer, et al., 2012; Ramnani & Owen, 2004). Thus, we specifically interrogated activity in the frontopolar cortex as a predictor of state creativity. Consistent with our prediction, the region of left frontopolar cortex that we have previously associated with creative integration of semantic information (Green

	Sweeper Street	Spark Fire	Planet Soil	Wax Candle	Orange Peel	Puppy Dog	Tea Honey	Dollar Fortune	Address House	Clock Time	Seed Tree	Scout Talent	Passport Border	Shampoo Hair
Watermelon Rind	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
Soap Hand	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓
Wool Sweater	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗
Ruler Length	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗
Kitten Cat	✗	✓	✗	✗	✗	✓	✗	✓	✗	✗	✓	✗	✗	✗

Figure 20.2 An illustration of a matrix for the Analogy Finding Matrix task (not a high-fidelity reproduction of the actual matrix used). Participants in this task indicated where word pairs along the left side connect with word pairs along the top to form valid analogies. Valid analogical connections (indicated here by green check marks for illustration purposes) vary with respect to semantic distance (e.g., the analogical connection between kitten : cat and puppy : dog is valid, but is not as semantically distant as the analogy between kitten : cat and spark : fire), and most of the possible connections between word pairs do not form valid analogies (for illustration purposes, nonvalid connections are indicated by red X marks). For a color version of this figure, see the color plate section.

et al., 2006, 2010; Green, Kraemer, et al., 2012) exhibited increased activity during cued augmentation of creative state. Cue-related state creativity augmentation was also associated with an increase in functional connectivity between the frontopolar cortex and regions of the anterior cingulate gyrus and the right frontopolar cortex, likely reflecting the need to inhibit prepotent responses when trying to think creatively. Notably, we found that differences between individuals in the magnitude of increase in frontopolar activity predicted differences in the amount by which individuals improved their creative performance. Toward further characterizing frontopolar activity as a biomarker of creativity, these data suggest that frontopolar recruitment supports conscious, proactive changes in state creativity (i.e., "putting on your thinking cap") rather than simply being reactive to the creative attributes of presented stimuli.

Charging a Head?

Neuroimaging characterizations of creativity in relational thinking and reasoning remain far from complete. It may be surprising, then, that, aiming by the relatively dim light of extant neuroimaging evidence, attempts are already underway to enhance the function of brain systems related to creativity and reasoning using targeted transcranial electrical stimulation (Brunye et al., 2015; Cerruti & Schlaug, 2009; Chi & Snyder, 2011, 2012; Chrysikou et al., 2013; Colombo, Bartesaghi, Simonelli, & Antonietti, 2015; Goel, Eimontaite, Goel, & Schindler, 2015; Green et al., 2017; Mayseless & Shamay-Tsoory, 2015; Simis et al., 2014). The near-term efficacy of this endeavor remains to be determined, but incomplete understanding of the mechanisms being targeted does not necessarily imply that those mechanisms cannot be successfully modulated.

On the contrary, the history of neural modulation through pharmacology and most pertinently through electrical stimulation (e.g., for treatment of depression and Parkinson's disease) have achieved appreciable effects far in advance of a complete mechanistic understanding of the relevant brain systems (Fregni et al., 2006; Nitsche, Boggio, Fregni, & Pascual-Leone, 2009; Nitsche et al., 2008). Even as clinically applied electrical neural modulation techniques continue to be honed and achieve greater efficacy, understanding of exactly why they work remains incompletely resolved.

Much of the electrical modulation research to date has employed transcranial direct current stimulation (tDCS). tDCS introduces a tonic (rather than sinusoidal) level of stimulation, with current flowing between an anodal and cathodal electrode placed on the scalp. Anodal tDCS appears to potentiate neuronal firing in a targeted brain region by increasing the resting membrane voltage of neurons. When applied to regions in which neuroimaging evidence indicates that increasing activation is related to better cognitive performance, anodal tDCS may plausibly facilitate improved cognition. Investigations using verbal creativity measures, primarily targeting left prefrontal brain regions (Brunye et al., 2015; Cerruti & Schlaug, 2009; Colombo et al., 2015; Green et al., 2017; Metuki, Sela, & Lavidor, 2012) and at least one that used a creative drawing measure in stroke patients and targeted right frontoparietal regions (Simis et al., 2014) have reported improved creative performance with anodal tDCS. Based largely on the electrical recording work of Mark Beeman and colleagues that has characterized the role of temporal lobe activity in insight problem-solving, anodal tDCS has also been applied to medial and anterior temporal regions with improvements reported on verbal and nonverbal insight problem-solving tasks (Chi & Snyder, 2011, 2012; Goel et al., 2015).

Given these early indications that tDCS can induce creativity-related changes in brain function, as well as the above-described evidence relating creativity in relational cognition to increased activation in the frontopolar cortex, research in our lab has recently tested the effects of frontopolar tDCS on relational creativity. Our prior finding that the magnitude of increases in frontopolar cortex activity predicted individual differences in improvement of creative performance suggests the possibility that neural intervention to potentiate increases in frontopolar activity might facilitate greater creativity. In other words, potentiation of frontopolar neurons might enhance the capacity of an individual to deliberately think more creatively. We recently tested this hypothesis by targeting the frontopolar region implicated in our prior fMRI work with a high-definition tDCS method that utilizes an array of scalp electrodes for precise localization of stimulation. We found that anodal stimulation resulted in the formation of substantially more creative analogies in the AFM when participants were cued to think creatively (Green et al., 2017). Consistent with our prior creative state interventions, increased analogical creativity was not due to diminished accuracy in discerning valid analogies, indicating "real" creativity rather than inappropriate divergence. Moreover, using the creativity cue verb generation paradigm, we found that frontopolar tDCS interacted with the creativity cue. That is, tDCS further augmented the effect of the cue to increase semantic distance of verb generation. This study indicates the utility of neuromodulation to validate interpretations of regional brain activity drawn from non-interventive techniques such as fMRI, and to enable more causal inferences, e.g., about the role of frontopolar cortex in creative relational reasoning.

The fact that most extant tDCS effects on creativity have resulted from anodal stimulation does not imply that more activity is always better activity. The meaning of increases and decreases in neuronal activity vary by brain region and task context (Green, Kraemer, Deyoung, Fossella, & Gray, 2013; Poldrack, 2015). Indeed, using cathodal tDCS to dampen neuronal activity in regions of the inferior prefrontal cortex has yielded improved creative performance in the classical Alternative Uses of Objects creativity measure (Chrysikou et al., 2013; Mayseless & Shamay-Tsoory, 2015), putatively because the inferior prefrontal cortex exerts an inhibitory influence on more posterior regions that support creative production. In addition, intriguing results have been reported in a study using transcranial alternating current, a technique which entrains local electrical oscillations to a prescribed frequency, rather than tonically increasing or decreasing voltage (Lustenberger, Boyle, Foulser, Mellin, & Frohlich, 2015). This study found improvements on nonspatial measures of the classical Torrance Test of Creative Thinking (Torrance, 1974) when prefrontal oscillations were entrained to the alpha frequency band, which has previously been associated with thinking creatively (Fink & Benedek, 2014; Fink, Benedek, Grabner, Staudt, & Neubauer, 2007; Jauk, Benedek, & Neubauer, 2012).

What is clear from the somewhat checkered history of neuromodulation in clinical populations – and what ought to be clear anyway – is that caution is the watchword for any attempt to introduce exogenous electricity into the brain. In particular, given that efforts to enhance healthy relational thinking and reasoning do not confer direct health benefits – although clinical applications are also possible and may be hastened by work in healthy populations – such work should only be done using known-safe levels of stimulation. Recent for-profit marketing of devices for self-applied tDCS outside the laboratory are concerning, and are also premature given the nascent state of research supporting efficacy. However, the fundamental technology used for electrical modulation of brain function has been in use for more than two centuries, since Galvani and colleagues were experimenting with bioelectricity in twitching frog legs (Reilly, 2012). Thus, there is sufficient history and characterization of effects to have confidence in the safety of laboratory-based electrical modulation, and data being obtained through modern neuromodulation approaches are sufficiently promising to warrant further exploration.

Conclusions

Creativity expressed through relational reasoning may lack some of the aesthetic flourishes of other creative expressions, but can yield great value – and perhaps even beauty – in the form of novel insight and innovation. Efforts to study creative relational reasoning in the cognitive neuroscience lab have gained momentum in recent years. These efforts have been bolstered by the emergence of computational tools that enable quantified measurement of the semantic distance between the terms that relational reasoning connects. Extant evidence has converged on the function of frontopolar cortex as an important contributor to the formation of relational connections, particularly in the context of analogical reasoning. Taking semantic distance as a proxy for creativity, neuroimaging research has demonstrated a dose–response relationship between creativity and frontopolar activity. In addition, increase in frontopolar activity appears to support state augmentation of relational creativity (i.e., the "thinking cap" phenomenon of trying and succeeding at thinking more creatively). The great promise of this work, and of creativity neuroscience in general, is that the insights gained by observing how the brain thinks creatively could lead to effective interventions for bolstering creative cognition. Excitingly (or worryingly, depending on one's perspective), efforts to realize this promise are now underway through the use of electrical neuromodulation directed to targets provided by the neuroimaging literature. Evaluating the efficacy of such interventions will require considerable further study, and I anticipate that such study will be forthcoming. Given the potential value for the sciences, industry, and education, questions about how to harness the dynamism of creative cognition, both through neural intervention and through behavioral manipulation of creative state, are likely to account for a sizeable share of creativity neuroscience in the near future.

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21 Network Dynamics Theory of Human Intelligence

Aki Nikolaidis and Aron K. Barbey

Introduction

For centuries the nature of human intelligence has motivated considerable research and debate. What mental abilities underlie intelligent behavior and how do they contribute to the expression of genius and creativity? How are these abilities shaped by the environment, cultivated through experience, and represented within the architecture of the human brain? While the precision of scientific theories and methods for investigating these questions has evolved over the years, in recent decades advances in cognitive neuroscience have afforded unprecedented insight into the nature and mechanisms of intelligence and creativity in the human brain. Indeed, the advent of neuroimaging methods has provided an opportunity to study the structural and functional organization of the brain as a window into the architecture of these higher-order cognitive capacities in the human mind. Contemporary neurobiological theories have applied neuroimaging methods to establish that individual differences in general intelligence can be localized to a specific network – the frontoparietal network – whose functions are largely believed to reflect intrinsic and stable computational properties that enable core facets of both intelligence and creativity (Barbey, Colom, & Grafman, 2013a; Barbey et al., 2012; Beaty et al., 2014; Duncan, 2010; Jung & Haier, 2007). Recent evidence from network and developmental neuroscience further demonstrates that static networks undergo both short-term dynamic fluctuations (Beaty, Benedek, Kaufman, & Silvia, 2015; Byrge, Sporns, & Smith, 2014; Deco, Jirsa, & McIntosh, 2011), and long-term changes over the developmental trajectory of the child and adolescent brain (DiMartino et al., 2014; Hutchison & Morton, 2015), and therefore motivate new perspectives about the dynamic (rather than static) and system-wide (rather than singular) network properties that underlie human intelligence and creativity.

In this article, we introduce a cognitive neuroscience framework for understanding the nature and mechanisms of human intelligence, the Network Dynamics Theory, and review evidence to elucidate how functional brain networks and their dynamic properties underlie intelligence and its emergence over childhood and adolescence. According to this framework, intelligence emerges through the process of actively selecting and creating information that in turn modifies the brain's internal structure and dynamics (Figure 21.1). The development of these internal dynamics over childhood and adolescence contribute to the maturation of the higher cognitive abilities associated with intelligence (Byrge et al., 2014) and likely creativity. We begin by surveying recent theoretical and experimental advances in network neuroscience that elucidate the static and dynamic brain networks underlying human intelligence and creativity, followed by a review of the neurodevelopmental trajectory of intelligence, and how the maturation of these networks contributes to the formation of both intelligence and creativity in adulthood.

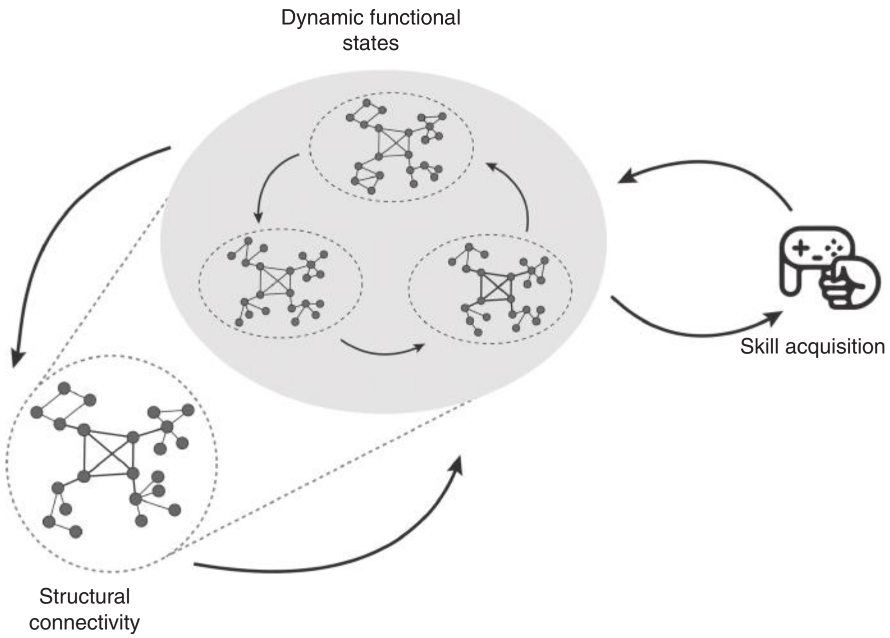

Figure 21.1 This figure represents how intrinsic and extrinsic forces drive the concurrent development of brain networks and cognitive function (Byrge et al., 2014). Structural brain networks (blue) play a constraining role on the intrinsic brain dynamics of functional networks (red), which in turn modulate the structural networks. We see how this interaction between structural and functional dynamics leads to differences in skill acquisition and response variation. The structure–function relationship constrains the generation of output, motor output in this case, although this could be generalized to cognitive skill performance as well. Sensory inputs deliver error feedback to the brain and new dynamics emerge to generate novel forms of activity. Novel forms of activity are generated and tested for relevant outcomes. Over the course of development this interactive process guides the maturation of structural networks and functional brain dynamics. For a color version of this figure, see the color plate section.

Information Processing Assumptions for Intelligence in the Human Brain

Network Dynamics Theory rests on six principles for information processing in the human brain (Just & Varma, 2007; Newman & Just, 2005). Each of the six principles is well established in the neuroscience literature and motivates predictions about the nature and origins of individual differences in general intelligence.

1. Intelligence is the product of the concurrent activity of multiple brain areas that collaborate in a large-scale cortical network (Barbey et al., 2012; Gläscher et al., 2010). Variation in the degree of synchronization or efficiency of the communication between regions may therefore predict individual differences in task performance (Nikolaidis, Goatz, Smaragdis, & Kramer, 2015).
2. Each cortical area can perform multiple cognitive functions, and conversely, many cognitive functions are performed by more than one area. The diverse functional role of brain regions is evident in literature indicating that regions of the prefrontal cortex serve multiple cognitive functions (Barbey, Colom, & Grafman, 2013b; Duncan, 2010; Miller & Cohen, 2001), and even motor regions play an important role in higher cognition (Nikolaidis et al., 2017; Nikolaidis, Voss,

Lee, Vo, & Kramer, 2014; Sabaté, González, & Rodríguez, 2004; Vakhtin, Ryman, Flores, & Jung, 2014). Conversely, the capacity for functional localization across multiple brain regions is well established by the neuroscience literature on cortical plasticity (for a review, see Pascual-Leone, Amedi, Fregni, & Merabet, 2005).

3. Each cortical area has a limited capacity of computational resources, constraining its activity. Evidence indicates, for example, that activity within working memory networks increases with performance gains on the N-Back task and plateaus or decreases as the participant reaches the ceiling of performance (Callicott et al., 1999; Jaeggi et al., 2007). The limited capacity principle has direct implications for individual differences in intelligence. First, it suggests that the amount of resources available or the resource capacity within the neural system varies across individuals, which is supported by evidence demonstrating that individual differences in brain metabolism contribute to cognitive performance (Jung et al., 1999, 2005; Nikolaidis et al., 2017; Paul et al., 2016; Ross & Sachdev, 2004). Second, the amount of resources required to perform a task likely differs across individuals due to variations in efficiency (Jaeggi et al., 2007).
4. The topology of a large-scale cortical network changes dynamically during cognition, adapting itself to the functional demands of the task and resource limitations of different cortical areas (Byrge et al., 2014). This principle is supported, for example, by evidence demonstrating that cognitive control networks shift their connectivity in a task-dependent manner to dynamically reconfigure brain networks for goal-directed behavior (Cole et al., 2013; Miller & Cohen, 2001). These dynamic network features may therefore contribute to individual differences in goal-directed, intelligent, and creative behavior.
5. The communications infrastructure that supports the transfer of information across multiple brain regions is also subject to resource constraints (i.e., bandwidth limitations). This principle is supported by a large body of neuroscience evidence demonstrating that white matter fiber tracts enable the integration of information across broadly distributed cortical networks and that the fidelity of these pathways is critical to general intelligence (Penke et al., 2012). Variation in the degree or quality of the anatomical connections between processing regions may therefore contribute to individual differences in task performance.
6. Neuroimaging measures of cortical activity (e.g., fMRI) provide an index of cognitive workload and computational demand. Extensive neuroscience evidence supports this principle, demonstrating that the amount of cortical activation within a given region increases with computational demands, for example, in sentence comprehension (Röder, Stock, Neville, Bien, & Rösler, 2002), working memory (Braver, Cohen, Nystrom, & Jonides, 1997), and mental rotation tasks (Just, Carpenter, Maguire, Diwadkar, & McMains, 2001).

Network Dynamics Theory of Human Intelligence

The reviewed operating principles provide the foundation for an interactive system of intrinsic connectivity networks, which together comprise the information processing architecture of human intelligence. Analysis of patterns of functional brain connectivity have revealed statistical dependencies in neural activity across regions, comprising core intrinsic connectivity networks of the brain (see Figure 21.2; Power, Cohen, et al., 2011), and indicates that these patterns of brain connectivity can be used to predict performance for both high- (Finn et al., 2015) and

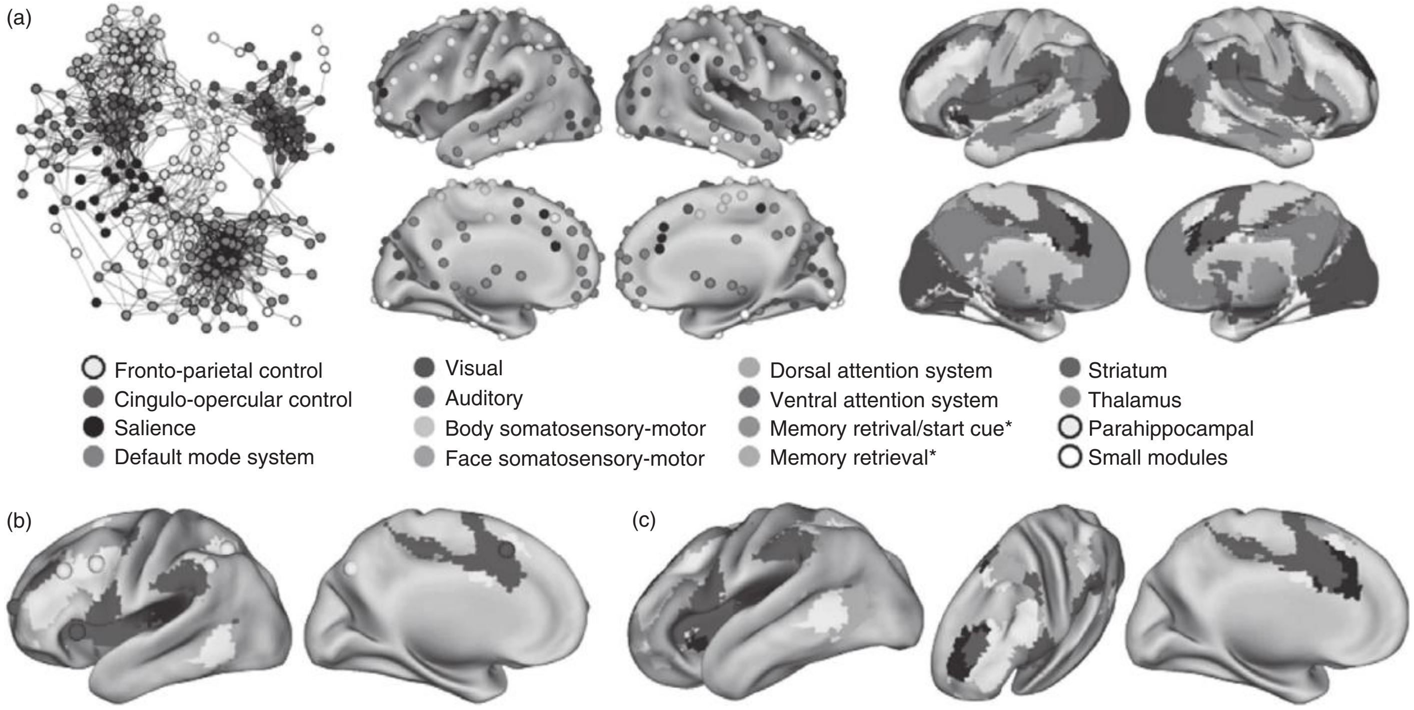

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Figure 21.2 This figure summarizes recent work extracting reliable functional networks based on a large-scale meta-analysis of peaks of brain activity for a wide range of motor, perceptual, and cognitive tasks (with permission from Dosenbach et al., 2006; Power & Petersen, 2013). (a) The upper left figure represents a graph-theoretic embedding of the nodes. Similarity between nodes is represented by spatial distance, and nodes are assigned to their corresponding network by color. The next two sections present the nodal and voxel-wise network distribution in both hemispheres. The bottom panel (b, c) displays a voxel-wise distribution of the cognitive control networks: the frontal parietal network (yellow), the cingulo-opercular network (purple), the dorsal attention network (green), the salience network (black), and the ventral attention network (teal). For a color version of this figure, see the color plate section.

low-level cognitive processes (Nikolaidis et al., 2015). Functional brain networks are known to fluctuate and evolve over short timescales and are constrained by structural connectivity, which modulate over longer timescales (Byrge et al., 2014; Deco et al., 2011). Critically, functional networks do not relay neural signals, but instead reflect neural communication within an underlying structural network (van den Heuvel & Sporns, 2013). In this way, functional networks are an important lens for understanding both low-level processing and a high-level holistic investigation of large-scale networks. Intrinsic connectivity networks are thus characterized by their micro- and macro-level topology. Micro-level topological properties describe local features of the network (e.g., the degree of a target node; Table 21.1). Macro-level topological properties reflect the large-scale architecture and global organization of the network (e.g., global efficiency; Table 21.1).

Network Dynamics Theory proposes that intelligence fundamentally depends on the learnability of macro-level network structures and dynamics (topological patterns) that emerge from external input. According to this account, intelligent, goal-directed behavior reflects the learner's capacity to utilize macro-level topological network patterns to process incoming information. This prediction motivates a more precise characterization of the large-scale cortical network properties that underlie human intelligence (from Information Processing Assumption 1). Specifically, hubs are known to play a central role in the formation of macro-level network structures and mediate many of the long-distance connections between brain modules (Figure 21.3; van den Heuvel & Sporns, 2013). Hub regions, such as the bilateral precuneus, anterior and posterior cingulate cortex, insular cortex, and superior frontal cortex, are also known to form a strongly interconnected network of regions (i.e., the rich club network; Figure 21.3; van den Heuvel, Kahn, Goñi, & Sporns, 2012). Given the range of network and functional roles of these hubs (Information Processing Assumption 2), their associated high computational cost (Information Processing Assumption 3), and high degree of interaction (van den Heuvel et al., 2012), Network Dynamics Theory proposes that the macro-level topological properties of this rich club network play a central role in human intelligence. Specifically, such properties are functionally valuable for integrative information processing and adaptive behavior. For example, network hubs in the frontoparietal network demonstrate a significant degree of task-specific interactions with a wide variety of cognitive and sensory networks, modulating their connectivity and supporting a diversity of cognitive tasks (Cole et al., 2013). Furthermore, interactions between rich club regions play an important role in determining global efficiency of communication in a network, as demonstrated by evidence indicating that almost 70% of the shortest paths through a whole brain network pass through the rich club (van den Heuvel et al., 2012). Given the role of efficiency of network communication in cognition (Bullmore & Sporns, 2009; Langeslag et al., 2013; Moussa et al., 2011), we propose that the construction of the rich club plays a primary role in the link between functional brain networks and intelligence.

As a systematically constrained information-processing organ that has evolved over millennia to maximize computational capacity toward reproductive success, the brain is driven to perform complex computations with a limited budget of resources (Gazzaniga, 2000; Güntürkün, 2005; Roth & Dicke, 2005). Nevertheless, network hubs are sinks for the brain's metabolic and communication resources. For example, the spatial distance of edges connecting hubs to the rest of the network (i.e., the wiring cost) is greater than the distance of edges connecting more peripheral nodes (i.e., hubs have a high wiring cost) (van den Heuvel et al., 2012). Rich club connections are comparatively costly and their connectivity alone accounts for

Table 21.1 *This table summarizes some of the most important micro- and macro-level graph-theoretical measurements of functional network construction (Bullmore & Bassett, 2011; Bullmore & Sporns, 2009; Rubinov & Sporns, 2009). The micro measurements characterize the role of a given node in the network as a whole, while the macro measurements describe various aspects of the construction of the whole network, such as the speed of information transfer.*

Micro-scale graph metrics

Node degree: The number of binary edges connected to a given node.
Node strength: The sum of the weighted edges connected to a given node.
Cluster coefficient: The ratio of the connectedness of the node’s neighbors when the node is and is not present. High clustering coefficient suggests that the node’s neighbors are tightly connected to one another.

Macro-scale graph metrics

Shortest path length: Describes the average shortest path between any two sets of points in a graph. A good representation of the ease of information flow through a network.
Global efficiency: A metric of inverse distances between any two nodes that compliments the shortest path length.
Small worldness: Measures the extent to which a graph demonstrates a ratio of randomness and lattice-like organization. Commonly found in most complex networks.

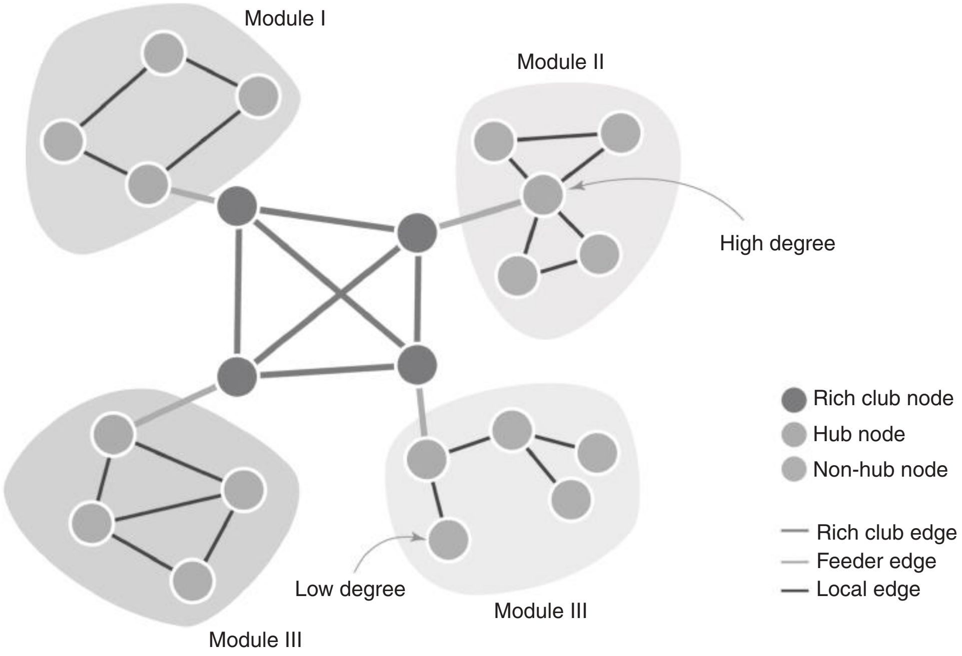

Figure 21.3 This figure displays a visual summary of basic network structure (van den Heuvel & Sporns, 2013). Each circle is a node and all the connections between them are labeled edges. Nodes of high or low degree, represented as black and gray circles, are those with edges connecting to many or few other nodes, respectively. Modules are clusters of nodes with relatively high within-cluster connectivity and low between-cluster connectivity. Among all nodes in the two graphs, the red nodes are designated as hubs given their high-degree and graph centrality (Harriger, van den Heuvel, & Sporns, 2012). This figure abstractly displays how normal and rich club nodes interact, demonstrating that the rich club nodes not only have high degree, but they also serve as critical way points that enable efficient graph traversal between distant nodes. For a color version of this figure, see the color plate section.

40% of the total whole-brain communication cost (van den Heuvel et al., 2012). As indicated by Information Processing Assumption 2, each brain region may perform multiple cognitive functions, and this assists with the computational and resource load on the brain. Network hubs are regions that are tightly integrated into single or multiple networks. Furthermore, hubs are known to have higher rates of cerebral blood flow, aerobic glycolysis, and oxidative glucose metabolism (Information Processing Assumption 3). This combination of higher metabolic rate and longer connection distance makes hubs biologically very costly (Crossley et al., 2014). Thus, the high value and high biological cost of hub regions makes them particularly sensitive predictors of individual differences in human intelligence. For example, recent work investigating the role of brain metabolism in cognition has demonstrated that the concentration of NAA, a marker of oxidative metabolism, is a strong predictor of intelligence (Nikolaidis et al., 2017; Paul et al., 2016). Given the brain's resource constraints, and the cost of using and maintaining these high wiring cost regions, Network Dynamics Theory proposes that the connectivity and activity of these regions may play a particularly important role in cognitive development and the emergence of intelligence. Understanding how these rich club nodes contribute to the development of executive functions is therefore essential to characterizing how the network architecture of the brain shapes intelligence.

Cognitive Control Functions are Central to Human Intelligence

Cognitive control is a hallmark of human intelligence. The capacity to adaptively reorganize one's thoughts and actions in accordance with internal goals is an important marker for the development of intelligence. According to Network Dynamics Theory, human intelligence reflects a self-organizing system that adaptively engages multiple brain networks to support goal-directed, purposeful behavior. To successfully perform a particular task, mental operations must be selected to achieve that specific task out of an infinite number of possible tasks and corresponding mental operations (Duncan, 2010). The process of selecting and implementing behavior-guiding principles that enable goal achievement is the central question of cognitive control. At least three signals may be defined that cognitive control regions should display across a wide variety of tasks (Figure 21.4; Power & Petersen, 2013). First, when a subject is given a cue to begin a particular task, control regions must send configuring signals to processors to establish the correct processing strategy needed for the task (the task set). A control region may therefore display start-cue activity as the task set is selected and instantiated. Second, for as long as a subject continues to perform the task, the task set must be maintained. A control region may therefore display sustained activity during task performance. Third, because successful control needs to recognize errors in performance and adjust task set accordingly, a control region may display error-specific activity (Figure 21.4).

Specific intrinsic connectivity networks are known to support cognitive control processes, including the frontoparietal network and the cingulo-opercular network (Dosenbach, Fair, Cohen, Schlaggar, & Petersen, 2008). The frontoparietal network supports moment-to-moment task adjustments and is engaged during start-cue and error-related activity (but does not demonstrate sustained activity during task set maintenance) (Dosenbach et al., 2008). The cingulo-opercular network operates over longer timescales and is recruited during start-cue, error-related, and sustained activity (Dosenbach et al., 2008). Recent evidence further suggests that cognitive control capacity may be supported by whole-brain network properties. Studies have shown that higher global efficiency of functional brain networks is positively correlated with better cognitive performance (Giessing, Thiel, Alexander-Bloch, Patel, & Bullmore, 2013; van den Heuvel, Stam, Kahn, & Hulshoff Pol, 2009),

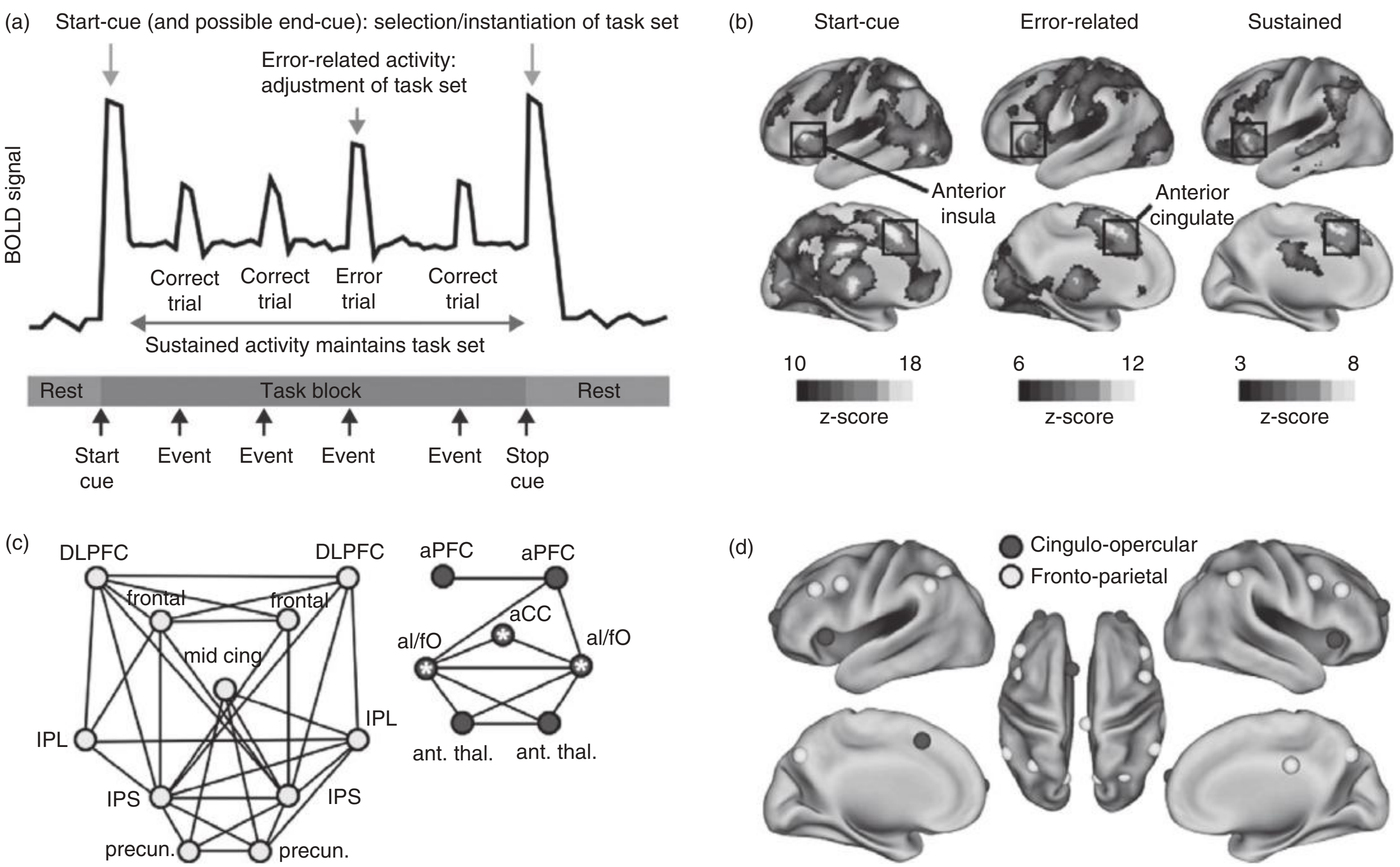

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Figure 21.4 This image represents the brain activity and network contributions to the three cognitive components of cognitive control: start cue, error related, and sustained activity (Power & Petersen, 2013). (a) A hypothetical hemodynamic response function time course from a region that elucidates the response for the start-cue, error-related, and sustained attention components of cognitive control. (b) fMRI activity maps that display the distribution of activity sensitive to the start-cue, error signal, and sustained attention. (c) A graph that summarizes the connectivity of the frontal parietal network (FPN, yellow) and the cingulo-opercular network (CON, purple). FPN: DLPFC-dosal lateral prefrontal cortex; IPL, inferior parietal lobe; IPS, intra-parietal sulcus. CON: aPFC, anterior prefrontal cortex; al/fO, anterior insula/frontal operculum; aCC, anterior cingulate cortex. (d) The anatomical mappings of the two cognitive control networks abstractly represented in (c). For a color version of this figure, see the color plate section.

and that cognitively more demanding tasks may necessitate long-range integrative connections (Kitzbichler, Henson, Smith, Nathan, & Bullmore, 2011). These data suggest that intelligence depends on an integrative network topology (Dehaene & Changeux, 2011). In particular, the rich club of highly interconnected hub nodes, many of which are in the frontoparietal network (Cole et al., 2013), are known to support performance in a variety of tasks, especially cognitive control tasks demanding goal-directed thought and behavior. This highlights the value of hubs for the dynamic integrative processes and adaptive behavior that are essential to cognitive control (Crossley et al., 2013, 2014). More recently, Cole and colleagues (2013) found that the frontoparietal network demonstrates especially high global connectivity across a wide variety of tasks. This finding suggests that global connectivity of specific control regions may be important for cognitive control capacity and would allow for a mechanism by which specific control regions can access and influence other relevant networks (such as sensory–motor networks involved in task-relevant processing) to adaptively monitor and regulate ongoing behavior (Dehaene, Kerszberg, & Changeux, 1998; Miller & Cohen, 2001).

Dynamic Variability of Functional Brain Networks in Human Intelligence

While the topology of the brain's structural connectivity plays an important role in constraining brain connectivity (Figure 21.1; Information Processing Assumption 5), the interactions between regions demonstrate significant variability over shorter time scales (Information Processing Assumption 4) (Deco et al., 2011). An emerging area of research in network neuroscience investigates how interactions between cortical areas enable human intelligence (Cole et al., 2013; Hampshire, Highfield, Parkin, & Owen, 2012). This research indicates that the interaction among brain regions is dynamic – the system adaptively configures and reconfigures itself in light of changes in processing demands and inherent limitations in available computational resources. While regions with highly stable pairwise connectivity may demonstrate such strong connectivity as the result of direct callosal fiber connections (e.g., in the case in bilateral homologies), many higher-order regions demonstrate greater variability in functional connectivity and tend to be involved in a greater range of functions (Deco et al., 2011).

On the basis of these findings, Network Dynamics Theory proposes that dynamic variability in functional connectivity is critical for the diverse range of processing involved in intelligence, and recent work on dynamic brain connectivity has shed light onto how these dynamic networks relate to static functional connectivity networks and cognition. Variability in functional interactions between nodes gives rise to a large set of functional network states that are strongly fluctuating over time, and which may differ from commonly defined static networks (Hutchison et al., 2013). In fact, well-defined static networks, such as the default mode network (DMN), actually pass through multiple metastable states (Allen et al., 2014), and these short-lived functional connectivity states are reproducible across subjects (Allen et al., 2014; Liu, Chang, & Duyn, 2013). The frontoparietal network is made flexible through its composition of hubs that rapidly modulate their pattern of global functional connectivity according to task demands (Cole et al., 2013). This work also demonstrates the strong relationship between the functional role of hubs and their participation in dynamic brain states; compared to other networks, the frontoparietal network was found to demonstrate the greatest dynamic flexibility, as it is preferentially engaged in a wide variety of 64 different motor, cognitive, language, visual, and auditory tasks (Cole et al., 2013).

While the contributions of intrinsic functional connectivity networks have been widely established in their associations with cognition, research into how dynamic functional connectivity states contribute to cognition and intelligence is still developing. Recent work has demonstrated that aspects of these dynamic brain states are relevant to some aspects of cognition (Sadaghiani, Hesselmann, Friston, & Kleinschmidt, 2010; Thompson et al., 2013) in both healthy populations and a wide range of psychiatric and neurological disorders such as schizophrenia (Sakoglu et al., 2010), Alzheimer's dementia (Jones et al., 2012), and Autism Spectrum Disorders (Starck et al., 2012). For example, some studies have shown that increases in DMN activity predicted error commission (Eichele et al., 2008), as well as temporary lapses in attention (Weissman, Roberts, Visscher, & Woldorff, 2006), which is supported by the countervailing role of the cingulo-opercular network in dynamic regulation of the DMN and sustained attention (Uddin, Kelly, Biswal, Castellanos, & Milham, 2009). Researchers have found that intraindividual differences in pre-stimulus network anticorrelation between the DMN and the frontoparietal network was strongly predictive of both response time (Thompson et al., 2013) and response time variability (Kelly, Uddin, Biswal, Castellanos, & Milham, 2008). Other work has demonstrated that variability in the connectivity of the DMN is associated with more instances of off-task mind wandering (Kucyi & Davis, 2014). More recently, researchers found that while performing a cognitive control task, metastable states with strong links to cognitive control and visual networks increased in frequency relative to rest, while states linked to drowsiness and inattention decreased in frequency relative to rest (Hutchison & Morton, 2015). These findings suggest that dynamic states that emerge from intrinsic brain activity play a critical role in the attention and cognitive control processing that contributes to intelligence. We propose that the dynamic states that modulate these varied attention and cognitive control processes are directly linked to the cognitive procedures deployed while solving complex problems exemplified by either (i) inductive reasoning and fluid intelligence or (ii) divergent thinking and creativity.

Overlapping Roles for Functional Brain Networks in Intelligence and Creativity

Traditional conceptualizations of the arts and sciences represented creativity and intelligence as separate domains, and the dominant trend in creativity research has supported this position, with meta-analyses showing very weak correlations between intelligence and creativity (Kim, 2005). More recently, studies have demonstrated strong associations between creativity and intelligence (Plucker & Kaufman, 2011; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002). In most modern psychology research creativity is measured by the family of divergent thinking tasks (e.g., to generate uncommon uses of a "brick"), and although this is an important metric of creativity, most common psychometric methods of analyzing divergent thinking suffer from statistical constraints of unstable metrics of creativity and high collinearity of item uniqueness with item fluency (Nusbaum & Silvia, 2011). More recently, studies have investigated new ways of measuring creativity in divergent thinking tasks that do not suffer from these issues or sacrifice statistical power (Nusbaum & Silvia, 2011), and these analyses have revealed a much stronger and direct association between intelligence, executive function, and creativity. For example, extensive evidence demonstrates that a range of executive functions are tied to creativity, such as working memory capacity (De Dreu, Nijstad, Baas, Wolsink, & Roskes, 2012; Süß et al., 2002), and both updating (Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014), and inhibition (Benedek, Franz, Heene, & Neubauer, 2012; Benedek et al., 2014). Furthermore, psychometric studies have demonstrated that general intelligence (Süß et al., 2002) and fluid intelligence are strongly coupled with performance in measurements of creativity such as divergent thinking originality (Süß et al., 2002), emotional metaphor creation (Silvia & Beaty, 2012), ideation originality (Benedek et al., 2012), and creative metaphor generation (Beaty & Silvia, 2013). These psychometric accounts are further buffeted by contemporary neuroimaging studies that detail further the mechanistic overlap between executive function and creativity.

Recent work has demonstrated that creativity and intelligence share an extensive array of overlapping neural correlates that center around the interaction between the default mode and frontoparietal networks (Jung, Mead, Carrasco, & Flores, 2013). The DMN plays an important role in internally generated thoughts that are both task-relevant and task-irrelevant, such as self-referential thought, autobiographical thoughts about the past and future (Andrews-Hanna, Smallwood, & Spreng, 2014; Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016). Regions of the DMN are known to interact with hubs of the salience network, such as the anterior insula, and the frontoparietal network, such as the dorsolateral prefrontal cortex (DLPFC). These executive networks are thought to play both a facilitating and constraining role on the DMN during creative tasks, for example, by engaging cognitive control processes that prevent interference from irrelevant self-generated items (Benedek et al., 2012). Beaty and colleagues found that high divergent thinking was explained by greater connectivity between the left inferior frontal gyrus and the entire DMN, and the right inferior frontal gyrus (IFG) showed greater connectivity to both the bilateral inferior parietal cortex and left DLPFC in the high creativity group as well (Beaty et al., 2014). In follow-up work, Beaty and colleagues found that global functional network efficiency was positively correlated with composite creativity scores, suggesting that greater efficiency of information transfer across networks is an important reflection of individual differences in creativity (Beaty et al., 2015). The importance of network connectivity in creativity has been underscored by studies demonstrating that white matter volume of the corpus callosum is positively correlated with creativity in the Torrance Tests of Creative Thinking, which may suggest that enhanced hemispheric specialization supports creative ideation through greater allowance for separate hemispheric processing (Moore et al., 2009). Furthermore, in a recent voxel-based lesion-symptom mapping study, researchers demonstrated that intelligence reliably predicted cognitive flexibility, that performance in these two factors both were dependent on a shared set of frontal, temporal, and parietal regions and white matter tracts (Barbey, Colom, & Grafman, 2013). More recently, intelligence researchers have begun experimentally probing the regions and networks involved in creativity. For example, one study found that in a divergent thinking task, cues to promote creative thought were associated with increased activity in the left frontopolar cortex and connectivity to the ACC (anterior cingulate cortex) and right frontopolar cortex (Green, Cohen, Raab, Yedibalian, & Gray, 2015). A creativity intervention study in which subjects were trained in divergent thinking found post-training behavioral improvements in response originality and fluency in untrained divergent thinking tasks (Sun et al., 2016). Furthermore, these changes were mirrored by group-level increases (post > pre) in functional activation in the bilateral dorsal ACC, DLPFC, and left inferior parietal lobe during an alternative uses task in the MRI scanner. This suggests that improving creative ability through training is both possible and dependent on regions of the brain critical to both cognitive control functions and self-generated thought.

Intelligence is thought to emerge through a dynamic hierarchical interaction between low level sensory regions, multimodal association regions in the parietal lobe, and frontal executive function regions such as the ACC and DLPFC (Jung & Haier, 2007). We propose that creativity emerges through a similar pattern of dynamic hierarchical networks, with the default mode network playing a central role in generating a stream of internal stimuli that are fed forward to the parietal and frontal regions for abstraction, comparison, and response selection. Recent experimental work has provided the first evidence for such dynamic reconfiguration between the DMN, FPN, and salience networks over the course of divergent thinking processing (Beaty et al., 2015). In this experiment, the authors split the time course of response to a divergent thinking trial into five sections, and tested the dynamics of connectivity of seeds in the PCC, DLPFC, and precuneus. Their results suggest that at the beginning of the divergent thinking trial, the PCC first interacts with the bilateral insula, which is supported by prior work demonstrating the interaction between the insula and DMN (Uddin et al., 2009). The PCC continues by maintaining this connection and developing greater connectivity to frontal executive regions such as the DLPFC and ACC. Unlike the PCC, the right DLPFC does not demonstrate any initial changes in connectivity, but then increases in connectivity to the right PCC and inferior parietal lobe, which are both regions of the DMN. These results suggest that as is the case with executive function, in creativity the interaction between the salience network and the DMN is initially important, but in tests of creativity there are time-delayed increases in DMN–FPN coherence as the trial progresses, pointing to important similarities and contrasts between the dynamic network processing of intelligence and creativity.

Collectively these results demonstrate that intelligence and creativity share significant overlapping variance both psychometrically and mechanistically. Creativity, like many other higher cognitive attributes, is associated with intelligence at the level of both static and dynamic networks. In some sense, this is unsurprising given that human creativity and intelligence are regarded as evolutionarily highly advantageous abilities that would likely have emerged concurrently during human evolution. While these slow changes may have contributed to the emergence of intelligence and creativity over millennia, modern-day children and adolescents provide us with other excellent models for the development of these higher cognitive functions. Understanding how these functional brain networks develop over the lifespan will give us important insights into the nature of creativity and intelligence.

Neurodevelopmental Processes for Human Intelligence

Cognitive development during early childhood is dominated by critical periods of sensory and motor development while higher cognitive functions are largely undeveloped. The cognitive abilities most crucial to intelligence, such as cognitive control, fluid reasoning, and working memory, undergo substantial development during adolescence (Asato, Sweeney, & Luna, 2006; Huizinga, Dolan, & van der Molen, 2006). The onset of puberty leads to a cascade of hormonal changes that contribute to concurrent maturation of cognitive ability and brain structure (Crone & Dahl, 2012). This sudden onset manifests as an apparent imbalance in the development of regulatory competence to manage increases in arousal. In early and middle adolescence, pubertal onset enhances emotional arousal, reward sensitivity, and sensation-seeking, and during middle adolescence low regulation of affect and cognition leads to vulnerability to risk-taking and problem behavior (Steinberg, 2005). By late adolescence, regulatory competence is increased and risks are considerably lessened. Overall, adolescent cognitive development is marked by the creation of greater ability for self-directed and regulated cognition (i.e., cognitive control functions). Individuals show improvements in the capacity and efficiency of information processing as evidenced by increased reasoning ability. By late adolescence, individuals have already become more capable of complex, planned, abstract, hypothetical, and multidimensional thinking (Keating, Lerner, & Steinberg, 2004). The development of these cognitive abilities is central to the emergence of intelligence, and therefore the maturational trajectory of the associated brain regions, networks, and dynamic metastable states are critical markers not only of the development of adolescent cognition, but also of the emergence of intelligence specifically.

Brain development is strongly tied to a wide range of factors, including an organism's physical environment (Greenough, Black, & Wallace, 1987), family, peers, nutrition, pubertal hormones, and education (Graber & Petersen, 1991). Intellectual stimulation during the first 12–30 months of life has a significant impact on a child's future IQ (Carew, 1987), and types of motor and visual stimulation support development in object memory, discrimination, and recognition (Ruff, 1989; Schwarzer, 2014; Soska & Johnson, 2013; Spear, 2000). While network hubs are closely involved in cognitive performance, they likely play a critical role in facilitating development as well. Recent work has found that the rich club organization of the brain emerges very early during development, at only the 30th week of gestation, followed by the integration of these rich club hubs with the rest of the brain (Ball et al., 2014). Furthermore, extensive changes in the size, myelination, and packing density of white matter axons during development contribute to an improvement in the efficacy of network communications (Paus, 2005; Paus et al., 1999). Thus, the Network Dynamics Theory proposes that the development of white matter tracts assists in alleviating resource constraints on the communications infrastructure of child and adolescent brain networks, thereby enabling the concurrent emergence of adult phenotypic functional networks for intelligence.

While foundational intellectual development occurs during the first years of life, adolescence is the time period during which increases in most cognitive abilities occur (Graber & Petersen, 1991; Levin et al., 1991; Spear, 2000). Coincidentally, this is also the time period during which the PFC matures to its adult volume, with the sensorimotor, parietal, and temporal cortices having already matured (Casey, Tottenham, Liston, & Durston, 2005). In adults the PFC plays a critical role in executive function and intelligence (Barbey et al., 2012; Barbey, Colom, Paul, & Grafman, 2013b; Kane & Engle, 2002; Todd & Marois, 2005), and individual differences in the development of this brain region have been linked to differences in executive function in children, further supporting the role of the PFC in the development of intelligence (Casey et al., 1997). Prefrontal regions are underdeveloped during childhood, yet during this time they play an important role in cognitive abilities central to intelligence, such as cognitive control and working memory (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Durston, Thomas, Yang, Zimmerman, & Casey, 2002; Klingberg, Forssberg, & Westerberg, 2002). During childhood, the prefrontal cortices increase in dendritic spine density, a critical marker of potential plasticity (Hering & Sheng, 2001), and this density peaks during human adolescence, reaching levels two- or threefold greater than adult levels (Petanjek et al., 2011). The frontoparietal network, which has been broadly implicated in cognitive control, working memory, and intelligence (Dosenbach et al., 2008; Jung & Haier, 2007; Nagy, Westerberg, & Klingberg, 2004), undergoes both gray matter and white matter maturation concurrently during development (Olesen, Nagy, Westerberg, & Klingberg, 2003). The maturation of this brain network parallels the development of intelligence as well, for during adolescence the long-range connections in this network strengthen and short-range connections weaken as it matures toward its adult form (Fair et al., 2007). Furthermore, recent evidence has shown that adolescents also demonstrate greatest cortical development and white matter myelination in network hubs, which are critical for managing both internal and between network dynamics (Whitaker et al., 2016).

As static networks demonstrate long-term changes over time during adolescence associated with development of intelligence, long-term changes in dynamic brain networks serve as important markers of developmental trajectories as well (DiMartino et al., 2014; Hutchison & Morton, 2015); furthermore, the Network Dynamics Theory proposes that the dynamic connectome should be even more sensitive to developmental changes in intelligence than static networks. The neuroscience community has become increasingly interested in analyzing and characterizing brain dynamics in younger populations, and recent work by Hutchison and Morton (2015) has revealed several insightful differences between the dynamic connectomes of children and adults. In a study of 9- to 32-year-olds, age was negatively associated with the number of brain states occupied during rest, meaning that adults switch between a more restricted set of brain states than children and teens. Furthermore, age was positively associated with the number of transitions between states and lower intertransition intervals, meaning that adults not only switched between brain states more frequently, but when they began a transition they also completed it more rapidly. Given that the cognitive control networks are critical for switching between functional networks (Uddin, Supekar, Ryali, & Menon, 2011), and these cognitive control networks are less developed in children and adolescents (Power, Barnes, Snyder, Schlaggar, & Petersen, 2012; Supekar, Musen, & Menon, 2009), the Network Dynamics Theory proposes that these cognitive control metastable states are heavily involved in intelligence for their ability to regulate other brain networks, therefore allowing for more rapid information access, manipulation, and integration. This position is further supported by recent findings that adults demonstrate greater variability of network-to-network coupling compared to children and adolescents, and that this difference is most pronounced in cognitive control networks (Cole et al., 2013; Hutchison & Morton, 2015). We propose that adults are thus capable of using cognitive control networks in a greater variety of ways, and increasing efficiency of use may support the developmental emergence of higher cognitive functions that contribute to intelligence.

Conclusions

Intelligence emerges through a set of extrinsically and intrinsically driven interactions. Dynamic brain networks interact with the extrinsic environment, which in turn drives the development of cognitive ability. Simultaneously, intrinsically driven developmental trajectories drive maturation of static brain networks and related dynamic network metastable states (Figure 21.1). We predict that while individual differences in static brain networks shed light on the development of intelligence from childhood to adulthood, concomitant changes in dynamic brain network metastable states should demonstrate even greater sensitivity to the development of cognitive abilities associated with both intelligence and creativity. Specifically, Network Dynamics Theory predicts that increasing network efficiency and modularity in dynamic states of the rich club and frontoparietal networks over development should mirror the improvements in executive and other higher cognitive functions associated with intelligence. Furthermore, we predict that as children and teens mature, the increasing speed of switching between dynamic metastable brain states should be a critical marker for the development of intelligence and creativity (DiMartino et al., 2014; Hutchison & Morton, 2015).

Network Dynamics Theory has important implications for both the study of intelligence and the efforts underway to improve intelligence and creativity (Table 21.2). Given that intelligence improves via development of

Table 21.2 *This table summarizes the key predictions made by the Network Dynamics Theory of intelligence regarding the role of specific brain networks and development in intelligence. ACC, anterior cingulate cortex; DLPFC, dorsolateral prefrontal cortex.*

Predictions of the Network Dynamics Theory
1. Adults have a greater capacity to use cognitive control networks to support a variety of cognitive tasks (relative to adolescents), and this increasing efficiency of use supports the developmental emergence of higher cognitive functions that contribute to intelligence
2. The dynamic connectome provides a more sensitive and specific marker of developmental changes in intelligence than classic approaches that focus on a single network or static network properties
3. Both intelligence and creativity depend on the emergence of macro-level network patterns, such as global efficiency and rapid metastable state switching, in response to both external and internal stimuli
4. The maturation of macro-level topological properties of the rich club network plays a central role in human intelligence
5. Dynamic brain states that modulate cognitive control support intelligence and creativity through their guidance of the cognitive procedures deployed while solving complex problems
6. The increase in frontoparietal network efficiency and modularity over development are predicted to mirror the improvements in executive and other higher cognitive functions associated with intelligence
7. Interventions aimed at training executive functions during adolescence are predicted to change the dynamic interactions between the frontoparietal and default mode networks that accompany the development of intelligence and creativity
8. Training on executive function tasks during adolescence will enable domain-general learning strategies that may be applied in new scenarios. For example, training that encourages adolescents to engage in faster switching between brain states may be more likely to demonstrate transfer across a broad spectrum of cognitive control tasks
9. Creativity emerges through a dynamic hierarchical interaction between default mode regions, multimodal association regions in the parietal lobe, and frontal executive regions, such as the ACC and DLPFC

dynamic network states during adolescence, we predict that interventions aimed at training executive functions during adolescence may see particular success in changing the dynamic brain states that accompany the development of intelligence. This is particularly supported by findings that the PFC is highly plastic during adolescence (Petanjek et al., 2011), suggesting that during adolescence executive processing may be subject to greater experience-induced plasticity. More specifically, we hypothesize that training on executive function tasks during adolescence may change the processing style of these tasks, training adolescents to engage in faster switching between brain states, which may be employed in other scenarios as well. Generalization of training may thus be more accurately detected through changes in the dynamic metastable states from which intelligence and creativity emerge.

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22 Training to be Creative: The Interplay between Cognition, Skill Learning, and Motivation

Indre V. Viskontas

Introduction

While the definition of a creative product as being both novel and useful has become standard in the psychological literature (Runco & Jaeger, 2012), how one rates originality and usefulness (or effectiveness) can vary with the individual's social environment (Amabile, 1983; Amabile & Pillemer, 2012). It follows, then, that in a discussion of how creativity develops with the goal of addressing whether it can be explicitly trained, one must take into consideration how social factors might interact with training methods and influence their efficacy. After all, the success of any kind of training depends at least in part on the trainee's motivation (for a review, see Colquitt, LePine, & Noe, 2000), which in turn is affected by the social context, particularly when it comes to creativity (for a review, see Shalley & Gilson, 2004).

In her influential and comprehensive componential theory of creativity, Amabile (1983, 1996) delineates three internal characteristics and one external component that, in conjunction, modulate creativity in a given individual. The individual characteristics are the presence of general creative cognition skills, such as a flexible cognitive style and openness to experience, as well as domain-specific skills and intrinsic motivation. The social context makes up the external component. With this framework as a guide, this chapter considers how each of these three individual factors might be trained, and how the social context might interact with training to foster or stifle the development of creativity, particularly with respect to the development of a growth mindset (Dweck, 2015).

Training General Creative Cognition

There is a large body of literature evaluating the many different training programs that have been designed to enhance general creative cognition (for a review, see Scott, Leritz, & Mumford, 2004). The sheer number of creativity training programs highlights both the importance that our current society places on creativity and the nebulous nature by which it is defined. Different training programs use different outcome measures to evaluate their effectiveness, as creativity is ultimately influenced by many different factors, including idea generation, idea evaluation, flexibility, originality, skill development, motivation, cultural relevance, and so on. For divergent thinking alone, Smith (1998) catalogued some 172 methods that have been used in the past, many of which remain popular. Training programs have been targeted toward many different subsets of the population, from kindergartners (Meador, 1994) to engineering students (Clapham & Schuster, 1992) and everyone in between.

Despite the widespread interest in enhancing creativity, Kim (2011) has reported that scores on the Torrance Tests of Creative Thinking may be in decline in the general population. Tracking normative data across some 272,599 children and adults from 1966 to 2008, Kim found that since 1990, even though IQ scores have either risen or reached a plateau, scores on these creative thinking tests have declined, with kindergartners through third graders showing the largest effects. The neural correlates of what's called the "fourth grade slump" in creativity (Torrance, 1968), or at least in performance on tests of creativity administered in academic settings (Claxton, Pannells, & Rhoads, 2005), has seen renewed interest among neuroscientists (Saggar, Stankov, Schreiber, & Reiss, 2016). However, an argument has been made that the slump has more to do with social pressures to conform that come online in middle school, rather than changes in training or the brain, since the slump is not observed on all creativity measures (Claxton et al., 2005; Runco & Cayirdag, 2006).

When evaluating any training method, one must assess how successfully gains made during training transfer to other contexts, specifically those in which the trained skill is to be applied (Reder & Klatzky, 1994). For example, as a child learns to play the piano, does he or she show improvement in other tests of fine motor discrimination as well? What about measures of general intelligence such as visuo-spatial reasoning or verbal memory? If the training method enhances similar functions, then we are said to observe near transfer effects, and research has shown that individual music lessons for 15 months can show measurable near-transfer effects and structural brain changes (i.e., greater volume) in musicians compared with nonmusicians in regions including the primary motor cortex, primary auditory cortex and the corpus callosum (Hyde et al., 2009). In addition, when musical training continues for three years or more, correlations between better performance on vocabulary and nonverbal reasoning tests have been found, which are distantly related to the skills trained (Forgeard, Winner, Norton, & Schlaug, 2008). In this case, if even seemingly unrelated functions are improved, then the training method has succeeded in achieving what is referred to as far transfer. Far transfer is, in some ways, the holy grail of creativity training: can we teach individuals to be more creative in general with a single intervention?

In terms of creative cognition training, the question of near and far transfer is an important one, and the difficulty in achieving far transfer is underscored by the specificity with which training programs address different components of creativity. For example, limiting the discussion to creative problem-solving, Mumford and colleagues have broken down the skill into component processes: problem identification and construction, information gathering, idea generation and evaluation, and finally, implementation (Mumford, Mobley, Reiter-Palmon, Uhlman, & Doares, 1991). Training programs, then, can be designed to target one or more of these specific processes.

Training programs have closely followed the development of creativity tests, as if testing creativity is only a precursor for enhancing it. Only 12 years after publishing his first study of creative thinking in schoolchildren, Torrance (1972) published a review of 142 creativity training studies, 103 of which used performance on his own test as the dependent measure. In his meta-analysis, he concluded that 72% of the interventions studied were effective, and emphasized the role that motivation and deliberate teaching play in ensuring success.

A more recent meta-analysis by Scott et al. (2004) reached much the same conclusions, finding a large effect size in the overall analysis. In their reading of the literature, interventions that included training methods targeting idea generation, problem identification, and conceptual combination showed the largest propensity toward positive effects. Data on the neural changes that accompany successful creativity training are sparse, although one recent study found that a five-week training method based on design thinking called the Creative Capacity Building Program resulted not only in improvements on measures of spontaneous improvisation but also in reduced task-related activation of the dorsolateral prefrontal cortex, cingulate gyrus, supplementary motor areas, and parietal regions (Saggar, Quintan, et al., 2016). These changes are very similar to the type of activation profiles that accompany jazz improvisation (Limb & Braun, 2008) in experienced musicians, suggesting that some of the same underlying capacities and related neural systems might have been targeted by the training intervention.

One key component of successful training seems to be providing a defined set of cognitive strategies or heuristics that help the trainees take advantage of existing knowledge (Scott et al., 2004). For methods that were more open-ended, exploratory, and less well-defined, improvements in creative cognition were more difficult to obtain. In some cases, trainees performed more poorly on subsequent testing. This component is not unique to the training of creative cognition, but as will be made clear later in this chapter, changing mental representations in relation to specific cognitive strategies and/or heuristics seems to be one of the keys to successful complex skill training, which we turn to next.

Training Domain-specific Skills

Many complex skills, including those required for artistic creativity, seem to continue to improve with each generation, with athletes, musicians, chess players, and masters of other complex skills besting world records every year. In the case of these individuals, a large and growing body of work has underscored the significance of adequate practice and expertise in the given domain, popularized by the "10-year rule," suggesting that it takes at least 10 years of work to become an expert across many disciplines (Bloom, 1985; Simonton, 1997). Even musical improvisation, often the poster-child of spontaneous creativity, is thought to depend upon many years of deliberate practice (Pressing, 1988). As such, how expertise is trained and what benefits it confers to the individual desiring to act creatively is of particular importance if we want to train more creative individuals.

For the vast majority of creative individuals, only when one can master the skills in a given domain can true creative eminence develop (Simonton, 1997). Because creative careers vary widely, one goal of this chapter is to address issues common to the training of many if not all of the complex skills upon which creative individuals must rely. Paradoxically, the kind of practice that skill expertise demands in most domains seems almost antithetical to the lay person's perception of creativity: it is often repetitive, incremental, and slow, unlike the sudden spark that is so often associated with a creative leap (Ericsson, Krampe, & Tesch-Römer, 1993). Virtually every longitudinal or large-scale study of eminent creative individuals has underscored the importance of a period of skill development, which is characterized by some form of deliberate practice (Ericsson et al., 1993; Simonton, 1997). Furthermore, successful deliberate practice leaves a measurable imprint on the brain, including changes in sensorimotor cortical representations and hemispheric connectivity in musicians (for a review, see Herholz & Zatorre, 2012), increases in hippocampal volumes in London taxi drivers who passed "The Knowledge" after four years of training (Woollett & Maguire, 2011), and even transient changes in visual processing regions in individuals who learned to juggle (Draganski et al., 2004). The fact that these neural changes take time and effort to occur, and that they can be transient if the individuals stop practicing the trained skill, underscores the idea that creativity training is not simply about igniting a spark, but rather laying down a foundation upon which creativity can flourish.

Deliberate Practice

A now famous large-scale study by Ericsson and colleagues (1993) transformed the way that scientists think about the relationship between talent, effort, and mastery in a given domain. Across disciplines as varied as music and medicine, expert performance directly correlated with the amount of deliberate practice or training a person had engaged in, not simply the number of hours spent engaging in activities related to the domain, nor were there any other "innate" factors that seemed reliably to account for higher achievement (Ericsson, 2004; Ericsson et al., 1993). The key takeaway from Ericsson's work is not that practice makes perfect, but that the type of practice a person engages in is what matters (see Ericsson, Charness, Feltovich, & Hoffman, 2006; Ericsson & Pool, 2016).

The first published evidence that called into question the popular notion that more practice of any kind yields better mastery arguably came from studies of Morse code operators at the turn of the twentieth century (Bryan & Harter, 1897). The operators in these studies would show improvements in their skills with repeated practice, but eventually their progress would plateau and further practice yielded no more gains.

By changing their practice techniques, however, the operators were able to jumpstart their learning and continue to improve. Why?

Bryan and Harter (1899) suggested that this type of motor-skill learning involves building a hierarchy of habits: an operator must first learn the codes for each letter, then the patterns for words, and then eventually full sentences in order to show leaps in improvement. Each plateau, then, is a point in time at which the lower-order habit, say learning the codes for each letter, has been mastered but is not yet automated to the point where the learner no longer needs to pay close attention to it, and can focus on developing a mental representation of the next step in the hierarchy.

This change in mental representations, akin to the "chunking" of items in working memory, is a fundamental outcome of deliberate practice and the building blocks upon which complex skills are built, and echoes the findings from evaluations of training programs that focus on creative cognition: the key intervention is one that changes mental representations, proposes new heuristics, and deliberately targets ways of thinking (see Scott et al., 2004).

Are plateaus an unavoidable consequence of learning? In 1958, F. S. Keller unearthed evidence that not all training methods lead to plateaus, even in Morse code learning (Keller, 1958). Exactly how training changes mental representations remains an open question.

Somewhat akin to the debate of whether the performance of highly skilled individuals in artistic or athletic domains is more attributable to talent or practice, a person's working memory capacity was, for decades, a good example of what was perceived to be an inalterable cognitive capacity. Few introductory psychology courses fail to mention the seminal paper by George Miller (1956) in which he so eloquently describes his persecution by the "magical number 7." Not only is the paper a wonderful example of excellent writing, but it has also been so influential that the notion that our working memory capacity taps out at 7 ± 2 has become almost a cliché.

Nelson Cowan (see Cowan, 2005) has written extensively in his efforts to supplant this number with one that more accurately encompasses decades of research following Miller's observations (even pointing out that Miller himself did not mean for the number to be taken quite as seriously as it has been). Cowan suggests that our capacity is closer to three or four items, when we take chunking into account. The fact that this number pops up again and again in many different studies of working memory, so much so that Miller feels "persecuted," is evidence of the fact that there is a universal limit on the number of unassociated items that we can hold in mind at a given time. There is growing evidence, however, that not all items are treated equally and that working memory is perhaps more accurately conceptualized as a limited resource to be divided among items in mind, some requiring more than others (Klingberg, 2012; Ma, Husain, & Bays, 2014).

In creative endeavors, a larger working memory capacity might give a person an extra edge, one that might separate the elites from the rest of the professionals in a domain. For example, there is some evidence that working memory capacity can benefit creative insight and musical improvisation by enabling better attentional focus (De Dreu, Nijstad, Baas, Wolsink, & Roskes, 2012). It follows that if working memory capacity were innate, then someone endowed with an exceptional ability to hold multiple ideas in mind might be more likely to find the remote associations or leaps that others miss. Working memory capacity, therefore, is a good candidate for one component of the elusive concept of talent.

But is there any evidence that we can improve our working memory capacity? It is the answer to this question that set Anders Ericsson on the path delineating the characteristics of deliberate practice (Ericsson & Pool, 2016). In the 1970s, Ericsson and his collaborator Bill Chase began working with an undergraduate student at Carnegie Mellon University named Steve Faloon. There was nothing outwardly remarkable about Steve, other than the fact that he had agreed to participate in what would end up being a long and grueling psychological experiment. He also happened to be a serious runner.

Every day for a week, Steve came to the lab and practiced recalling strings of digits. Starting out with a capacity of about seven digits, he improved slightly over the course of the first few days, moving his limit to about eight or nine digits, but then he felt that he had reached a plateau. Ericsson then tried a different method of practice: he would start each session with a five-digit string, one that Steve could recall easily. Then, in subsequent trials, he would increase the string by one digit, until Steve made a mistake. Then, he would drop down two digits and repeat the process.

On the first day in which he tried this new way of testing Steve's capacity, he found that his subject made a leap – leaving his former plateau of eight or nine digits to reach 11 digits. With each subsequent day of practice, Steve's memory continued to improve, reaching 40 digits after 100 sessions. This improvement was remarkable, not only because it defied the traditional notion of a working memory capacity limit, but also because it was more digits than any professional mnemonist had been able to remember. After more than 200 sessions, his digit span reached 82.

While this feat is impressive, it is not immediately clear what increasing a person's digit span might have to do with creativity. One might even argue that repeating numbers back is among the least-creative tasks a person might engage in. However, the lessons that psychologists and educators can take away from this early work of Ericsson and Chase are far more profound than they might seem.

What accounts for Steve's astonishing improvement? Ericsson and Pool (2016) outline two important factors: the type of practice, in which Steve was challenged but not overwhelmed, and a change in the way that he performed the task, which resulted in the creation of new mental representations. What these factors have in common is that they both lead to mental and/or physical changes that make what was previously out of reach feel almost effortless and automatic. Indeed, this automaticity of a complex skill might explain why, in neuroimaging studies, deactivation of dorsolateral prefrontal cortex bilaterally correlates with spontaneous creativity such as that observed during musical improvisation (Limb & Braun, 2008), and that deactivation in the temporal-parietal junction seems to be modulated by expertise (Berkowitz & Ansari, 2010; Pinho, de Manzano, Fransson, Eriksson, & Ullén, 2014). Expertise, in turn, is found to increase connectivity between prefrontal regions (Pinho et al., 2014).

Ericsson, having studied individuals from domains as diverse as chess, tennis, music, and gymnastics, noted that to master a field, and to reach eminence, a person must learn to do something that was previously impossible, by gradually pushing the brain and the rest of the body to its limits, thereby harnessing its adaptability. Whether learning Morse code or lifting weights, it is not sufficient to simply repeat what a person can already do: repetition can lead to initial gains but eventually to learning plateaus. Furthermore, a desire to improve is also insufficient. Even thoughtful, or as Ericsson calls it, *purposeful* practice will only get you so far.

A person engaging in purposeful practice sets goals and moves toward them making incremental progress, focusing attention on the skill in question. It also involves feedback, preferably on every trial, so that the trainee can find and ultimately fix weaknesses. Purposeful practice, in Ericsson's view, also involves getting out of one's comfort zone – pushing beyond current limits. This key feature – going past what's comfortable and what feels easy – also seems to be important when measures of structural or functional changes in neural activity are the outcomes of training.

For example, introducing desirable difficulties into the training sessions, as coined by Bjork and colleagues (Bjork, 1994; Bjork & Bjork, 2011), is particularly effective in terms of long-term retention and training efficiency, even though it makes the training sessions feel more difficult and students report less satisfaction (Bjork, 1994; Jacoby, Bjork, & Kelley, 1994). One such desirable difficulty is interleaving rather than blocking practice trials. Instead of practicing the same piece over and over again (A1, A2, A3, B1, B2, B3, etc.), for example, a pianist would ultimately see greater benefit in terms of retention and efficiency if she interleaved her practice of different pieces in a random order (A1, B1, A2, C1, B2, etc.), as demonstrated in a study by Abushanab and Bishara (2013).

Bjork and Bjork (2011) suggest that the reason introducing desirable difficulties such as interleaving practice trials enhances learning is because it slows down the rate of learning, allowing for better encoding. In line with this idea, Lin et al. (2011) found that during interleaved practice, slower response times were correlated with greater frontal–parietal blood-oxygen-level-dependent (BOLD) responses, greater excitability in the motor cortex (M1) (as measured by paired-pulse transcranial magnetic stimulation or TMS) and sensorimotor regions, compared with blocked practice. These differences also correlated with the improved retention seen in the interleaved condition.

Furthermore, how interleaving practice enhances learning might have different neural bases in younger and older individuals. In a study of age-related differences in the neural underpinnings of motor sequence learning, Lin et al. (2012) found that both younger and older adults benefitted from interleaved compared with blocked trials. Both groups also showed slower response times during interleaved compared to blocked training. Again pairing BOLD and TMS measures, the authors found that the benefit of interleaved practice seemed to be modulated by activity in the dorsolateral prefrontal cortex in the younger group. Among older adults, the benefit correlated with activation in sensorimotor and rostral prefrontal cortex, suggesting that they may approach the tasks with different strategies, and that increased sensorimotor activation might represent compensatory mechanisms in the older group.

Regardless of age, purposeful practice is still not the whole story when it comes to becoming an expert: deliberate practice, which Ericsson argues is the key, is more than just purposeful practice. Deliberate practice almost always requires a teacher, or someone who can help the trainee create new and more effective mental representations, echoing the key feature of effective general creative cognition training methods mentioned earlier in this chapter. Within those new mental representations, arguably, lies the creative component of skill acquisition.

Steve Faloon, the star (and co-author) of Ericsson and Chase's famous 1980 study of digit span training, did not overcome his plateaus by simply trying harder (Ericsson, Chase, & Faloon, 1980). Steve, a runner, created a hierarchy of mnemonics related to running times that he could call upon when learning a new string of digits. He harnessed his long-term memory so that he could free up his working memory in order to organize the information, rather than having to rehearse individual items. He changed his mental representation of a string of digits from single units to an organized set of retrieval structures. He devised a new way of performing the task: arguably, he made a creative leap that revolutionized his field. He was the Mozart of digit spans.

Changing Mental Representations

There is perhaps no better body of literature investigating the importance of changing mental representations to enhance performance than studies of chess players. Indeed, one of the earliest examples of how different mental representations give experts an edge came from an exploration of the memory abilities of chess masters.

Adriaan De Groot (1946/1965) first documented how expert chess players are better able to remember where the chess pieces were on a board than were novices. Bill Chase, along with Herbert Simon (1973), followed up this work to show that this memory enhancement was only seen when the placement of the pieces on the board made sense, in terms of an actual game. When chess pieces were arranged haphazardly on the board, the ability of the masters to recreate the board from memory was no better than those of an amateur or even a novice.

What accounts for this improvement in memory? As chess masters seemed to be no better than novices at remembering random chess boards, Chase and Simon (1973) suggested that superior chunking – grouping individual items into meaningful “chunks” and thereby increasing working memory capacity for individual items – was a critical part of expert training. This interpretation was further supported by Chase and Ericsson’s (1982) work with Steve Faloon. The idea is that chess experts are able to “see” meaning in groupings of chess pieces, forming “chunks” that they can then hold in working memory. The greater the expertise, the more chunks a given player has access to. This library of chunks is estimated at somewhere between 10,000 and 100,000 bits in the most skilled players, according to Simon and Gilmartin (1973). However, Chase and Ericsson (1982) and later Gobet and Simon (1996) indicated that chunking only told half of the story.

Practice not only increases the number of chunks, but also their *size*: in a follow-up experiment, Gobet and Simon (1998) found that the size of the chunks, that is, how many pieces each chunk incorporates, was largest for the Masters, decreasing with chess skill. What is more, with greater skill, the Masters develop not just chunks but templates of pieces placed on a chess board, with the templates corresponding to frequently observed patterns of entire boards (Gobet & Simon, 1996). These templates then serve as scaffolds into which the current perceptual information – that is, the representation of the board either physically in front of the participant or a recollection of it from memory – can fill in.

Therefore, it is not only a matter of *what* (the number of chunks) changes with practice but *how* the information is encoded. Skill training changes the *mental representations* of the task, generating templates and a novel way of perceiving chess boards in chess experts. Only through long-term deliberate practice can these chunks and templates be laid down in long-term memory; but once that is accomplished, the experts can perform the task in a way that is fundamentally different from the slow, conscious, deliberate process upon which the novice must rely.

Training and Intelligence

One might argue that these differences in how the chess pieces are represented are just as closely related to visuo-spatial processing, or other aspects of intelligence captured by the Intelligence Quotient (IQ), as they are to practice. Perhaps those destined for mastery are simply endowed with greater intelligence. Is there evidence that intelligence largely accounts for variations in expertise? This question, too, has been addressed by studying chess skill development.

Bilalić, McLeod, and Gobet (2007) noticed that the link between higher intelligence and chess skill had thus far been somewhat elusive. To test this relationship directly, they measured the IQ of 57 young chess players (using four subtests from the WISC III), along with their chess skill. They also noted how much practice each player had so far engaged in, via face-to-face interviews with the youngsters cross-checked with questionnaires filled in by their parents. Their initial results showed that intelligence did factor into the players' performance, although practice was the biggest explanatory variable. Even with practice factored in, however, scores on the composite IQ tests were correlated with better skill.

Except, that is, for the best chess players. In a subsample of the 23 most skilled children, composite IQ scores did not predict, or if anything were negatively correlated with, chess prowess (note that the variance in the subsample was slightly smaller than the variance in the full sample: standard deviations of 12 and 15.3, ranges of 108–157 and 83–146, respectively). The smartest kids were not as good at chess as those who scored somewhat lower on the WISC III subtests. This finding is not limited to chess, however. The threshold hypothesis posits that creativity and intelligence are positively correlated up until an IQ of about 120 (Jauk, Benedek, Dunst, & Neubauer, 2013). Above that number, there is less evidence of IQ as being a major driver of creativity and other factors can exert greater influence, including motivation, mindset, opportunities, and so on.

What might account for these results in the chess players? Practice. The most intelligent children in the elite subsample spent *less* time practicing than their lower-scoring counterparts (Bilalić et al., 2007). In the elite subsample, practice, not IQ, differentiated the best from the pretty good, and there was a significant negative correlation between intelligence and practice among the best players.

This result is not out of line with several other studies of the relationship between measures of IQ and chess ability, dating back to 1927 when Djakow, Petrowski, and Rudik (1927) found no differences in measures of general intelligence and visuo-spatial memory comparing eight chess grandmasters with a control group of nonplayers. More recently, Unterrainer, Kaller, Halsband, and Rahm (2006) also found no correlation between chess skills and performance on the Raven's Progressive Matrices, digit span, or Corsi block-tapping tests among 25 chess experts. Nor did the chess group differ from the age and education matched control group of nonplayers.

Chess expertise has played a dominant role in the talent versus practice debate, as the chess prodigy is often hailed as a prime example of innate gifts. It is such a poster-child for genetically endowed differences that two Hungarian teachers, Laszlo and Klara Polgar, turned to chess to overturn the perception that women are inferior by nature in terms of the skills needed to master the game. They took the education of their three daughters into their own hands, and, among other things, taught them to play chess at an early age. All three girls became expert chess players, with the youngest, Judit, beating Bobby Fischer's record of becoming the youngest grandmaster at age 15. She went on to become the strongest female player of all time. Her elder sister, Susan, is known for breaking the gender barrier in 1986, qualifying for the men's world championship, and becoming an advocate for women's equality in chess (see Charness, Krampe, & Mayr, 1996).

While the story of the Polgar sisters is little more than anecdotal (see Howard, 2011), there has been a more in-depth exploration of the gender differences in chess players. Bilalić and colleagues (2009) suggested that because there are many more men playing chess than women, the reason why there are so few women in the top spots in the chess hierarchy has more to do with statistical sampling than biological or even cultural differences. With more women playing, there would be a higher likelihood of outliers in the distribution, with more of them attaining higher levels of skill.

Certainly, intelligence has a high heritability (Galton, 1865), but the question of the extent to which creative cognition, encompassing a different set of traits, is trainable remains to be considered. When we watch someone execute a complex skill, whether in gymnastics, music, painting, sculpture, dance, or any number of other domains, our brains often jump to the conclusion that this person is special – unlike ourselves – at least in this field. This experience is particularly powerful when the domain is completely unfamiliar to us – when it is difficult for us to even imagine how that action might have been accomplished. We have a label for the subset of skills involved in a complex task whose development we do not understand yet – we call it talent.

Talent, as a concept, can become a catch-all term for those aspects of skill development that we have yet to uncover (but see Howard, 2009). These aspects might include genetic influences, which account for less of the variability in creativity than in some other cognitive traits, such as intelligence (for review, see Barbot, Tan, & Grigorenko, 2013). Indeed, Barbot and colleagues call the heredity of creativity "low to moderate," whereas intelligence is considered highly hereditary, with genes accounting for some 50% of the variance in individuals. Where creativity is concerned, that number is likely closer to 9%–10% (Reuter, Roth, Holve, & Hennig, 2006). Aside from genetics, the concept of talent certainly incorporates many other processes of which we remain, as of yet, unaware.

On the surface, there seems to be little harm in using the term "talent" to label what we have yet to discover about excellence in a domain, but when it comes to the training of creativity, there is a dark side to this practice. In fact, many eminent performers, whether they are opera singers, golfers, or acrobatic pilots, respond in the same way when an admirer expresses awe in the face of their "talent": they point out that it is not dumb luck that resulted in their superior performance, but rather years of deliberate practice.

Mindsets and Motivation

Because skill development and ultimately the creative process requires a great investment of time and energy, motivation must figure prominently in any discussion of the development of creative thoughts and actions. Therefore, we now turn to a discussion of mindsets and their relationship to motivation – the third of Amabile's (1983) internal characteristics – and how they relate to the specifics of skill development with a consideration of how these factors interact to enhance or suppress creative behaviors.

Much of the evidence supporting the idea that internalizing a belief that intelligence or talent is innate rather than developed comes from the work of Carol Dweck and her colleagues (Dweck & Leggett, 1988). Dweck distinguishes two types of mindsets, or implicit or nonconscious beliefs about intelligence and, by extension, talent: growth and fixed, or incremental and entity, respectively. Individuals with a fixed or entity mindset internalize the belief that intellect or performance in a particular domain, be it math, music, or sports, for example, is innate. That is, they believe that we are each born with some potential and while we can work to reach it, ultimately we are limited by our natural "gifts." A fixed mindset has been shown to be favored when a child is praised for achievement rather than effort (Mueller & Dweck, 1998).

With a growth or incremental mindset, in contrast, an individual internalizes the belief that skills, whether academic, creative, or physical, are developed with effort and practice. As a result, growth mindset individuals approach learning and, importantly, failure, fundamentally differently, compared to people with a fixed mindset. They tend to put in more effort, are less affected by setbacks, focus on the content rather than the emotional impact of corrective feedback, and ultimately are often more successful later in their careers.

Evidence for the effect that beliefs about intelligence can have an impact on academic success comes from a study by Blackwell, Trzesniewski, and Dweck (2007) of adolescent students. In this study, the authors found that a growth mindset predicted improvement in academic achievement over the course of two years, while a fixed mindset correlated with a flat trajectory. In addition, when the students experienced an intervention, designed to teach them a growth mindset, they demonstrated greater classroom motivation compared with a control group. The control group then showed a downward trajectory in terms of their grades, while the opposite was seen in the experimental group. Furthermore, Haimovitz, Wormington, and Corpus (2011) found that, in a sample of 978 elementary and middle school students, children whose intrinsic motivation to succeed academically declined over the course of a year were more likely to have endorsed an entity theory of intelligence, akin to a fixed mindset, than students whose motivation was maintained or increased over the course of the year.

Well before Dweck and her colleagues published their findings, music teachers in particular had been wary of giving too much praise: Ivan Galamian, an Armenian violin teacher who became the head of the Juilliard Violin department in 1946, cautioned that too much praise causes students "to relax their efforts" (Galmanian, 1962, p. 106). He observed that too much early recognition leads to "prima donna" behavior and less work, which ultimately leads to less improvement: observations that Dweck has confirmed in children with fixed mindsets.

It is important to note, however, that a growth mindset is not just about effort: it also involves trying different strategies, being open to alternative approaches and seeking help when needed. Traits like openness and flexibility are key features of creative individuals, exhibited consistently with their higher scores on openness to experience (Silvia et al., 2008; Silvia, Nusbaum,Berg, Martin, & O'Connor, 2009). Dweck (2015) also pointed out that we must acknowledge the existence of talent – keeping a growth mindset does not necessitate banishing any fixed ideation, or ignoring natural gifts.

Mindset can influence how a person will feel when criticized or corrected, and therefore what type of information will be remembered about the learning event. In a clever study of Columbia University undergraduates, Mangels and colleagues (2006) asked their participants to take a general knowledge test while undergoing an electroencephalogram (EEG). Before beginning, the students took a test of their theory of intelligence (TOI), answering questions such as "how strongly do you agree or disagree with the following statement: You have a certain amount of intelligence and you can't do much to change it." On the basis of their answers on the TOI test, they were divided into two groups: entity theorists, who, akin to those with a fixed mindset, leaned more toward a view that intelligence is innate; and incremental theorists, who viewed intelligence as acquirable.

During the general knowledge test, the participants were first told whether their answers were correct, and then they were given the correct answer. The difficulty of test questions was titrated such that participants answered around 40% correct overall. A few minutes later, participants were given a surprise retest on the questions which they failed to answer correctly during the first part of the experiment. On the retest, students labeled as incremental theorists, that is, those with a growth mindset, performed significantly better than entity theorists, or those with a fixed mindset, despite comparable performance on the initial test. These results lend credence to the notion that mindset affects ultimate success by enhancing learning in people with a growth mindset.

But just how does this enhancement happen? To answer that question, Mangels et al. (2006) analyzed the EEG data using an event-related potential (ERP) approach, in which they could compare brain activity in specific regions during the different phases of the general knowledge test. When the students first learned whether their answers were correct, those with an entity TOI showed greater activation in frontal regions often associated with emotional responses when their answers were incorrect, compared with incremental theorists. While this type of reverse inference has many pitfalls, the idea that students with a fixed mindset respond more emotionally to negative feedback is in line with models of how mindset affects motivation (Dweck, Mangels, & Good, 2004).

Furthermore, when the correct answers were presented to the students during the general knowledge test, those with an incremental TOI showed more encoding-related activity in frontotemporal networks, which might explain why they were more likely to retrieve the correct answer on the surprise retest. Mangels et al. (2006) interpret these results as suggestive of the idea that incremental theorists orient more toward deeper semantic processing of the content of the criticism, resulting in more effective learning, while entity theorists engage in more emotional processing and fail to attend to the corrective feedback.

These findings match my own observations working with undergraduate and graduate students at the San Francisco Conservatory of Music. In my experience, students with a fixed mindset regarding musical talent tend to spend more time practicing pieces that they have already mastered, while shying away from challenging repertoire; become upset when criticized; and envy or denigrate colleagues who win competitions or auditions, rather than finding inspiration in the success of others, ultimately affecting their motivation to engage in deliberate practice.

If one considers the long-term effect of this relatively subtle difference on many trials during training, it becomes clear how mindset can make or break a career in which skill development plays a large role. Indeed, as mentioned above, Haimovitz et al. (2011) published results of a longitudinal study in which they found that children whose intrinsic motivation declined over the course of an academic year were more likely to endorse an entity TOI, while those with an incremental TOI were more likely to maintain or even increase their intrinsic motivation.

Researchers of creativity have long known that motivation is a major predictor of whether someone will stick with a problem long enough to come up with a creative solution, whether it be in music, visual art, writing, chess, or any other domain in which creativity is valued (Sternberg & Lubart, 1991). Teresa Amabile has focused much of her research on understanding how environmental constraints affect intrinsic motivation, and therefore creativity, and has found five "sure-fire killers of creativity: the expectation of a reward, the expectation of being evaluated, overt competition, surveillance, and time limits" (Amabile, 1983, 1996; Hennessey, 1996). Even on an individual basis, sometimes measuring an activity can take away its capacity for providing pleasure. For example, Jordan Etkin (2016) recently found that quantifiyng an activity, which has become far more common and easy to do with the emergence of countless wearables and other devices, can make it feel like work, diminishing intrinsic motivation.

Turning to the domain with which I am most familiar, music, there is a growing body of evidence that what distinguishes the great players, those who go on to play in world-renowned symphonies, or have successful solo careers, is the amount of deliberate practice that they engage in (Ericsson et al., 1993). However, what leads one person to spend more hours in this effortful practice than another still remains somewhat mysterious, enough so that the concept of talent creeps up again and again in discussions with music educators.

Yet research that is now almost two decades old has shown that students who practice more, whether that practice involves playing for fun, or improvising, working on new or existing repertoire or technical skills, like scales and arpeggios, are more cognitively engaged during practice sessions, running music in their minds, and have distinct goals and ways in which they can evaluate how well they are playing in the moment (McPherson & McCormick, 1999). This engagement suggests that they are more efficient in their practice time, and ultimately, maintain greater intrinsic motivation.

In a follow-up study, McPherson and McCormick (2006) surveyed music students' state of mind and self-evaluation immediately before entering a musical examination. Their most striking finding was that a student's self-confidence in his or her own performance that day accounted for the greatest amount of variance (18%–29%) of the results of the exam, compared with general self-efficacy (i.e., how good a musician are you?) and the student's interest in playing their instrument. Most recently, Bonneville-Roussy and Bouffard (2015) have proposed a model integrating self-regulation, deliberate practice strategies, and practice time, which proved to be a better predictor of musical achievement than other traditional measures, such as practice time alone.

Conclusions

Taken together, evidence is mounting that creativity is not only trainable, but involves deliberately changing how a person thinks (i.e., his or her mental representations), through incremental steps. A trainee staying the course and therefore the individual's success in a program is closely tied to motivational factors, with a growth mindset making the trainee more likely to succeed by engaging in the kind of variable deliberate practice that is optimal for building critical domain-specific skills. Furthermore, brain changes that accompany training gains are specific to the skills developed, and may include more efficient neural processes reflected in deactivations of executive control regions and greater activations, connectivity and/or volume in sensory, motor, and association domain-specific areas, depending on the type of creative activity in which the person engages.

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23 Intelligence and Creativity from the Neuroscience Perspective

Emanuel Jauk

This chapter deals with the relationship between intelligence and creativity from a neuroscientific perspective. The common and differential aspects of the two constructs are first illustrated on the basis of behavioral findings, and it is suggested that both cognitive constructs draw on similar elementary-cognitive processes. These findings are then reevaluated from the view of cognitive neuroscience, which provides additional support for the behavioral findings, but also helps to better understand the factors that discern creativity from intelligence. The interplay of both constructs is illustrated based on functional connectivity studies. Finally, structural neuroimaging studies are reviewed, which point to relatively stable interindividual differences in brain morphology in relation to creativity. The findings are summarized in the light of dual-process models of human cognition, which emphasize the necessity of controlled and spontaneous processes for creativity.

Psychometric Research on the Relationship Between Intelligence and Creativity

There is a long-standing debate on whether intelligence and creativity are different, overlapping, or conjoint abilities (e.g., Sternberg & O'Hara, 1999). Creativity, in terms of cognitive creative potential, is commonly defined in terms of the ability to produce novel and useful ideas (Barron, 1955; Runco & Jaeger, 2012; Stein, 1953; see also Diedrich, Benedek, Jauk, & Neubauer, 2015). Guilford, who was one of the first to conceptualize human creativity in terms of a normally distributed trait – divergent thinking ability – conceived creativity as a subset of general intelligence in his well-known structure of intellect model (Guilford, 1967), thus putting emphasis on the similarity between both constructs. On the contrary, other early accounts of creativity emphasized the independence of the two constructs (e.g., Getzels & Jackson, 1962; Wallach & Kogan, 1965). As Silvia (2015) points out in his in-depth methodological review, these different conceptualizations might originate from substantially diverging approaches to the operationalization of creativity. Creative potential is commonly evaluated by means of divergent thinking tasks (e.g., "find many creative uses for a brick"). While Guilford took many criteria into account to score divergent thinking tasks, among them the originality (quality) of responses, Wallach and Kogan (1965) focused on the scoring of unique responses in terms of statistical infrequency, thereby disregarding their quality. Guilford's approach led him to conclude that intelligence and creativity are highly related abilities, while Wallach and Kogan assumed that they are essentially unrelated. As can be seen, the emphasis of quality or quantity in the assessment of creativity can lead to dramatically different conclusions with respect to the relationship between intelligence and creativity.

About 50 years after the debate on the relationship between intelligence and creativity began, it is still highly relevant: In an attempt to clarify the situation by means of meta-analysis, Kim (2005) estimated the average correlation among the two constructs at

r = .17 and concluded that the relationship is small and “negligible” (p. 57). She also acknowledged, however, that the correlation is heterogeneous and that using different types, modalities, and scoring of divergent thinking tasks influences the estimate. Besides new methodological approaches to the scoring of divergent thinking tasks (see Silvia et al., 2008 and Benedek, Mühlmann, Jauk, & Neubauer, 2013), more recently, latent variable modeling has gained increasing popularity among creativity researchers. It allows for the estimation of error-free, “true” associations among latent constructs (not observed variables). In a re-analysis of Wallach and Kogan’s (1965) data, Silvia (2008a) reported a correlation of r = .20 (instead of the initial estimate of r = .09) among the two constructs. He concluded that the true relationship might have been underestimated by relying on observed test scores rather than using latent variables, although the data are based on (quantitative) uniqueness scoring. When latent variable modeling is applied to scores of ideational originality instead, as assessed by means of (inter-)subjective ratings of peers (i.e., consensual assessment technique; Amabile, 1982), the estimates are again considerably higher: standardized effects of (fluid) intelligence on originality range from β = .43 (Silvia, 2008b) over β = .51 (Benedek, Franz, Heene, & Neubauer, 2012) to r = .62 (Jauk, Benedek, & Neubauer, 2014).

These results demonstrate that, using sophisticated scoring methods and latent variable modeling, creativity and intelligence are found to be highly related constructs, which led Silvia (2015) to conclude that “intelligence and creativity are pretty similar after all” (p. 599). This raises the question: What makes these two constructs so similar? Most likely, this similarity is grounded in a common set of underlying, lower-level cognitive abilities in terms of executive functions (sometimes also referred to as “frontal lobe” functions: inhibition, shifting, updating; see Miyake et al., 2000). There is a well-documented relationship between intelligence and executive functioning: not only is there a considerable correlation between intelligence and high-level tests of executive functioning (e.g., the Wisconsin Card Sorting Test; cf. Ardila, Pineda, & Rosselli, 2000), but also low-level, elementary-cognitive executive functions, particularly updating, were found to be closely tied to intelligence (e.g., Friedman et al., 2006). This fits with the finding that intelligence is highly correlated with performance on working memory tasks (Ackerman, Beier, & Boyle, 2005; Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004; Oberauer, Süß, Wilhelm, & Wittmann, 2008).

There is also a growing body of evidence for the involvement of executive functions in creativity: the ability to produce original responses in divergent thinking tests depends on updating (as does intelligence) and inhibition (of pre-potent responses; Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014; Edl, Benedek, Papousek, Weiss, & Fink, 2014). Most importantly, interindividual differences help to explain some of the common variance between creativity and intelligence (as the latent correlation decreases from r = .45 to r = .34 when executive ability is statistically controlled for; Benedek et al., 2014). The involvement of updating in creativity is further substantiated by research showing a correlation between working memory tests and divergent thinking ability (De Dreu, Nijstad, Baas, Wolsink, & Roskes, 2012; Oberauer et al., 2008). Turning to other executive functions, it was also found that shifting ability impacts the relationship between intelligence and creativity (Nusbaum & Silvia, 2011; Pan & Yu, 2016), which provides additional evidence for the indirect association between both constructs. Taken together, elementary-cognitive functions, such as updating and manipulation of relevant memory content, are likely to represent a common ground for convergent (intelligence-related) and divergent (creativity-related) thinking processes.

The Nonlinear Relationship Between Intelligence and Creativity

While Guilford (1967) was one of the first to incorporate creative ability in a complex model of human intelligence, thus assuming a substantial correlation between the higher-order *g*-factor and creative ability, he also noticed that the correlation between the two constructs varies at different levels of IQ: In scatterplots of the bivariate relationship, he observed a "triangular pattern"[1] in the distribution of data points which indicates that creative potential is correlated with intelligence only in the lower but not in the upper IQ range. This observation has become known popularly as the "threshold hypothesis," which posits that above-average intelligence (usually IQ > 120; see Jauk, Benedek, Dunst, & Neubauer, 2013) reflects a *necessary, but not sufficient condition* for high creative capacity. The threshold hypothesis implies that there should be a substantial correlation between measures of intelligence and creativity in the mid–lower (IQ < 120), but not in the upper (IQ > 120) ability range.

Although the threshold hypothesis has high face-validity (i.e., it is hard to imagine a creative genius like Mozart being of low intelligence), it led to much controversy in scientific research and discourse in the past 50 years. While earlier studies mostly yielded support for a threshold effect (Barron, 1963, 1969; Getzels & Jackson, 1962), the previously mentioned meta-analysis did not find evidence in favor of the threshold hypothesis (Kim, 2005). This might at least partially be attributed to different methodological accounts (e.g., Silvia, 2015). Preckel, Holling, and Wiese (2006), for instance, investigated the threshold hypotheses in a large-scale study of 1300 gifted and nongifted schoolchildren. The correlations between indicators of intelligence and creativity ranged from $r = .30$ to $r = .40$ across all levels of intellectual ability, thus rejecting the idea that the two constructs would only be related in the lower ability range. Moreover, correlations between the two constructs vanished completely when speed of information processing was controlled for (see also Preckel, Wermer, & Spinath, 2011), which is in favor of Wallach and Kogan's (1965) early study (in which untimed tests were used). It is important, however, to note that this large-scale study relied on ideational fluency, a purely *quantitative* marker of ideational capacity, as an indicator of creativity. As outlined above, the correlation between measures of intelligence and creativity is much more pronounced when the (peer-evaluated) *quality* of ideas is taken into account.

Thus, in an attempt to replicate and extend previous accounts of the threshold hypothesis, we investigated the threshold hypothesis using different indicators of creative potential (Jauk et al., 2013). As threshold effects were shown to be sensitive to the hypothesized IQ breakpoint (Karwowski & Gralewski, 2013), we additionally aimed for an empirical detection of possible thresholds by means of segmented regression analyses[2] (rather than comparing correlations in subsamples below and above a given IQ threshold). We found evidence for threshold effects in the way that IQ thresholds increase as the criterion under study becomes more demanding: For the purely qualitative criterion of ideational fluency, the IQ threshold was rather low (IQ 86.09), which might explain the absence of threshold effects in other studies investigating fluency (e.g., Preckel et al., 2006). For the production of two or more

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[1] "Triangular" because the bivariate distribution lacked data points in the low intelligence/high creativity quadrant.

[2] Segmented regression is a statistical method that is commonly used in epidemiology, for instance. It allows for the detection of possible breakpoints in continuous bivariate distributions by means of iterative computation and is thus suited to answer research questions like "which level [breakpoint] of stressor X must be attained for an impact on health outcome Y?" We used this method to empirically determine the intelligence level at which intelligence and indicators of creativity are still correlated, but beyond which intelligence has no predictive power anymore.

original ideas, however, IQ thresholds were markedly higher (IQ 104.00 for top-2 and 119.6 for average originality scores), with the latter actually perfectly resembling the frequently mentioned IQ 120 threshold. A recent large-scale investigation (*N* = 12,255) of the threshold hypothesis by means of necessary condition analysis (Dul, 2016) yielded further evidence for the idea of intelligence as a necessary but not sufficient condition for creativity (Karwowski et al., 2016).

How could these results be reconciled with the findings on creativity and executive functioning outlined above? Although it has not been explicitly investigated to date, it appears likely that creativity benefits from executive functions (associated with intelligence) especially in the lower range of the intelligence distribution (as a tentative guess, probably below IQ 90, similar to the fluency threshold described above). Divergent thinking ability could, for instance, be limited by updating ability in terms of a necessary but not sufficient condition: the ability to maintain and manipulate ideas in the working memory system is highly relevant when thinking of alternate uses for a brick, for example, in order to try out (and evaluate) different combinations ("could I use it as a flower pot?" "… or maybe as a sieve?"). Intelligence-related abilities also foster creative thought through the implementation of effective strategies (Nusbaum & Silvia, 2011), which demands high attentional control. However, as the threshold hypothesis posits, intelligence-related abilities alone will not guarantee high-quality outcomes in terms of creative ideas. There must be other bases for creative idea generation that tap more into the intersection between ability and personality factors, as outlined in the section on the neurophysiology of creativity below.

The Neurophysiology of Intelligence

The search for the neural bases of intelligence has a long-standing tradition in cognitive psychology. Long before the use of electroencephalography (EEG) or functional magnetic resonance imaging (fMRI), efforts were undertaken to relate interindividual differences in human intelligence to characteristics of the nervous system, for instance Galton's (1888) measurement of head size or mental speed (Galton, 1883) in relation to mental ability. To date, the neuronal processes underlying human intelligence are commonly studied using EEG or fMRI while participants perform classic intelligence tasks that are highly *g*-loaded (e.g., Raven's matrices; cf. Deary, Penke, & Johnson, 2010). By these means, inter- and intraindividual differences in intelligence test performance can be related to differences in brain activation. This functional imaging approach is complemented by structural studies of gray and white matter volume, thickness, and integrity in healthy individuals as well as patients with brain lesions (i.e., lesion mapping).

Based on a review of 37 such neuroimaging studies, Jung and Haier (2007) formulated the Parieto-Frontal Integration Theory (P-FIT), which is to date arguably the most well-known and comprehensive theory on the neural bases of human intelligence and has received repeated empirical support (e.g., Colom et al., 2009; Deary et al., 2010). The P-FIT proposes a four-phase model of information processing during goal-directed reasoning: first, sensory information is processed by occipital and temporal areas (BAs 18, 19, 37, 22). This information is then integrated in parietal (associative) cortical regions (BAs 39, 40, 7), where symbolism, abstraction, and elaboration are thought to emerge. During the hypothesis-testing phase, frontal and parietal areas (BAs 6, 9, 10, 45, 46, and 47) interact, forming a working memory network, to evaluate and test hypotheses on possible solutions to a specific problem at hand. Finally, the selection and inhibition of possible solutions is associated with activation of the anterior cingulate cortex (BA 32). The P-FIT thus proposes a dynamic interplay between frontal (executive) and parietal (associative) brain areas during goal-directed reasoning. In line with this, it was found that functional connectivity between frontal and parietal brain areas is higher in more intelligent individuals (Song et al., 2008), even at young age (Langeslag et al., 2013). Importantly, this higher connectivity appears to be an intrinsic feature of brighter individuals' brains that can be observed during rest (i.e., the absence of any particular cognitive task). A recent meta-analysis of functional and structural brain imaging studies on interindividual differences in intelligence yielded further support for the P-FIT, although the authors acknowledged that the question of functional and structural overlap needs to be further refined, and the role of subcortical structures might have been underestimated in previous research (Basten, Hilger, & Fiebach, 2015; see also Burgaleta et al., 2014; Grazioplene et al., 2015).

While the P-FIT is based mainly on a localization approach (associating a cognitive process with a specific brain region), recent neuroimaging approaches have begun to unveil the network dynamics of the human brain (e.g., Sporns, 2014). Using independent component analysis and related techniques during fMRI, the existence of several networks such as the default mode network, the executive control network,[3] or the salience network (among others) were proposed. Interestingly, recent evidence from functional connectivity studies shows that the cognitive control network aligns very well with brain areas postulated in the P-FIT (Vakhtin, Ryman, Flores, & Jung, 2014). This concerns particularly the dorsolateral prefrontal cortex (DPLFC; BAs 9, 46) and the posterior parietal cortex (BAs 39, 40). The (right and left) DLPFC, in turn, is consistently activated during working memory demands (Curtis & D'Esposito, 2003), and lesion to the DLPFC impairs working memory function (Barbey, Koenigs, & Grafman, 2013). Adding to psychometric research on the relationship between working memory and intelligence (Ackerman et al., 2005; Colom et al., 2004), these neuroimaging studies point to working memory as a central neurophysiological basis for more complex reasoning processes.

While the efforts to locate brain regions corresponding to interindividual differences in intelligence could be seen as reflecting a contemporary account of Galton's early structural approach (brain volume is still considered a robust correlate of general intelligence with correlations around $r \sim .30$; cf. McDaniel, 2005), another account of the neuroscientific study of intelligence relates to his mental speed approach. The investigation of brain characteristics influencing global speed of information processing can be seen as a complementary approach to the localization of structures or networks that relate to intelligence. One such characteristic is the integrity of white matter fiber tracts, which were found to be higher throughout the entire brain in more intelligent individuals (Penke et al., 2012). This likely enables highly intelligent individuals to process information more quickly and thus more efficiently. Intelligent individuals were also found to display a more efficient organization of functional brain networks (in terms of path length in graph analyses), particularly in frontal and parietal brain regions (van den Heuvel, Stam, Kahn, & Hulshoff Pol, 2009). In line with the idea of efficient information processing in the brain, it was also found that individuals of higher intelligence display a more efficient functional allocation of brain resources in terms of comparatively lower metabolic activity during cognitive tasks (Haier et al., 1988). This phenomenon, which might appear somewhat counterintuitive at first sight, has become popular as the *neural*

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[3] Research on functional brain networks is currently flourishing and different terms such as "cognitive" or "executive" control network or "central executive" network were introduced and are sometimes used interchangeably. Although "executive" appears to be the more specific term, more studies will be needed to clarify which one might be more adequate in terms of functional characteristics.

efficiency hypothesis, and has been investigated thoroughly in the past decades. Neural efficiency is known to depend upon factors such as level of expertise and task complexity (e.g. Dunst et al., 2014), among others (Neubauer & Fink, 2009).

Taken together, current neuroscientific research on human intelligence shows that reasoning processes crucially involve frontal and parietal brain areas, as outlined in the P-FIT. Specifically, activation in frontal areas is thought to reflect executive cognitive processes, while parietal activation is assumed to reflect associative integration and elaboration. Connectivity studies demonstrate that, together, these areas form the executive control network (Bressler & Menon, 2010; Yeo et al., 2011). An effective communication between frontal and parietal areas is further associated with higher intelligence, as is neuronal integrity of white matter tracts throughout large parts of the brain. In line with this, highly intelligent people display relatively lower brain activation than their less-intelligent counterparts in terms of neural efficiency.

The Neurophysiology of Creativity

The brain processes underlying creative idea generation are commonly studied using divergent thinking tasks during EEG or fMRI. A divergent thinking paradigm usually encompasses an idea generation period, during which participants are instructed, for example, to find novel and useful uses for everyday objects (e.g., a brick; Fink, Benedek, Grabner, Staudt, & Neubauer, 2007). After a certain time period or a button press, participants then overtly or covertly name their ideas. Until recently, reviews of the neuroscience of creativity yielded a rather inconsistent picture of creative cognition in the human brain (Arden, Chavez, Grazioplene, & Jung, 2010; Dietrich & Kanso, 2010; Sawyer, 2011). They concluded that creative thought processes seem to activate various regions of the entire brain, rather than consistently engaging any particular region or set of regions. Thus, these reviews also rejected the (historical) view that creative cognition would depend exclusively upon the right hemisphere. It was further acknowledged that lower integrity or damage of brain structure can lead to enhanced creativity in certain cases (e.g., Jung & Haier, 2013).

Recent meta-analyses of functional imaging studies show that creative cognition indeed engages a widespread network of brain areas, including predominantly left-hemispheric frontal and parietal regions that are also implicated in reasoning processes: divergent thinking as measured in both verbal and visual modalities involves the activation of left prefrontal, temporal, and parietal areas (Gonen-Yaacovi et al., 2013), more specifically the lateral prefrontal cortex, the posterior parietal cortex (including the inferior parietal lobe [BA 40] and precuneus [BA 7]), the anterior cingulate (BA 32), and several temporal regions (Wu et al., 2015). Interestingly, these findings are largely consistent with the P-FIT of intelligence, which might not be considered particularly surprising in light of the psychometric research presented above: divergent thinking, much like goal-directed reasoning, draws upon elementary cognitive processes such as working memory and executive control. Working memory training was, for instance, found to lead to *de*creased activation in the DLPFC (a key region of the working memory system) during divergent thinking, which provides further experimental evidence for the involvement of intelligence-related functions during divergent thinking (in terms of neural efficiency; Vartanian et al., 2013). Besides the neurophysiological commonalities of intelligence and creativity, however, what is particularly interesting for the study of creativity are brain activations during divergent thinking that are *not* commonly implicated in convergent thinking. One of these regions is the precuneus (Gonen-Yaacovi et al., 2013).

The precuneus is a structure that lies in the medial part of the parietal lobe and is currently believed to be a central hub in the brain's default mode network (DMN; Fransson & Marrelec, 2008). The DMN received its name from studies investigating the human brain at rest (i.e., when participants were instructed to lie still and not think of anything in particular during fMRI). In these studies, it was discovered that a widespread network of cortical midline structures were consistently activated during resting state (Gusnard & Raichle, 2001; Raichle & Snyder, 2007). As soon as attention is externally directed to a specific task at hand, the default mode network disengages and other networks, particularly the Cognitive Control Network (CCN), become more active (Buckner, Andrews-Hanna, & Schacter, 2008). The observation that the DMN disengages as a consequence of external task demands led to the DMN being labeled a "task-negative network" (Fox et al., 2005). As Leech and Sharp (2014) point out, however, "this is misleading as increased DMN activity is observed in many situations where attention is internally directed" (p. 15). Further studies found that DMN regions are also activated during states of mental simulation (Spreng, Stevens, Chamberlaine, Gilmore, & Schacter, 2010), episodic memory retrieval and anticipation of future events (Buckner & Carroll, 2007), as well as mind-wandering (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Hasenkamp, Wilson-Mendenhall, Duncan, & Barsalou, 2012; Mason et al., 2007). In line with this, we found, in a recent functional imaging study on internal and external attention during divergent thinking, that DMN activity is not related to internal attention *per se*, but rather to *self-generated thought* (which cannot be commonly disentangled unless using specific experimental paradigms; Benedek et al., 2016). Consequently, DMN activity might be understood as a brain state pointing to the active generation of new mental representations by integrating different memory contents (Andrews-Hanna, Smallwood, & Spreng, 2014). Chapter 10 by Benedek in the present volume provides an in-depth discussion of the relationship between attention and active generation of mental content.

The view of DMN activity as an indicator of active generation of new mental representations aligns very well with different conceptions of the creative process: the generation of new ideas has long been hypothesized to depend crucially on primary process cognition (Kris, 1952), divergent thinking (Guilford, 1967), loose associative processing (Mednick, 1962), defocused attention (Mendelsohn, 1976), or Type 1 processes (Kahneman, 2011; Stanovich, 1999). As Martindale (1999) concluded, many of these theories are "more or less identical but expressed in very different vocabularies" (p. 139). Creative cognition is associated with rather implicit than explicit and abductive than deductive processing (Jung, 2014), which can be characterized by self-generated and loose-associative cognitive processes that are currently attributed to the DMN.

However, creative ideas do not arise from divergent thinking *alone* but have since been hypothesized to emerge from an interplay between divergent and convergent thinking processes (e.g., Guilford, 1966, 1967), particularly during states in which the individual is concerned with the evaluation of creative ideas (e.g., Cropley, 2006). Creative individuals were also found to be better able to flexibly shift between divergent and convergent thinking demands (Jauk, Benedek, & Neubauer, 2012). Creative cognition can thus be conceptualized in terms of a deliberate interplay between spontaneous and controlled cognitive processes (Benedek & Jauk, 2017). In line with this, recent functional connectivity studies point to higher coupling of DMN and executive control networks in highly creative individuals during rest (Beaty et al., 2014) and during divergent thinking (Beaty, Benedek, Kaufman, & Silvia, 2015; see also Beaty, Benedek, Silvia, & Schacter, 2016). During divergent thinking, connectivity between the precuneus/posterior cingulate cortex and frontal and parietal regions was found to increase over time, which points to increased coupling at later stages of task processing (Beaty et al., 2016). Chapter 14 by Beaty and Schacter in the present volume provides more detailed information on the interplay between DMN and executive networks.

Further evidence for the involvement of the DMN in creativity stems from a growing number of structural MRI studies associating structural characteristics of the precuneus with interindividual differences in creative potential (Chen et al., 2015; Fink et al., 2014; Jauk, Neubauer, Dunst, & Benedek, 2015; Kühn, Ritter, Müller, van Baaren, Brass, & Dijksterhus, 2014; Takeuchi et al., 2010; one study did not spot evidence for precuneus involvement, Zhu, Zhang, & Qiu, 2013). Unlike functional studies associating activity in DMN regions with the process of creative idea generation, structural studies point to relatively stable interindividual differences in DMN morphology in relation to creativity. This would suggest that the DMN is not only functionally involved in the creative process, but stable differences in trait creative potential relate to variations in precuneus gray matter volume. Because the existing structural studies are cross-sectional in nature, no definitive answer can be provided to the question whether creativity is a cause or a consequence of differences in brain structure. However, it can be concluded that creative potential is tied to morphological variations in some regions, such as the precuneus, more than others, such as P-FIT regions. This might help to discern the unique features of "creative brains" from those of "intelligent brains" (cf. Jung & Haier, 2013). Despite creative idea generation involving many P-FIT areas on a functional level, the long-term structural correlates seem to tap more into DMN regions, which might extend our understanding of the creative person: creative individuals are not only of above-average intelligence (e.g., Jauk et al., 2013), but they also seem to display a higher engagement of default-mode processes in everyday life. This notion is supported by the finding that creative individuals have high fantasy activity (Martindale, 1999) and spend more time in mind-wandering activities (Baird et al., 2012). It was also found that creative people "fail" to deactivate default mode regions during a working memory task (Takeuchi et al., 2011), which suggests that their DMN is relatively more active even under conditions of increased cognitive load. Taken together, this evidence provides a more in-depth understanding of creativity beyond "mere" high intelligence.

The threshold hypothesis on the relationship between intelligence and creativity was also investigated on a brain structural level: in a spectroscopic MR study, Jung et al. (2009) observed different correlations between creative potential and *N*-acetyl-aspartate (NAA), a marker of neuronal integrity, in groups of lower and higher intelligence. The findings point to increased left-hemispheric functioning in participants of higher intelligence, which might facilitate access to left-hemispheric semantic networks in creative idea generation. In a similar vein, we investigated possible threshold effects with respect to regional gray matter volume. We found that, when splitting the sample at the intelligence median, creative potential was related to brain structure only in lower- but not in higher-intelligence individuals (Jauk et al., 2015). More specifically, ideational fluency was correlated with gray matter volume in the cuneus, a visual-associative area in the occipital lobe, which we interpreted such that the ability to fluently produce ideas might be limited by the brain's visual-imaginative capacity in participants of lower intelligence. Taken together, these studies provide the first evidence for possible biological bases of a threshold effect in the way that lower- and higher-intelligent individuals might utilize different strategies (fluent production vs. semantic elaboration) when it comes to creative idea generation. Although these findings seem to stand in accordance with psychometric research, more studies are needed to gain a deeper understanding of the neuronal bases of the threshold effect (because participants' sex, for example, is known to moderate the relationship between brain structure and indicators of creative potential; Ryman et al., 2014).

Conclusion

From the evidence reviewed above, it can be concluded that intelligence and creativity are highly overlapping constructs. This notion is substantiated by methodologically sophisticated psychometric studies reporting high and robust latent correlations between the two facets of human ability. The relationship between intelligence and creativity is likely to be nonlinear in nature in the way that creativity depends upon intelligence, particularly in the lower intelligence range, which is commonly referred to as the threshold effect. Studies on executive functions provide important insights on the commonalities and differences of the two constructs in terms of elementary cognitive processes, as do neuroscientific investigations: fMRI studies of divergent thinking reveal that the creative process recruits widespread cortical regions, many of which overlap with P-FIT (parietal and frontal) regions. These regions, being part of the executive control network, are involved in goal-directed reasoning and are currently regarded as the neurophysiological bases of human intelligence. However, creative cognition also draws upon structures that are not commonly implicated in intelligence, most notably the DMN. Beyond the functional involvement of the DMN in divergent thinking, current evidence points toward relatively stable interindividual differences in DMN morphology in relation to creative potential. These studies can help to augment our understanding of the creative person as they indicate their habitually higher tendency to engage in spontaneous cognitive processes such as mind-wandering or daydreaming. It was also shown that creative individuals do not rely solely on spontaneous, Type-1-like, processes, but display higher cooperation between spontaneous (default-mode) and controlled (executive) brain networks. These findings corroborate long-standing theories on the creative process, which regard creative cognition as a dynamic and flexible interplay between implicit, associative-intuitive, and explicit, goal-directed processes.

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Part VII

Individual Differences

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24 The Genetics of Creativity: The Underdog of Behavior Genetics?

Davide Piffer

Defining Creativity, Creative Potential, and Creative Achievement

Having a clear definition of creativity is a fundamental starting point for any discussion or study involving this concept. Confusion on the concept has plagued research in this field for several decades, causing many paradoxes and hampering progress (Piffer, 2012), although arguably, the situation has improved in the last few years. There has been a positive shift from an exclusive focus on divergent thinking (DT) tests to one on creative performance (Velazquez, Segal, & Horwitz, 2015) and achievement (Hur, Jeong, & Piffer, 2014; Kyaga et al., 2013; Piffer & Hur, 2014; Power et al., 2015). However, the traditional focus on DT for studying creative cognition persists, and whilst this practice is not without its rationale, sometimes the slip of equating DT to creativity is still made at the expense of other convergent processes that are also valid predictors of creativity, such as associative ability (Mednick, 1962) or IQ (Nusbaum & Silvia, 2011). For example, in a recent study, a larger increase in DT scores compared to scores on the Remote Associates Test (RAT) performance was taken as evidence that squeezing a soft ball is more likely to lead to creativity than squeezing a hard ball (Kim, 2015), despite the fact that RAT and DT are both valid measures of creative potential.

Over the last decade, a consensual definition of creativity has gradually emerged (Runco & Jaeger, 2012). Originality and effectiveness/usefulness/appropriateness are perceived as the core elements of creative behaviors or products, although this definition can also be extended to people (Piffer, 2012). A focus on the product is perhaps what distinguishes creativity research from the psychometric tradition focusing on intelligence, which zeroes in on people and their behaviors instead. For example, IQ tests were initially designed to separate dull from bright students (Nicolas, Andrieu, Croizet, Sanitioso, & Burman, 2013; Terman & Merrill, 1937), and they are still used to assess a person's intelligence. However, they arguably cannot – and generally are not – used to assess the intelligence of a product or an idea. On the other hand, an idea or a product can be evaluated according to criteria that define creativity. In this sense we say that Picasso's Guernica, Da Vinci's Mona Lisa or Einstein's theory of relativity are highly creative products, and we can evaluate their creativity level based on their impact and originality (i.e., see Simonton's analysis of Shakespeare's sonnets; Simonton, 1989). In contrast, we do not usually say that they are intelligent products, let alone assign an IQ score to them. Thus, whereas intelligence is an attribute of living creatures, creativity is also an attribute of nonliving things – the creations of intelligent entities. In a way, the creator imbues the creative product with a life of its own.

Impact (that is, the trace that is left on a particular field or on the culture in general) is not a necessary prerequisite for a product to be creative. Arguably, the vast majority of original and adaptive behaviors and activities that people perform during their daily lives leave no discernible impact on the culture as a whole and are never "published" in the traditional sense, yet they deserve to be considered creative. In scientific jargon, these belong to "little-c" creativity. Conversely, eminent creativity (as measured by its broader impact) belongs to "Big C" creativity (Kaufman & Beghetto, 2009). In theory, there could be many Einsteins or Picassos that never had their work published, yet their work might be as creative as that of their more popular counterparts. Nevertheless, because impact is easier to measure objectively (e.g., citation counts for scientific papers), it continues to be used widely as a gauge of creative accomplishment.

Francis Galton was the first to study the heritability of creativity, by attempting to show that exceptional ability (i.e., genius) tends to run in families (Galton, 1869). In reality, Galton's work included many professions that do not require particularly high levels of creative talent (e.g., judges) as much as knowledge and intelligence. One of the main critiques of Galton's work is that he ignored the possibility that families with greater resources could further their children's careers, thus generating confusion between familiarity (familial aggregation) and heritability. Familial aggregation indicates potential genetic influences but cannot exclude confounding effects from the environment (i.e., exposure to similar environment within the same family). Nevertheless, Galton can be credited with starting the nature vs. nurture debate regarding genius that persists to this day.

In contemporary research, the study of creativity can be divided into the study of creative performance/products versus creative potential. Creative potential is a set of cognitive and personality traits that participate in the generation of creative products. When creative potential is analyzed within a cognitive psychology or experimental approach, it is commonly referred to as creative cognition (Finke, Ward, & Smith, 1996). The creative cognition approach breaks the creative process down into its basic components, such as visualization, concept formation, categorization, memory retrieval, and problem-solving. This approach enables the contribution of each component to creative potential.

On the other hand, individual differences (or "differential") psychology focuses on the personality and cognitive correlates of variation in creative performance among individuals.

In this context, a set of personality or temperamental traits has been identified that is positively correlated to creativity. Openness to experience is particularly important because it seems to be correlated with creativity across all domains (Feist, 1998; Piffer, 2014). For example, Feist's (1998) meta-analysis compared the personality traits of three large sets of samples: scientists versus nonscientists, artists versus nonartists, and more-creative versus less-creative scientists. The results demonstrated that creative people were more open to experience, less conscientious, and more hostile and impulsive. In turn, artists were less emotionally stable, more unconventional, and rule-doubting than scientists. On the other hand, less-creative scientists were more conscientious, conventional, and close-minded than their more-creative peers. Feist also showed that, although scientists were more extraverted than nonscientists, this effect was related to the dominance or "assertiveness" facet of extraversion and not to the sociability facet. Dominance can also be described as assertiveness and self-directedness – traits that have been associated with creativity (Chavez-Eakle, Ma. del Carmen, & Cruz-Fuentes, 2006). A similar construct is ego-strength. Individuals high on this trait have greater resourcefulness, vitality, and self-direction, while the low scorers tend to exhibit effeminacy, inhibition, and affectation (Barron, 1953). Fodor (1995) found that psychosis-prone persons high in ego strength exhibited the highest level of evaluated creativity in their solutions to an engineering problem and also received the highest scores on the RAT.

Hypomania, which is a mood state characterized by persistent disinhibition and pervasive elevated (euphoric) or irritable mood, and conceptualized as a trait or temperament (Akiskal, Akiskal, Haykal, Manning, & Connor, 2005), has also been shown to lead to higher creativity (Piffer, 2014), probably via the effect of positive mood states (e.g., happiness). Indeed, positive mood has been shown experimentally to lead to higher creativity (Baas, de Dreu, & Nijstad, 2008). A recent meta-analysis showed that positive schizotypy (mania, hypomania) and risk of bipolar disorder are associated positively ($r = .22$) with creativity (Baas, Nijstad, Boot, & de Dreu, 2016). However, severe hypomania is linked to psychopathology, and can become mania, leading to bipolar disorder when left untreated (Post, 2007).

The relationship between creativity and psychopathology has always sparked the interest of scholarly and lay-people alike, since at least the time of the ancient Greeks. The first serious attempt to treat this topic scientifically can perhaps be traced back to Eysenck's theory of psychoticism (P). This trait is conceptualized as lying on a spectrum leading to schizophrenia at the extreme, and involves cold, unempathic, and impulsive behavior in the normal range (Eysenck, 1995). According to Eysenck, people with schizotypic tendencies have flatter "association hierarchies," leading to overinclusive thinking which gives them access to a broader sample of ideas (Eysenck, 1993). This thinking style enables them to come up with more original, innovative, and unusual ideas than people with a more conventional cognitive style. He stated that "this theory explains (a) the observed differences between creativity as a personality trait (originality) and creativity as demonstrated by scientific or artistic achievement and (b) the difference between creativity and intelligence" (Eysenck, 1993, p. 148).

A familial association with bipolar disorder, schizophrenia, and anorexia nervosa was found for scientists and artists, as inferred from the higher risk of psychopathology among their first-degree relatives. Specifically, being an author was associated with greater risk for many different psychopathologies (Kyaga et al., 2013). However, people in creative professions were not themselves at an increased risk of psychopathology, and scientists had much lower risks of psychopathology. Kinney et al. (2008) found that creativity was higher in adult adoptees of biological parents with schizophrenia than in demographically matched control adoptees with no biological family history of psychiatric hospitalization. Peak creativity levels were observed among nonschizophrenics with either schizotypal or schizoid personality disorder or multiple schizotypal signs among index and control subjects alike. Perhaps this paradoxical pattern of results masks a curvilinear (inverted-U) relationship between psychopathology and creativity, so that a mild degree of psychopathology, expressed in latent forms, can be beneficial to creativity, whereas the detrimental effects on cognition (particularly working memory and focused attention) associated with full-blown psychosis are deleterious to creativity.

Molecular genetic studies support the theory of a genetic link between schizophrenia, bipolar disorder, and creativity. Power et al. (2015) found that genetic scores (inferred from genome-wide association studies) that predict risk for these psychiatric disorders were found to be associated with artistic and scientific achievements or professions in Icelandic and replication cohorts. This genetic risk among creative people was much lower (30%) than that for schizophrenia and bipolar patients and was only partially explained (¼) by having a relative affected with schizophrenia or bipolar disorder.

With regards to cognitive processes leading to creativity, research has traditionally focused on DT. Tests of DT have been positively associated to creative achievement in longitudinal studies, such as a 40- and 50-year follow-up using performance on the Torrance Test of Creative Thinking (TTCT) as predictor (Cramond, Matthews-Morgan, Bandalos, & Zuo, 2005; Runco et al., 2011). Although the correlations were weak, this was to be expected given the long time-lag and the difficulty with assessing creative achievement from self-report measures. Fluency (number of ideas generated) was correlated to creative achievement measured as quantity and quality, (*r* = .23 and .30, respectively). Similar correlations with creative production were found for originality (*r* = .24–.39) and flexibility (*r* = .17–.35). In a structural equation model, TTCT scores predicted 23% of the variance in creative production. IQ was an equally good predictor (*r* = .30–.32). Indeed, in a structural equation model, the combination of TTCT and IQ explained 54% of the variance in creative achievement (Cramond et al., 2005).

Heritability of Creative Potential

Behavior genetics studies estimate the relative genetic and environmental contributions to individual differences in traits by comparing the relative similarity of monozygotic (MZ) and dizygotic (DZ) twins. In turn, the environmental influences are either shared or nonshared, referring to environmental factors that contribute to similarity between twins (e.g., being raised in the same home) and to factors that contribute to differences between twins (e.g., friends, illness unique to each twin), respectively. A(a^2), C(c^2), and E(e^2) represent the proportion of the variance attributable to additive genetic, shared, and nonshared environmental factors, respectively.

As there are already many reviews on the genetics of more traditional personality and cognitive traits, such as IQ and the Big Five, I will focus specifically on a review of the literature of measures traditionally associated with creativity. Admittedly, the studies are scarce, and most of them are not very recent.

Here I will also present for the first time unpublished data from a twin study (Piffer, 2016). The sample included 338 Italian twins, consisting of 79 complete pairs of MZ and 90 complete pairs of same-sex DZ twins. Three divergent thinking tasks taken from Torrance (1968) were translated into Italian, and the instructions were as follows: “Suppose that all humans were born with six fingers on each hand instead of five. List all the consequences or implications that you can think of,” “List all the uses you can think of for a brick,” “List all of the questions you can think of concerning the figure shown below. Ask all of the questions you need in order to know for sure what is happening. Do not ask questions that can be answered just by looking at the drawing.” Answers were scored for fluency, which can be scored easily and can show positive and high correlations with originality (e.g., *r* = .8–.9; Mouchiroud & Lubart, 2001; Torrance, 2008). Three Insight problems and seven items from the Standard Progressive Matrices (SPM) along with a battery of personality scales were also administered (see Appendix 24.1).

The results are largely in line with previous findings (see Piffer, 2014) from an independent sample. Openness to experience was a predictor of total, artistic, and scientific creative achievement, as well as a predictor of DT (*r* ≈ 0.2). The SEEK scale, which taps a construct similar to openness to experience but is best conceptualized as “novelty-seeking,” was also related to the same variables. SEEK assesses feelings of curiosity, striving for solutions to problems and puzzles, propensity to explore, a sense of being able to accomplish almost anything, and positively anticipating new experiences (Davis, Panskepp, & Normansell, 2003). Hypomania’s role as creativity-enhancer was also confirmed, being related positively to all the creative achievement scales. However, it was not correlated with DT performance. Artistic but not scientific achievers were also more cyclothimic and prone to unusual experiences (e.g., paranormal, magical beliefs). Assertiveness and risk-taking also showed positive correlations with creative achievement. Creative achievement was also positively correlated with DT. Divergent thinking was in turn correlated with fluid intelligence as measured by Raven’s SPM (*r* = .34) and insight problem-solving (*r* = .27).

Table 24.1 *Intraclass correlations for observed variables.*

	MZ	DZ
logDT	.700	.387
Raven’s Matrices short form	.514	.343
Openness to experience	.178	.109
SEEK	.308	−.016
Hypomania	.380	.156

Notes. MZ, monozygotic twins; DZ, dizygotic twins; DT, divergent thinking.

MZ and DZ intraclass correlations are reported in Table 24.1. Twin model fitting was run using OpenMx.

Substantial additive genetic variance was found (66.7%) for ideational fluency scores on DT tests, with zero shared environmental influence. However, the openness to experience, hypomania, and SEEK scales were largely explained by nonshared environment plus measurement error (83%, 66.1%, and 76.1%, respectively), with relatively little variance explained by additive genetic influences (16.9%, 33.9%, and 23.8%, respectively). Performance on a short version of the Raven’s SPM (a measure of fluid g) revealed about half additive genetic and half nonshared environmental influences.

Heritability of General Factors

Confirmatory factor analysis was applied to the data. Intraclass correlations are reported in Table 24.2. Two general factors of Openness/Novelty-seeking (Op) and Impulsivity had similar heritabilities (27.8% and 25.9%). The additive genetic component of “Op” did not contribute significantly to the variance between individuals. “Op” loaded positively on Hypomania, openness to experience, Assertiveness, and Novelty-seeking and positively predicted creative achievement. (Lack of) “Impulsivity” loaded on conscientiousness, planning, divertible (distractibility), but this factor had no effect on creative achievement, except a small negative effect mediated by intelligence.

Table 24.2 *Intraclass correlations for latent personality factors.*

	MZ	DZ
Openness/Novelty-seeking	.306	.178
Schizotypy	.524	.316
Impulsivity	.343	−.066

Notes. MZ, monozygotic twins; DZ, dizygotic twins.

However, a general factor of psychopathology or schizotypy (“Schiz”) had higher heritability (52.4%) than Op and Impulsivity. No effect of shared environment was detected and the rest was nonshared environment plus measurement error. This factor loaded on Cyclothimia (a temperament characterized by mood swings and emotional instability) and four aspects of schizotypy: Unusual Experiences (magical thinking and superstitious beliefs); Introvertive Anhedonia (being socially withdrawn and reduced capacity for experiencing positive feelings); Impulsive Nonconformity (impulsiveness and disregard for social norms); Cognitive Disorganization (a tendency for thoughts to become derailed, disorganized or tangential). Schizotypy has been linked in previous studies to creativity (Nettle & Clegg, 2006). In a structural equation model, Psychopathology/Schizophrenia and Openness/Novelty-seeking both independently predicted creative achievement (Beta weights = .16 and .37, respectively), along with fluid intelligence “gf” (Beta weight = .21) and DT (Beta weight = .12 plus an effect mediated by gf: .5 × .21 = 0.1) (Piffer, 2016). This is illustrated in Figure 24.1.

Previous Findings

Table 24.3 reports the heritability coefficients (and when possible, the shared (C) and nonshared E components) for various measures of creative cognition obtained from available publications. DT tests appear to have lower heritability than personality, remote associates, or IQ.

The average heritability across the seven measures of divergent thinking is rather low

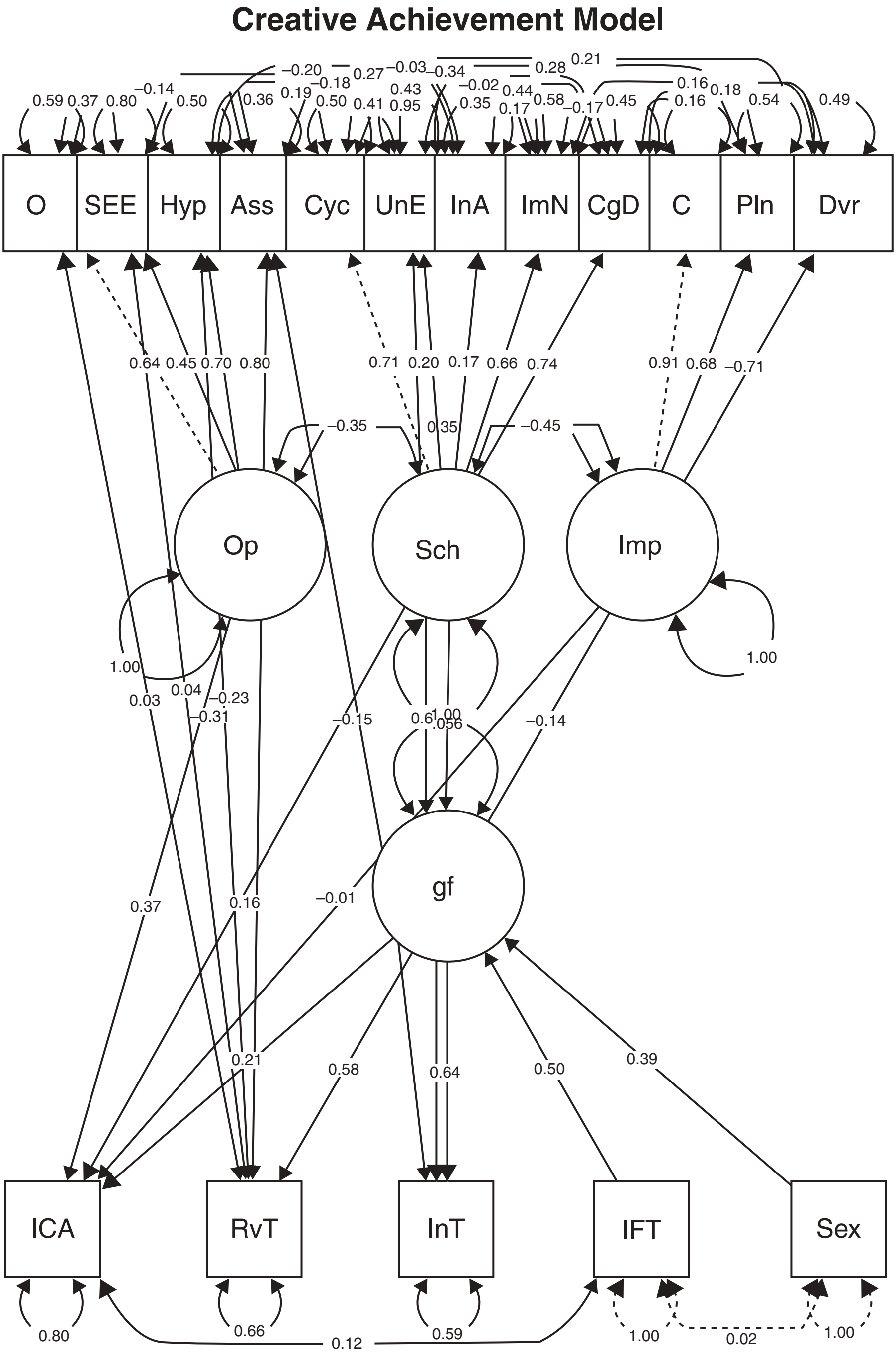

Figure 24.1 Creative achievement model.

O, Openness to experience; SEEK, Seek; Hyp, Hypomania; Ass, Assertiveness; Cyc, Cyclothimia; UnE, Unusual Experiences; InA, Introvertive Anhedonia; ImN, Impulsive Non-Conformity; CgD, Cognitive Disorganization; Op, Openness factor; Schiz, Schizotypy/Psychopathology factor; lCA, Creative Achievement; RvT, Raven's Progressive Matrices; InT, Insight Problems; gf, fluid intelligence; lFT, Ideational Fluency (divergent thinking); Sex (female, 0; male, 1).

Table 24.3 *Additive genetic (A), shared (C), and nonshared (E) contributions to individual differences in creative cognition and personality.*

Measure	**A**	**C**	**E**	**Age**	**Publication**
Remote Associates	.56			13–19	Reznikoff et al., 1973
Alternate Uses (DT)	.32			13–19	Reznikoff et al., 1973
Possible Jobs (DT)	.30			13–19	Reznikoff et al., 1973
Plot Titles (DT)	.21			13–19	Reznikoff et al., 1973
Obscure Figures Test (DT)	–.44			13–19	Reznikoff et al., 1973
Similes Test	.39			13–19	Reznikoff et al., 1973
Perceived Creativity	.62	0%	.38	18–70	Kandler et al., 2016
DT (Figural Creativity)	.26%	.24	.50	18–70	Kandler et al., 2016
DT (Figural Creativity)	.33%	0%	.67	18–77	Velazquez et al. (2015).
DT (TTCT)	.44	.42	.14	N/A	Grigorenko et al., 1992
DT	.22	N/A	N/A	N/A	Nichols, 1978
Creative Personality (CPS)	.54	0%	.46	18–77	Bouchard et al., 1993

Notes. DT, divergent thinking.

(≈ 0.2). Admittedly, these tests did not correct for unreliability, so the actual heritability might be slightly higher, but still much lower than that reported for most cognitive or personality traits. One study corrected for unreliability, but still found low heritability (26%) (Kandler et al., 2016). RAT scores and scores on the Creativity Personality Scale had higher heritability (around 55%). In contrast, the heritability coefficient found for DT in my data set (67%) is significantly higher than any of those reported in the literature, but only after normalization (i.e., log transformation). Raw DT scores were highly (positively) skewed. Perhaps lack of normalization in previous studies accounts for the lower heritabilities reported for DT compared to other tests. Another possibility is that figural DT has lower heritability than verbal DT and that this distinction should be considered in future studies.

Heritability of Creative Performance/Achievement

Given the low heritability of DT, but the higher heritability of other predictors of creativity such as IQ, RAT, and openness to experience, one could try to estimate what the heritability of creative achievement might be. As it is a biographical phenomenon, we might expect it to be highly affected by environmental circumstances, family background, and so on. Hence, intuitively, its heritability should be lower than a more "culture-free" measure of creative potential, such as the RAT or DT. So far, only one study dealing with the heritability of creative achievement has been published. This employed the same twin data set used here for my previous analysis, and showed heritabilities of 61%, 67%, and 43% for total, artistic, and scientific creative achievement (Piffer & Hur, 2014), with the remaining variance fully accounted for by E (i.e., nonshared environment), but zero shared environmental influences. The measure of creative achievement employed was the CAQ (Creative Achievement Questionnaire) (Carson, Peterson, & Higgins, 2005), a self-report measure which includes questions on creative achievements in 10 different domains, i.e., visual arts (painting & sculpture), music, dance, architectural design, creative writing, humor, invention, scientific discovery, theater and film, and culinary endeavors. A subsequent manuscript based on the same sample found that the phenotypic relationship (r = .54) between artistic and scientific achievement was mediated by shared genetic (*r* = .71) and nonshared environmental influences (*r* = .36) (Hur et al., 2014).

Family Background or Gene–Environment Correlation?

A variety of developmental factors tend to exhibit an association with creativity. These are based on the biographical profiles that show up when studying the lives of eminent creators, such as writers or scientists. For example, Berry (1981) found marked differences in the family backgrounds typical of Nobel prize-winners from different fields. Physicists came from more stable and educated families than chemists, who in turn were raised in more stable environments than writers. Specifically, 17% of writers, 11% of chemists but only 2% of physicists had lost their fathers while still young. Moreover, 27% of the physicists came from families where the father was an academic professional, but the figure dropped to 17% for chemistry and was as low as 6% for literature. Similar differences were found in another study, with fiction and nonfiction authors coming from unhappy home environments but scientists and philosophers enjoying better home conditions (Simonton, 1986). A corresponding pattern was found in the degree of formal educational attainment, being highest for scientists and lowest for artists and performers (Simonton, 1986) (also see divorce rates, Roe, 1953). There is a widespread notion that home environments, family backgrounds, and life events partly reflect the influence of nurture on outcome measures of interest. For example, Simonton (2010) noted that "At least in part, dispositional traits must have some foundation in the early environmental experiences that shape creative development. Disposition is as much a function of nurture as nature, if not more. It should come as no surprise, therefore, that highly eminent individuals who contribute to different domains of creative achievement also tend to differ in their developmental backgrounds. In a sense, the creators in each domain exhibit distinctive biographical profiles"; "Yet it is also the case that creative genius is made. The inventory of environmental experiences that contribute to creative development is quite large. It includes family background factors, educational and training experiences, and early career opportunities" (p. 182).

Of course, behavior geneticists have long known that apparently pure environmental events can mask underlying genetic predispositions (Jaffee & Price, 2007). These gene–environment correlations can be instantiated in two ways:

(1) Passive gene–environment correlation: when parents pass on certain behaviors to their children along with genes that influence these behaviors. For example, if parents who get divorced are less emotionally stable and more neurotic (personality traits that are moderately heritable), they can pass on the genetic predispositions for neuroticism to their children. Thus, the children's emotional problems are not necessarily the direct effect of having experienced divorce, but can also be due to a heritable component. If scientists tend to be born in households with educated parents, this does not show a direct causal link between parental education and the offspring's scientific creativity. It could simply show that educated parents pass on their genes for personality traits that lead to scientific creativity and educational attainment to their children, such as conscientiousness and high intelligence.

(2) Active gene–environment correlation: an individual possesses a heritable propensity to select environmental exposure. For example, if scientists tend to attain a higher formal educational level than artists, it does not necessarily imply that formal education contributes to scientific achievement more than artistic achievement. It could also signify that artists have certain personality traits (e.g., norm doubting, lower conscientiousness) that make them less-suited to a structured environment such as that of academia.

Conclusions

The literature on quantitative genetics (i.e., twin and adoption studies) of creativity is tiny in comparison to the vast body of research on personality and intelligence, making it a sort of "underdog" of behavior genetics. This is in part due to the lack of a clear definition of the construct of creativity that has plagued research until some time ago (and to some extent, still does today). A prominent construct in creativity research, DT, seems to have lower heritability compared to more traditional constructs such as IQ or the Big 5. However, variability in the age of samples, unreliability of the measures, nature of the tasks (figural vs. verbal DT), or lack of normalization (i.e., DT scores are highly skewed) could potentially explain this difference. For example, in Piffer (2016), a verbal DT task administered to adults showed high heritability in a twin sample after normalization. Overall, more research, both quantitative and molecular, is needed to shed light on the genetic bases of divergent thinking.

Eysenck's theory of an association between "madness" or schizotypy and creativity and on the genetic influence on this trait (Eysenck, 1993) was supported by the data, although perhaps Eysenck overemphasized the importance of schizotypy at the expense of other psychological variables whose influence on creativity seems to be even stronger, such as openness to experience, novelty seeking and hypomania. The heritability (a^2) of openness to experience (a robust predictor of creativity) is among the highest for personality traits, around 65% (Vernon, Martin, Schermer, & Mackie, 2008), comparable to that of IQ (Plomin, DeFries, McGuffin, & McClearn, 2008), and contrasts with the low heritability found in the Italian twin data set presented here (Piffer, 2016).

Assertiveness or ego-strength is another personality trait common among creative people, which had not escaped Eysenck's attention (Eysenck, 1997). This construct was found to load on a latent factor along with hypomania, openness to experience and novelty-seeking (Figure 24.1). Arguably, these characteristics belong to an "approach motivational system," relying on dopaminergic brain circuitries (Depue & Collins, 1999; Flaherty, 2005), and are characterized by approach behavior toward rewarding and novel stimuli. This system leads to higher flexibility and creativity (Baas et al., 2016).

A short, self-report questionnaire on creative achievement (Carson et al., 2005) has been shown to have validity and heritability comparable to traditional psychometric instruments (Piffer & Hur, 2014). The finding that a "biographical" measure such as creative attainment reached higher heritability than its psychometric predictors could be counterintuitive; however, this is not unusual. For example, measures of educational performance have been shown to be even more heritable than their psychological predictors such as personality or intelligence (Krapohl et al., 2014). An advantage of using questionnaires of self-reported creative achievement is that they are easy and quick to administer, enabling researcher to collect the extremely large samples (100 K+) necessary for genome-wide association studies (GWAS) of highly polygenic traits. Nonetheless, future studies of creativity should also include DT tests or insight problems in cognitive batteries, along with more traditional measures of IQ or general cognitive ability, with the goal to elucidate their genetic relationships with one another, and if or how much they predict creative achievement above and beyond general intelligence (g). GWAS offers a promising approach for identifying genetic variants related to creative achievement and genius, thanks to the dramatic reduction in sequencing costs. The molecular bases of cognitive, personality and temperamental constructs that contribute to creativity such as DT, novelty seeking, hypomania and openness to experience have yet to be investigated, and the GWAS design offers a promising approach.

Several genetic variants for educational attainment have recently been identified by GWAS (Rietveld et al., 2013), and the same methodology could be successfully extended to creativity. However, creative achievement and educational attainment share the feature of being multifactorial, and this poses a problem as the genetic variants tend to be related to a swathe of different traits. For example, using quantitative genetic methods, intelligence, self-efficacy, conscientiousness, well-being, and behavior problems were found to account for 75% of the heritability of educational performance (Krapohl et al., 2014), although phenotypically only 45% of the variance in educational attainment was explained. Another study by the same group focused on molecular data and found an overlap between educational attainment genes with cognitive ability and behavior/conduct disorders (Krapohl et al., 2015). Similarly, a test of creative achievement could be administered to a large twin sample along with measures of creative potential such as personality, psychopathology, DT, and intelligence to determine how much of the heritability in creative achievement can be explained by these features.

In addition, measures of family environment should be included within genetically informed designs (e.g., twin study) to control for the effects of gene–environment correlations and interactions (Jaffee & Price, 2007). For example, Kendler and Gardner (2011) provided a developmental model of depression, whose etiology was explained by a variety of genetic, personality, and environmental risk factors such as neuroticism, childhood adversities, and recent stressful events. An analogous etiological model could be applied to the study of creative achievement. Thus, hypotheses about environmental influences on creativity should be tested using a longitudinal design based on a twin sample, enabling one to control for genetic influences on environmental events. Alternatively, prospective experimental protocols can be employed, although the studies carried out to date have covered a time period too short to observe lasting effects (Leung & Chiu, 2008).

Retrospective correlational studies provide only the starting point for generating hypotheses to be tested using longitudinal, genetically informed designs. Claims about the effects on creativity of exposure to certain environments rely on very limited correlational or experimental evidence, and to date neither quasi-experimental (i.e., genetically informed designs employing structural equation modeling) nor prospective longitudinal studies have been able to isolate putatively "pure" environmental causes.

In conclusion, although the genetic study of creativity is still in its infancy, it offers tremendous possibilities for progress in this area. High creativity (and possibly even genius) is not the result of a single cognitive or personality factor. Rather, it is the product of a combination of personality (e.g., openness to experience, novelty-seeking, assertiveness or ego-strength, risk-taking), subclinical (e.g., psychoticism, schizotypy), and cognitive (e.g., DT, general intelligence) traits that contribute additively or interact to increase the probability that an individual will make a more or less lasting contribution to the culture. Although these factors are known to have a moderately large genetic influence, the specific genetic variants underlying variation in these phenotypes have yet to be identified (i.e., by means of GWAS).

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Appendix 1

Scales

Italian version of the validated short TEMPS-A (Preti, 2010).

(39 items):

- Cyclothimia, Temps-A
- Hypomania, Temps-A

The Oxford Liverpool Inventory of Feelings and Experiences (OLIFE): a four-scale questionnaire for measuring schizotypal traits in healthy individuals (Mason & Claridge, 2006):

- Introvertive Anhedonia
- Impulsive Nonconformity
- Unusual Experiences
- Cognitive Disorganization

The Affective Neuroscience Personality Scales (ANPS; Davis et al., 2003)

- SEEK scale

Big Five: A 60-item Italian adaptation (Flebus, 2006) of the IPIP version of the Big Five Questionnaire (International Personality Item Pool, Goldberg et al., 2001):

- Assertiveness scale
- Openness to Experience

Impulsivity:

The Hierarchical Structure of Self-Reported Impulsivity (Kirby & Finch, 2010).

- Impetuous
- Divertible
- Thrill- and Risk-seeking
- Pleasure-seeking
- Reserved.

25 Structural Studies of Creativity Measured by Divergent Thinking

Hikaru Takeuchi and Ryuta Kawashima

Introduction

In this chapter, we would like to discuss structural studies on brain imaging to evaluate creativity as measured by divergent thinking (CMDT). Human intellectual abilities have been shown to be strongly associated with structural volumes and microstructural properties of the brain using structural magnetic resonance imaging (sMRI) techniques (Jung & Haier, 2007; Posthuma et al., 2003). More specifically, these studies used T1-weighted high-resolution structural images to evaluate regional gray matter (GM) and white matter (WM) volumes (rGMV and rWMV, respectively) via voxel-based morphometry (VBM), and to evaluate cortical thickness and the surface area of the brain. These studies also used diffusion tensor imaging (DTI) to evaluate fractional anisotropy (FA) and mean diffusivity (MD) of the brain. A number of recent studies in the field have used similar methods to identify correlations between properties of brain structures and CMDT. In this chapter, these CMDT studies are reviewed, and their methodologies and implications described.

Creativity is conventionally measured using divergent thinking tests, in which the subject is instructed to generate as many ideas or uses as possible in response to certain stimuli (e.g., a brick). These tests include not only verbal divergent thinking tests but also figural divergent thinking tests, in which the subject is presented with a picture and is required to respond with their own variations of drawings. Divergent thinking has been proposed as a key aspect of creativity (Guilford, 1967) and is currently the dominant measure of creativity in the field. Scores of CMDT have a stronger relationship with creative achievement than scores of intelligence tests (for a meta-analysis, see Kim, 2008). Therefore, among the many aspects and components of creativity, CMDT studies will be the focus of this chapter. The chapter will begin by offering a brief review of some methodological approaches to structural studies of the brain before delving into a discussion of their associations with CMDT.

VBM and Cortical Thickness Analysis

VBM is a structural processing technique using brain MRI that involves a voxel-wise correlation between rGMV or rWMV and any factor of interest, such as age and cognitive function (Ashburner & Friston, 2000). The individual structural images are segmented into GM, WM, and cerebrospinal fluid. The spatial normalization of high-resolution images of all subjects is performed in the same stereotactic space, allowing for comparisons to be made across subjects. In this normalization step, the volume of the original native space is usually preserved in the signal strength. Subsequently, correlations between rGMV or rWMV and CMDT in every voxel of the stereotactic space can be analyzed.

Measures of cortical thickness and surface area are also used to evaluate quantitative information of brain structures. As shown in Figure 25.1, the cortical volume of GM is calculated as the product of cortical thickness, defined

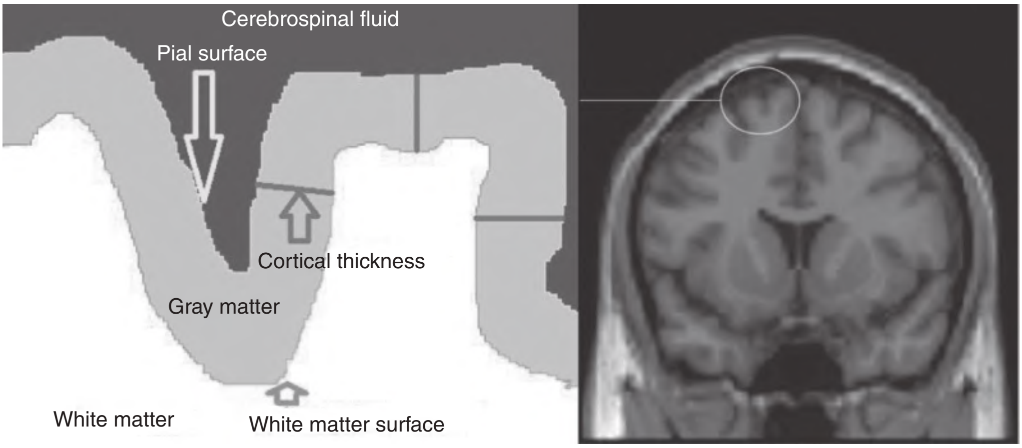

Figure 25.1 Schema of GM, WM, cortical thickness, WM surface, and pial surface.
Notes. GM, gray matter; WM, white matter. For a color version of this figure, see the color plate section.

as the distance between the white and pial surfaces, and the surface area, which is defined as the area of the white matter surface (Wierenga, Langen, Oranje, & Durston, 2014). GM extent is suggested to reflect the number and size of neurons and glial cells, the level of synaptic bulk, and the number of neurites, as these tissue components exist within the GM (May & Gaser, 2006; Takeuchi et al., 2011), although this presumption remains to be verified by histological studies. WM is composed chiefly of long-range axon tracts and considered to relay information between regions of the brain. As such, the structural properties of WM can be regarded as a property of the structural connectivity in the brain.

DTI

As summarized in our previous report (Takeuchi et al., in press), mean diffusivity (MD), and fractional anisotropy (FA) measures by diffusion tensor imaging (DTI) (Beaulieu, 2002) can be used to assess the microstructural properties of various regions of the brain. MD is a measure of the free movement of water molecules independent of directionality. In the normal brain, lower MD is thought to reflect greater tissue density, such as the increased presence of cellular structures. Cellular structures that might affect MD include capillaries, synapses, spines, and macromolecular proteins; properties of myelin, membrane, and axons; the shape of neurons or glia; and enhanced tissue organization, although MD is not specifically sensitive to any one of these (Figure 25.2) (Beaulieu, 2002; Sagi et al., 2012).

On the other hand, FA is relatively more strongly associated with microstructural properties related to brain connectivity. Increased FA is considered to be associated with the development of myelination processes and increased axonal membrane thickness, diameter, and/or the volume of parallel organization of the axons (Beaulieu, 2002; Takeuchi, Sekiguchi, et al., 2010). Thus, increased FA is often thought to reflect faster information processing of WM tracts (Takeuchi, Sekiguchi, et al., 2010).

Associations Between CMDT and GM Properties

The results of nine studies of the associations between the measures of GM properties (GM volume/density, and cortical thickness) and

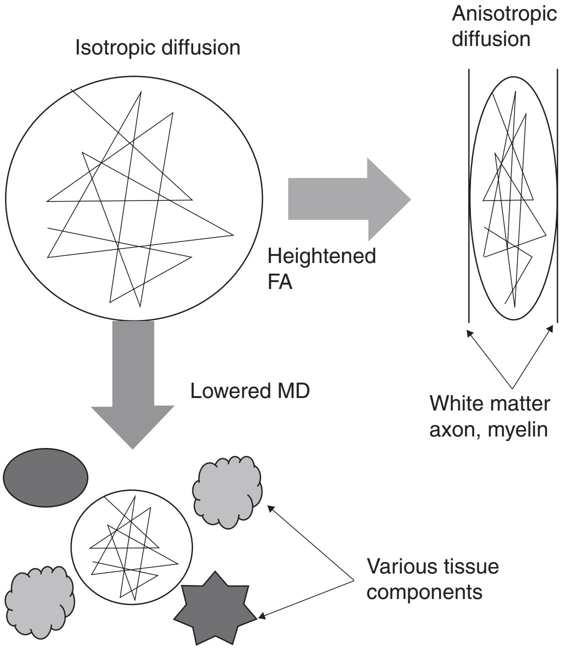

Figure 25.2 Schema of associations among DTI measures (FA and MD), anisotropic and isotropic water molecule diffusion, and brain tissue components.

Notes. MD, mean diffusivity; FA, fractional anisotropy. For a color version of this figure, see the color plate section.

CMDT (total scores and subscales) are summarized in Figures 25.3 and 25.4. As shown, most of the findings have not been replicated, as the methods were somewhat different among the various studies (e.g., nationality, measures used, number of subjects, image-processing methods, etc.). The findings of these prior studies frequently suggested that CMDT is associated with brain properties of the posterior midline structures, including the precuneus/cuneus and posterior cingulate cortex, which have been thought to gather information from a wide range of brain regions, and contribute to visual and mental imagery, as well as self-related mental representations and episodic memory retrieval (Cavanna & Trimble, 2006) – all of which likely contribute to creativity. This may be congruent with the findings showing that even verbal CMDT is positively associated with visual mental imagery ability (for a meta-analysis, see LeBoutillier & Marks, 2003) as well as the traditional view that the combination of ideas of a different nature is critical for creativity (Heilman, Nadeau, & Beversdorf, 2003). However, the observed structural associations between gray matter properties and CMDT within these regions are sometimes positive (e.g., higher volumes, density) and sometimes negative (e.g., lower volumes, density), the implications for creativity of which need to be more fully determined by neuroscientists as seen in Figures 25.3 and Fig. 25.4.

Our current impression based on this review is that the associations between GM amount and CMDT in healthy young subjects are elusive at best. The lack of robust associations may be partly due to the fact that CMDT is associated with some favorable psychological factors, such as greater processing speed (Preckel, Wermer, & Spinath, 2011) which is associated with greater brain volume (Betjemann et al., 2010), and

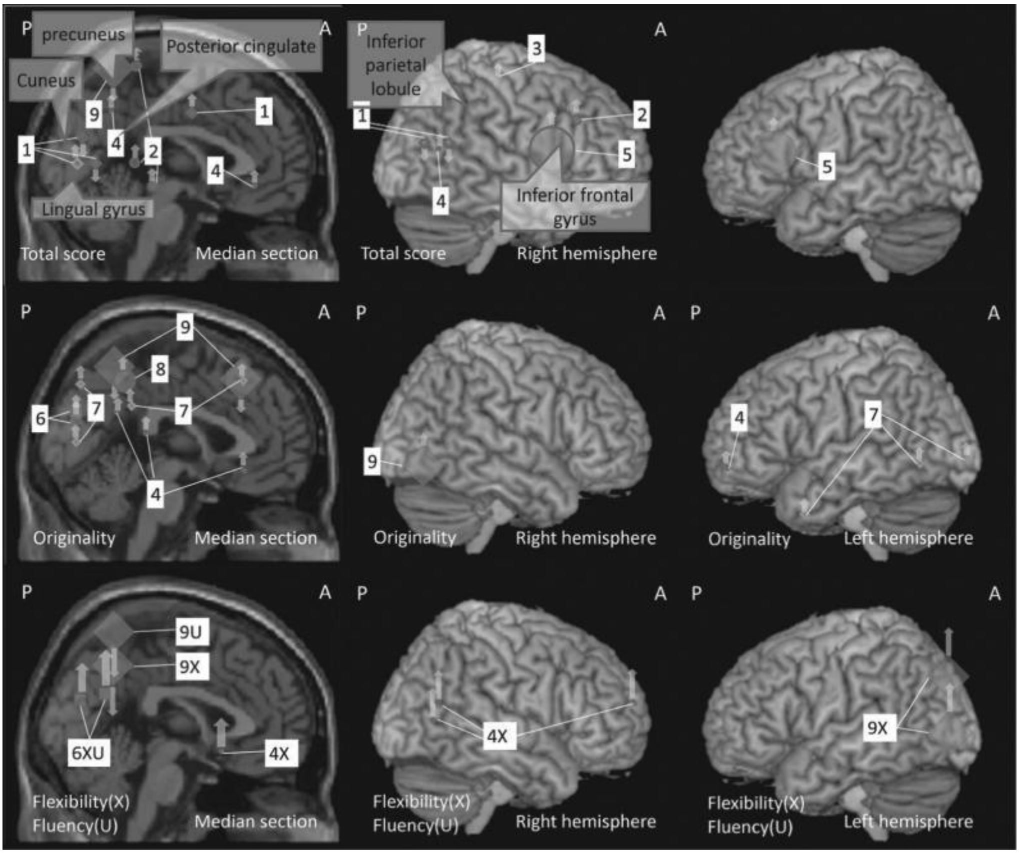

Figure 25.3 GM correlations with CMDT and subscales.

Notes. GM, gray matter; CMDT, creativity as measured by divergent thinking. Circles (○) represent findings of GM volume. Squares (□) represent findings of GM density. Diamonds (◇) represent findings of cortical thickness. Blue marks represent findings of verbal CMDT, and red marks represent findings of visuospatial CMDT. The width of these marks represents the sample size of each study. Upward (or downward) arrows attached to these marks represent positive (or negative) correlations. The number in the figure is the study number. (1) Jung, Segall, et al. (2010) with 61 healthy young adults (28 females). (2) Takeuchi et al. (2010a) with 55 healthy young adults (13 females). (3) Gansler et al. (2011) with 18 healthy middle-aged males. (4) Kühn et al. (2014) with 21 healthy young adults (16 females). (5) Zhu et al. (2013) with 285 healthy young adults (155 females). (6) Fink et al. (2014) with 71 healthy mainly young adults (27 females). (7) Cousijn, Koolschijn, Zanolie, Kleibeuker, & Crone (2014) with 45 adolescents and young adults (24 females). (8) Jauk, Neubauer, Dunst, Fink, & Benedek (2015) with 135 healthy young adults (84 females). (9) Chen et al. (2015) with 268 young adults (143 females). In the lowest line, findings of flexibility and fluency were combined and X represents findings of flexibility and U represents findings of fluency. For a color version of this figure, see the color plate section.

some that are unfavorable, such as the tendency toward psychosis (Woody & Claridge, 1977), which is associated with lower GM volume in widespread areas (Koutsouleris et al., 2009). In addition, the associations between creativity and psychopathology may also be complex, and it may be that creative ones may be more psychologically healthy compared with noncreative ones, but among the creative ones, the most creative ones may nevertheless be more prone

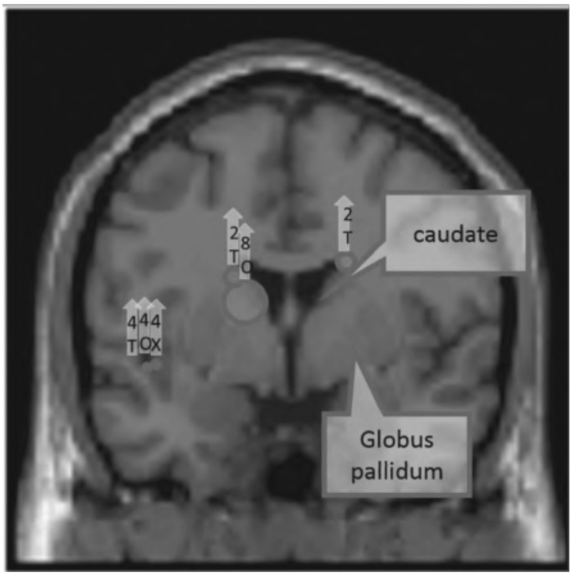

Figure 25.4 GM correlation with CMDT and subscales in the axial view.

Notes. GM, gray matter; CMDT, creativity as measured by divergent thinking. The marks, arrows, and numbers represent the same thing as those of Figure 25.3. In addition, in this figure, the letter “T” in the figure represents findings of total score, “O” represents findings of originality, and “X” represents findings of flexibility. For a color version of this figure, see the color plate section.

to psychopathology (Simonton, 2014). These factors may cancel out or hide the true association between creativity and GM properties. Also, lower GM volume may reflect advanced (or adaptive) cortical thinning during the developmental period as well as atrophy or maldevelopment (Takeuchi, Taki, Sassa, et al., 2014). For example, a study showed that children with superior intelligence show steeper cortical thinning during specific phases of development (Shaw et al., 2006). Therefore, the associations between specific cognitive functions and volumetric properties of cortical structures are expected to be complex.

The source of the sporadic and seemingly elusive findings throughout the brain, as shown in Figures 25.1 and 25.2, could be due to a number of factors, although it should be noted that due to the stringent corrections of multiple statistical tests over the whole brain, nonsignificant findings in whole-brain analyses do not necessarily reflect evidence for a lack of association. In hindsight, it is likely that the associations between GM properties and CMDT are weak; however, the samples sizes in most studies were too small to highlight the relatively weak (if any) associations with creativity, indicating the tendency for false positive findings instead of true positive findings (for the mechanisms of how this can happen, see Button et al., 2013). Past studies also occasionally used statistical methods to correct multiple statistical tests over the whole brain that turned out to be inappropriate mainly because simulated brain images and real brain morphologies have substantially different characteristics (Silver, Montana, & Nichols, 2012).

Associations Between CMDT and WM Volume

To date, three studies have investigated the associations between CMDT and WM volume. Our submitted study (Takeuchi et al., 2017) found female-specific positive correlations between the total score of verbal CMDT and WM volume within regions that were spread across the entire brain using approximately 1336 subjects (Figure 25.5), and in this study we did not regress out effects of total intracranial or brain volume and total WM volume in the multiple regression analysis to test the association between regional WM volume and verbal CMDT. A previous theoretical review suggested that "connectivity, including the myelinated subcortical connections, might be important for creativity" (Heilman et al., 2003, p. 371). This is because creativity is thought to require "transitions from one idea to another … unheard of combination of elements, the subtlest associations of analogy … where partnerships can be joined or loosened" (James, 1890). Larger rWMV is believed to be due to microstructural and architectonic mechanisms of brain connectivity. As introduced in the following subsection, in this relatively large sample, there was no evidence of an association between CMDT and different aspects of WM structural properties (FA of WM). The possible physiological mechanisms that lead to greater rWMV and cognitive abilities and unchanged FA include "the size and number of glial cells (forming a major portion of WM), number of axon collateral spines, or a pure increase in WM volume (or an increase in all of the physiological components of WM, while the composites remain the same)" (Takeuchi et al., 2013). Thus, this female-specific positive correlation between CMDT and rWMV suggests that brain structural connectivity is important for creativity, at least in females.

Also, our study identified positive correlations between originality of verbal CMDT and regional WM volume of the region close to the right inferior parietal lobule among both males and females. It is difficult to interpret this finding, as the inferior parietal lobe (IPL) is associated with many functions (Desmurget & Sirigu, 2012). Nonetheless, the IPL plays a key role in attention (Macaluso, Frith, & Driver, 2000), and previous studies have suggested that creative people have a broader focus of attention and a greater attentive capacity (for review, see Folley, Doop, & Park, 2003). Also, the IPL plays a key role in mental imagery synthesis (Yomogida et al., 2004). The results of a meta-analysis revealed an association between visual imagery and CMDT, regardless of whether CMDT is verbal or visual (LeBoutillier & Marks, 2003). We hypothesize that, through these associated cognitive functions, increased rWMV may facilitate originality of CMDT.

Meanwhile, Zhu et al. (2013) adopted different approaches to investigate the associations

Figure 25.5 WM correlation with total scores of CMDT among females in a large sample.

Notes. WM, white matter; CMDT, creativity as measured by divergent thinking. Areas of significant correlations were overlaid in the WM template. Significant widespread positive correlations were observed in the female subjects. For a color version of this figure, see the color plate section.

between verbal CMDT and relative rWMV (i.e., rWMV divided by total WM volume) and reported positive correlations between the total score of verbal CMDT and relative regional volume of WM areas close to the left and right inferior frontal gyrus (IFG) among 285 healthy young adults. Lesions to the IFG are known to be associated with decreased linguistic output as well as depressed mood that can further inhibit speech, which in turn was suggested to be related to a reduction of creative production (Flaherty, 2005). Thus, we interpret the relatively increased volume of this area to lead to greater verbal CMDT. This finding may be partly congruent with the findings of our submitted study (in which we did not regress out the effects of total WM volume) because the strongest correlations in females were found in the WM region within the IFG, precentral, postcentral, and inferior parietal lobules, as shown in Figure 25.5 (meaning relative WM volume in the same areas are likely to be associated with CMDT among the females).

Finally, Moore et al. (2009) reported a negative association between figural CMDT and the size of the corpus callosum, which is the structure that connects the bilateral cerebral hemispheres (Figure 25.4). However, this study had a sample size of 21 middle-aged adults, and the results were marginally significant. Future studies may be needed to reveal the complete picture of correlations between WM volume with figural CMDT.

Associations Between FA and CMDT

With respect to FA of the WM structures, Jung, Grazioplene, Caprihan, Chavez, and Haier (2010) investigated the associations between FA and verbal CMDT of 72 young adults and found a negative association between CMDT performance and FA in the right inferior frontal WM. In contrast, our previous study using the data of 55 young adult samples (Takeuchi, Taki, et al., 2010b) reported positive associations between verbal CMDT and FA of widespread WM areas, including the corpus callosum and extensive frontal areas, suggesting a substantial discrepancy with the study of Jung, Grazioplene, et al. (2010). Our ongoing study (Takeuchi et al., 2017) using the data of approximately 1300 young adults failed to find any significant associations between verbal CMDT and FA in any of the areas and failed to replicate the findings of either of these previous studies. Advanced preprocessing techniques were used in this analysis (Takeuchi et al., 2013) to remove the contamination of FA signals of GM into WM areas, which could not be achieved in our previous study (Takeuchi, Taki, et al., 2010b). This as well as the instability of the results due to an insufficient sample size in our previous study (Takeuchi, Taki, et al., 2010b) may explain why we previously found positive associations between FA and CMDT that could not be replicated in a much larger sample size. Thus, we currently believe that our previous finding of FA was caused by the tendency of larger WM areas in subjects with higher CMDT. Perhaps, for FA, which reflects the advancement of myelination processes, studies using samples in which there are substantial individual differences in the advancement of myelination processes may be more effective (i.e., developing children).

MD Studies of CMDT

The results of our previous study (Takeuchi et al., 2015) to identify associations among MD, verbal CMDT, and personality traits of several hundred young-adult subjects using brain imaging, psychological data, whole-brain analyses, and structural equation modeling showed that lower MD in the left globus pallidus led to higher persistence (personality characterized by perseverance despite frustration and fatigue, as well as a tendency toward a persistent pursuit of desired goals), which in turn led to higher verbal CMDT (Figure 25.6). Furthermore, the results showed that lower MD in the right globus pallidus primarily led to lower harm avoidance (personality characterized by excessive worrying, pessimism, shyness, and being fearful, doubtful, and easily fatigued), which in turn led to higher self-directedness (personality trait of self-determination, that is, the ability to regulate and adapt behavior to the demands of a situation in order to achieve personally chosen goals and values), self-transcendence (personality trait associated with experiencing spiritual ideas, such as considering oneself an integral part of the universe), and novelty-seeking, all of which then led to higher verbal CMDT (Figure 25.6). The associations between CMDT and these personality traits were mostly consistent with those identified by Chavez-Eakle, del Carmen Lara, and Cruz-Fuentes (2006), suggesting that robust replicable associations exist between these cognitive individual differences.

Also, our another recent study (Takeuchi et al., 2016) involving the data of several hundred young-adult subjects revealed very robust associations between MD in the right globus pallidum and the mood state of stronger vigor but not with other mood states (depression, anger/hostility, anxiety, confusion, and fatigue). Similarly, verbal CMDT was very robustly associated with the mood state of stronger vigor but not with other mood states in this study.

Evidence from various fields points out that the globus pallidus and adjacent areas play a key role in motivation (Smith & Nichols, 2009; Takeuchi, Taki, Nouchi, et al., 2014). In addition, we previously reported that the personality traits that were robustly associated with CMDT and MD in the globus pallidum were all robustly associated with traits and states related to motivation (Takeuchi et al., 2015). These findings suggest that increased motivation involves more tissues in the globus pallidum (lower MD in this

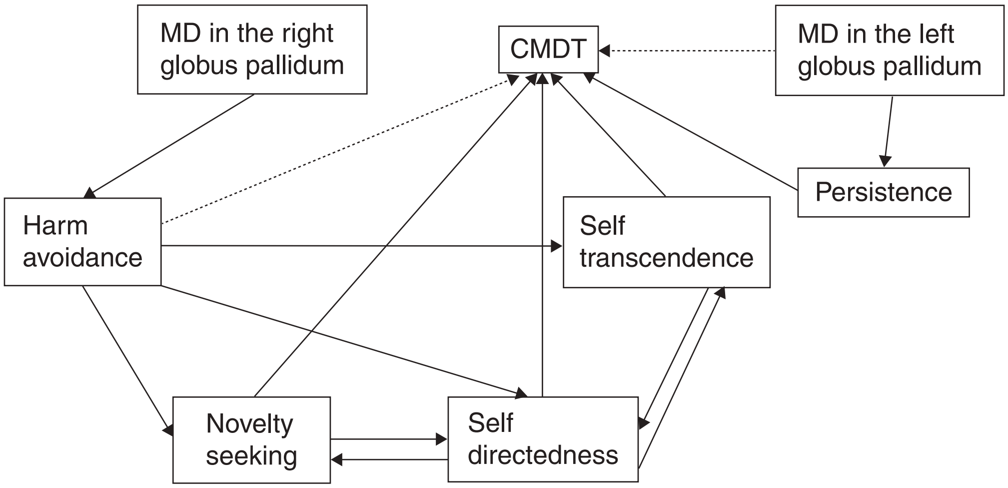

Figure 25.6 A schema of the models of associations among CMDT, personalities, and MD in the bilateral globus pallidum.

Notes. MD, mean diffusivity; CMDT, creativity as measured by divergent thinking. Red arrows show positive effect, and blue arrows negative effects. Dotted lines show the case where the model with the existence of the path fit the model best, but this path failed to reach significance. Bidirectional arrows indicate the models with both the directions fit the data equally. Note the model involving MD in the right globus pallidum and the model involving MD in the left globus pallidum were separately analyzed but combined in this scheme for clarity. For a color version of this figure, see the color plate section.

area), and that it plays a key role linking the associations between verbal CMDT and mood states as well as personality traits (Takeuchi et al., 2015).

The globus pallidus receives dopaminergic input from the substantia nigra (Greenstein & Greenstein, 2000; Lindvall & Björklund, 1979). It has been suggested that dopaminergic function plays a key role in creativity (e.g., Flaherty, 2005). As we previously summarized (Takeuchi et al., 2015), the abundance of evidence suggesting that the associations between dopamine and creativity is well supported by the literature and worthy of further enquiry. For example: (a) creativity positively associates with schizotypy (Cooper, 1998; Eysenck & Furnham, 1993; Kline & Cooper, 1986; O'Reilly, Dunbar, & Bentall, 2001), which is associated with dopamine-related genes (Ettinger, Joober, De Guzman, & O'Driscoll, 2006) and overactivity of subcortical dopaminergic systems (Kirrane & Siever, 2000); (b) CMDT positively associates with CMDT and novelty-seeking (Chavez-Eakle et al., 2006), while novelty-seeking have been positively associated with dopaminergic functions (Bódi et al., 2009; Kaasinen, Aalto, Någren, & Rinne, 2004; Schinka, Letsch, & Crawford, 2002; Suhara et al., 2001; Tomer & Aharon-Peretz, 2004); (c) creativity positively associates with motivation that is not caused by external incentives (Prabhu, Sutton, & Sauser, 2008), which has been associated with dopaminergic functions (Kaplan & Oudeyer, 2007); (d) CMDT positively associates with extraversion (King, Walker, & Broyles, 1996), which has been associated with dopaminergic functions (Ashby & Isen, 1999; Depue & Collins, 1999); (e) dopamine's antagonist suppresses creativity (Flaherty, 2005), and dopamine suppresses latent inhibition (a behavioral index of the ability to habituate to sensations)(Ellenbroek, Budde, & Cools, 1996; Swerdlow et al., 2003), while reduced latent inhibition is associated with creativity among intelligent subjects (Carson, Peterson, & Higgins, 2003); (f) CMDT associates with dopamine-related genes(Mayseless, Uzefovsky, Shalev, Ebstein, & Shamay-Tsoory, 2013); (g) CMDT is reduced in the pathology of the dopaminergic system (Drago, Foster, Skidmore, & Heilman, 2009) and artistic creativity recovers in response to dopaminergic agonist (Kulisevsky, Pagonabarraga, & Martinez-Corral, 2009). In consideration of the available evidence discussed in this chapter, we hypothesize that MD of the globus pallidum mediates the associations among dopaminergic function, motivation and related states, traits, and expression of creativity.

Overall Discussion

In summary, the study of a large sample revealed robust positive associations between WM volume and CMDT in females across widespread areas of the brain, further supporting the theoretically hypothesized importance of brain structural connectivity in creativity. In addition, prior studies showed that lower MD in the globus pallidum was robustly associated with the state of vigor and a number of other personality traits that are associated with motivation, and lead to greater CMDT. These findings might underlie the theoretical link between dopaminergic function and creativity.

The findings of associations between CMDT and GM properties are divergent and often contradictory, and the study with the largest sample failed to find any significant associations. Therefore, in our opinion, these associations are currently elusive at best. Similarly, the associations between CMDT and FA, which reflect developmental myelination processes, are similarly elusive. To tap into these associations, different approaches (such as using different samples) may be necessary. Overall, the associations between these macro-level neuroimaging structural properties and CMDT seem very weak, if they exist at all. The use of large sample sizes and rigorous statistical and preprocessing techniques will be necessary to produce reliable findings.

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26 Openness to Experience: Insights from Personality Neuroscience

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Introduction

There is general consensus among researchers that thoughts or behaviors that jointly satisfy two criteria – namely, novelty and usefulness – can be deemed creative (see Kaufman & Sternberg, 2010; Sternberg, 1999). Having defined creativity as such, research in this domain of inquiry is driven by a search for proximal and distal factors that can explain the emergence of creative thoughts and behaviors. One such factor that has historically been a major focus of research involves personality – defined as “the unique and relatively enduring set of behaviors, feelings, thoughts, and motives that characterize an individual” (Feist, 2010, p. 114). Essentially, researchers have sought to isolate the contribution of relatively stable individual differences in personality structure to creativity. A particularly noteworthy example of this approach is reflected in the classic contributions of the Institute of Personality Assessment and Research (IPAR) to the scientific study of creativity in the twentieth century. Considered by many to be the birthplace of the scientific study of creative personality (Helson, 1999a; see also Barron & Harrington, 1981), findings that emerged at IPAR contributed to numerous methodological and theoretical innovations that underlie our current understanding of creative persons. Indeed, the strong standing of the personality approach to our contemporary understanding of creativity is reflected in its ubiquitous inclusion in textbooks of creativity (e.g., Kaufman, 2009; Sawyer, 2012).

Personality’s Effect on Creativity

Here it is important to ask a critical question: *How* does personality contribute to the emergence of creative thought and behavior? In an influential model proposed in the 1990s, Feist (1998, 1999) proposed that personality influences creativity by lowering the behavioral thresholds that make creativity more likely. Since updated and revised, Feist’s (2010) functional model of the creative personality is depicted in Figure 26.1. According to this model, the causal arrow moves from the left to the right, such that genetic and epigenetic factors are perceived to influence brain characteristics (e.g., structure and function), which in turn influence the four clusters of personality traits most consistently associated with creativity – namely, cognitive, social, motivational-affective, and clinical – which in turn influence creative thoughts or behaviors. In this sense personality mediates the link between brain characteristics and creative thoughts and behaviors. In support of this model, Feist (1998) conducted a large-scale meta-analysis to demonstrate empirically that personality can be used to distinguish scientists from nonscientists, more-creative scientists from less-creative scientists, and artists from nonartists. Although each of the aforementioned three comparisons revealed the importance of different personality dimensions, generally speaking the results showed creative people to be more open to new experiences, less-conventional and conscientious, more self-confident, self-accepting, driven, ambitious, dominant, hostile, and impulsive. These findings were broadly consistent with findings that had

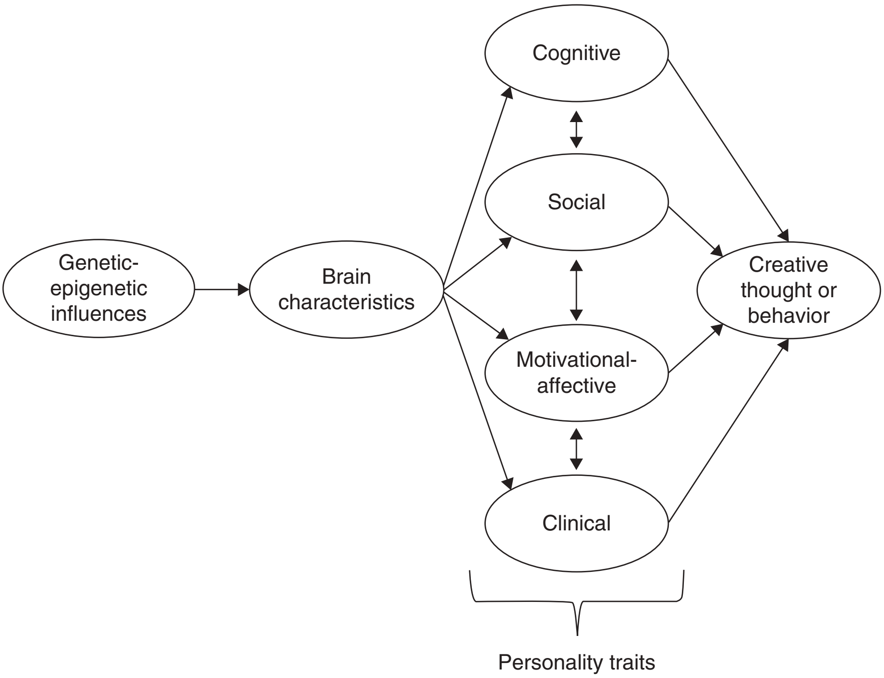

Figure 26.1 Feist's (2010) functional model of the creative personality.
Notes. Adapted with kind permission from Feist (2010).

emerged from more classic studies of creative personality, including those conducted at IPAR (see Helson, 1999b).

Personality, Creativity, and the Brain

Since the publication of Feist's (1998) influential meta-analysis nearly two decades ago, substantial empirical evidence from personality neuroscience has accumulated to solidify the link between personality and brain characteristics. Research in personality neuroscience is motivated by the premise that "the whole person cannot be understood without understanding the brain" (DeYoung, 2010, p. 1165), and takes as its aim the testing and refining of neurobiological theories of personality (DeYoung et al., 2010) to arrive at better representations of the brain's contributions to the emergence of personality structure. The emergence of personality neuroscience as a new area of inquiry has benefitted greatly from two developments. The first is the establishment of the Big Five – a comprehensive taxonomy of traits that categorizes the majority of personality traits within five broad domains: Extraversion, neuroticism, agreeableness, conscientiousness, and openness to experience (Digman, 1990). By providing a common taxonomic platform, the emergence of the Big Five has greatly facilitated the accumulation of knowledge about personality structure. Second, advances in brain sciences, specifically neuroimaging of brain structure and function, have made it possible to more accurately quantify the relationship between various individual-differences measures including personality and brain characteristics using diverse methodologies (see Vartanian, Bristol, & Kaufman, 2013). In conjunction, the parallel developments of these two strands of research have begun to solidify the position of personality neuroscience as an important contributor to refining our models of personality structure.

Among the Big Five's broad domains, openness to experience – defined as "the breadth, depth, originality, and complexity of an individual's experiential life" (John, Naumann, & Soto, 2008, p. 120) – has been the factor most consistently associated with creativity across a broad spectrum of tasks, outcome measures, and ages (e.g., Batey & Furnham, 2006; Carson, Peterson, & Higgins, 2003; Feist & Barron, 2003; King, Walker, & Broyles, 1996; McCrae, 1987; Silvia, Kaufman, & Pretz, 2009; Silvia, Nusbaum, Berg, Martin, & O'Connor, 2009; Silvia et al., 2008). Recently, DeYoung, Quilty, and Peterson (2007) have demonstrated that openness to experience can be differentiated into two aspects – intellect and openness. In turn, they hypothesized that each aspect might be associated with different biological substrates. For example, they noted that some facets of the openness aspect (i.e., Fantasy, Aesthetics, and Feelings) are correlated with crystallized intelligence but not with fluid intelligence or working memory. In contrast, a facet of the intellect aspect (i.e., Ideas) is correlated with fluid intelligence and working memory. This dissociation suggests that the neural bases of intellect and openness might vary to the extent that they draw on the neural systems that underlie intelligence and working memory. Although not directly relevant to the hypothesized dissociation noted above, there is indeed psychometric evidence to suggest that the Big Five factors can be dissociated based on their correlations with measures of cognitive ability, including intelligence. For example, DeYoung, Peterson, and Higgins (2005) have demonstrated that scores on tests that measure dorsolateral prefrontal cortex (DLPFC) function such as fluid and crystallized cognitive ability were correlated positively with openness to experience but not to any other personality factor. Their approach highlights the utility of theoretically driven psychometric investigations that can lay the foundation for the search for the neural bases of personality factors and their associations with creativity.

Particularly strong evidence regarding the predictive validity of the dissociation between the openness and intellect aspects of openness to experience was provided recently by Kaufman et al. (2016), who based their findings on data from four demographically diverse samples totaling 1035 participants, and demonstrated that, whereas openness predicts creative achievement in the arts, intellect predicts creative achievement in the sciences. In addition, they were able to show that the contribution of intellect to scientific creativity may, in part, be due to general cognitive and divergent thinking abilities. Drawing on dual-process terminology, this double dissociation is consistent with earlier findings in which openness but not intellect predicted implicit learning (which draws on System 1), whereas intellect but not openness predicted working memory capacity (which draws on System 2) (Kaufman et al., 2010). Given the strong evidence regarding the discriminant and predictive validity of partitioning the factor of openness to experience into its openness and intellect aspects, for the remainder of this chapter I will adopt the convention of referring to it instead as *openness/intellect*.

Personality Neuroscience: Focus on Openness/Intellect

Given the well-established link between the personality dimension of openness/intellect and creativity, in the remainder of this chapter I will conduct a selective review of the literature from personality neuroscience to demonstrate the myriad ways in which variations in openness/intellect have been related to variations in brain structure and function. Needless to say, the neuroscientific literature focusing on the link between personality and the brain extends beyond neuroimaging approaches involving neurologically healthy adults. For example, important contributions have been made to our understanding of personality structure using molecular genetic approaches (e.g., DeYoung et al., 2011) and studies of humans in disease states (e.g., Mahoney, Rohrer, Omar, Rossor, & Warren, 2011), among others (for review see DeYoung, 2010). Nevertheless, insofar as creativity researchers are concerned, the majority of their research has focused on the assessment of openness/intellect in neurologically healthy young adults. Therefore, by focusing on this small but growing body of literature, we are in a position to observe the emergence of certain consistent findings across studies, which in turn might enable one to draw some inferences regarding the interplay between openness/intellect and creativity in the brain. The findings will be discussed separately in relation to studies that have focused on brain structure versus function, and I will close by highlighting some of the outstanding theoretical and empirical issues that require attention for moving the field forward.

Openness/Intellect and Creativity: Insights from Brain Structure

Regional Brain Volume

DeYoung et al. (2010) conducted a study (*N*=116) to investigate the relationship between variations in scores on the Big Five and regional brain volume, measured using MRI. Importantly, rather than conducting an exploratory analysis, the authors focused on theoretically derived regions of interest (ROIs). For openness/intellect, they hypothesized that it would be associated with "structural variation in some or all of the brain systems involved in the regulation of working memory, attention, and reasoning, including dorsolateral PFC, anterior PFC (frontal pole), and anterior parietal cortex" (p. 822). This prediction was based on the association between scores on openness/intellect and various measures of intellectual ability and executive functions observed in previous behavioral studies (see DeYoung et al., 2005). Indeed, structural and functional studies have highlighted the involvement of the frontoparietal system in the aforementioned cognitive processes in the service of intelligence (Jung & Haier, 2007). However, DeYoung et al.'s (2010) results did not support the hypothesized link between regional brain volume and openness/intellect in ROIs of interest when corrections for multiple comparisons were made. However, when those statistical corrections were relaxed, the authors did observe an association between openness/intellect and the regional brain volume in the inferior parietal lobule – a structure associated with working memory, control of attention, and intelligence (Gray, Chabris, Braver, 2003). These suggestive results highlighted a region that could be examined in future studies.

Kapogiannis, Sutin, Davatzikos, Costa, and Resnick (2013) similarly investigated the relationship between variations in scores on the Big Five and regional brain volume – measured using MRI and analyzed using voxel-based morphometry (VBM). Because the authors were in part interested in studying the long-term stability of personality (and its neural correlates), data were collected from participants (*N* = 87) on two occasions, two years apart. The researchers found that openness/intellect correlated positively with gray matter volume within right frontopolar cortex and left thalamus, but correlated negatively with gray matter volume in a large number of regions including right medial orbitofrontal cortex (OFC), bilateral fusiform gyrus, left insular cortex, right superior frontal gyrus and left supplemental motor area, left postcentral gyrus, right precuneus, and left inferior parietal cortex. The authors noted that the frontopolar cortex has a well-established role in cognitive control and subgoal processing, and its positive volumetric association with openness/intellect suggests a heightened role for those cognitive functions underlying variation in that personality factor. Moreover, many of the regions that exhibited a negative association with openness/intellect tend to be implicated in inhibitory or cautionary responses to aversive and/or fearful stimuli, including the medial OFC and insular cortex, suggesting that perhaps higher scores on openness/intellect might be associated with reduced reliance on those psychological processes. Importantly, although the authors' interpretations are plausible and generally consistent with our understanding of the construct of openness/intellect, inferences regarding the association between regional volume and the propensity to engage more or less in particular types of thinking must be verified directly to be considered conclusive.

Jauk, Neubauer, Dunst, Fink, and Benedek (2013), also relying on VBM for their statistical inferences, investigated regional gray matter volume differences associated with creative potential in a large sample ($N = 135$). Although investigating the correlation between variation in regional gray matter volume and creative potential rather than openness/intellect was the main focus of the study, the latter measure was administered to all participants. Behaviorally, ideational originality and openness/intellect were correlated positively. In contrast, whereas voxel-wise, whole-brain analyses revealed that openness/intellect exhibited a negative correlation with regional gray matter volume in the right precuneus, the reverse pattern was observed for ideational fluency. When the aforementioned analysis was conducted separately for participants of higher versus lower intelligence, openness/intellect was correlated negatively with regional gray matter volume in the right middle temporal lobe among individuals of lower intelligence. No association was observed between openness/intellect and regional gray matter volume in participants of higher intelligence. The interpretation of these results is complicated by the fact that whereas behaviorally openness/intellect and ideational fluency were correlated positively, at the neural level they exhibit opposite patterns of correlation with regional gray matter volume in the precuneus. The authors offered the following explanation to account for their findings:

> Thus, it seems that while creative potential and intelligence as well as openness are positively related on a behavioral level, there seems to a trade-off on the neurostructural level. This might at least partially be explained along the line presented above: While primary processes such as mind wandering are generally beneficial to creative thought, they can be detrimental to intelligence related demands. Thus, highly creative people (who are, given the substantial correlation, also of higher intelligence) may devote some of their gray matter to primary process cognition while – at the same time – this primary processes may hinder convergent thinking ability to a certain extent. (p. 317)

The authors' proposal of a neural-level trade-off is interesting, but requires further study. Nevertheless, this explanation also highlights some of the difficulties in interpreting the psychological meaning behind the association between openness/intellect and brain structure, especially insofar as they relate to the way in which other related constructs (e.g., creativity, intelligence) are associated with brain structure in the same study.

Li et al. (2015) contributed to this literature in a novel way by examining the *mediating* role of openness/intellect in the relationship between trait creativity and regional gray matter volume. Specifically, they conducted a VBM analysis based on MRI data collected from a large sample ($N = 246$) to test whether trait creativity would be associated with variations in gray matter volume in a number of ROI in both directions: they hypothesized that higher trait creativity would be related to *larger* volume in a brain region linked to the inhibition of control (i.e., DLPFC) and in another brain region implicated in novelty seeking, curiosity and imagination (i.e., right posterior superior temporal sulcus), but that higher trait creativity would be related to *smaller* volume in a brain region associated with novel goal-directed behavior (i.e., OFC). Furthermore, they hypothesized that openness/intellect would mediate the link between trait creativity and regional gray matter volume in relation to all three ROIs. Partly supporting their predictions, the results demonstrated that openness/intellect mediated the association between the right posterior middle temporal gyrus (pMTG) volume and trait creativity. What was the functional explanation for this observed relationship? The authors noted that "openness to experience might induce some particular patterns of cognitive processing associated with intuition, imagination, curiosity, and fantasy through 'semantic processing' functions related to the right pMTG. That is, the basic personality features related to the trait of openness to experience might play an important role in shaping an individual's trait creativity" (p. 196). Li et al.'s (2015) study is important because it suggests that openness/intellect plays an important role in the mechanism relating trait creativity to brain structure.

Another important contribution to this literature was conducted by Bjørnbekk et al. (2013), notable not only because of its large sample size ($N = 265$) but also because the researchers provided a rather comprehensive investigation of the brain–personality relationship using multiple neuroimaging modalities that went beyond measures of total and regional brain volume, and included measures of regional cortical thickness and diffusion tensor imaging (DTI) indices of white matter microstructure. Interestingly, the results demonstrated that there was no reliable association between openness/intellect and brain structure based on any of the acquired measures. As such, insofar as regional brain volume is concerned, the results of Bjørnbekk et al. (2013) are inconsistent with the results of previous studies investigating the relationship between openness/intellect and brain structure (but see DeYoung et al., 2010). The observed inconsistencies suggest that more study is needed to elucidate factors that underlie the association between openness/intellect and brain structure as measured by regional brain volume.

White Matter Integrity

Jung, Grazioplene, Caprihan, Chavez, and Haier (2010) examined the relationship between white matter integrity – assessed by fractional anisotropy (FA) – and openness/intellect ($N = 72$). As explained by Jung et al. (2010), a measure of FA can be derived by tracking the diffusion of water in the brain. According to this model, higher FA suggests greater axonal coherence and myelination. As such, FA measures are considered to be overall measures of axonal integrity because they reflect increased axonal caliber, increased myelin thickness, increased fiber coherence in a given direction, or some combination thereof. The researchers found that openness/intellect was related inversely to FA within the right inferior frontal white matter (i.e., regions overlapping the uncinate fasciculus and anterior thalamic radiation). Given the paucity of data in this domain, Jung et al. (2010) suggested that the main takeaway point from their study was the observation of an inverse relation between openness/intellect and FA. Specifically, they noted that whereas in studies involving intelligence the typical pattern of findings involves a positive association between neural resources and intellectual capacity in the frontoparietal network of brain regions (Jung & Haier, 2007), studies involving creativity appear to suggest that less is often better in a different network of brain regions (see Jung & Haier, 2013; Jung, Mead, Carrasco, & Flores, 2013).

In turn, Xu and Potenza (2012) examined the association between white matter integrity and openness/intellect in a sample of healthy participants ($N = 51$) using DTI. As noted by the authors, white matter mediates communications in the brain, and is critical for the integrity of brain function. Like Jung et al. (2010), the authors measured FA and also mean diffusivity (MD). Importantly, both FA and MD represent indexes of white matter integrity: decreased FA and/or an increased MD value in white matter reflect poorer white matter integrity. They found that although there were no correlations with FA, openness/intellect were correlated negatively with white matter MD in superior longitudinal fasciculus, corona radiata (which are tracts that connect the PFC, the parietal cortex, and subcortical structures), as well as in the anterior cingulum, forceps minor, and corpus callosum. In addition, openness/intellect was correlated negatively with white matter MD adjacent to the DLPFC in both hemispheres, including the middle and inferior frontal gyrus. These findings suggest that the integrity of white matter adjacent to the DLPFC as well as fiber tracts that jointly connect most cortical and subcortical regions is a positive contributor to openness/intellect. As such, this study provided evidence indicating that openness/intellect is associated with the integrity of fiber tracts throughout the brain, rather than simply the PFC. Notably, however, Xu and Potenza's (2012) results were not consistent with those of Jung et al. (2010), who found that openness/intellect was related inversely to FA within the right inferior frontal white matter. Aside from methodological differences, the reason behind the inconsistent results across the two studies remains unknown, and requires further study.

Openness/Intellect and Creativity: Insights from Brain Function

Resting State

To date, a number of studies have investigated the relationship between resting-state brain activity and individual differences in openness/intellect, using different methods and focusing on different populations. First, Sutin, Beason-Held, Resnick, and Costa (2009) investigated this relationship focusing on a sample of older (> 55 years of age) adults (*N*=100), using resting-state positron-emission tomography (PET) data. As in the other study conducted by the same group discussed earlier in this chapter (Kapogiannis et al., 2013), due to the researchers' interest in stability in personality and its related neural correlates, each participant was assessed twice, two years apart. The results revealed interesting sex differences in resting-state brain activity associated with openness/intellect. Specifically, whereas openness/intellect was correlated positively with PFC activity in females, it was correlated positively with anterior cingulate activity in males, and with OFC activity in both sexes. The authors argued that the same personality trait might rely on the contributions of different neural structures (and by extension psychological processes) for its expression in the two sexes. Specifically, the results suggested that openness/intellect is driven by a cortical structure associated with cognitive flexibility in females (i.e., PFC), monitoring processes in males (anterior cingulate cortex), and reward and emotional processing in both sexes (i.e., OFC). These results highlight the utility of investigating sex differences in personality neuroscience. In addition, insofar as individual differences in openness/intellect contribute to creativity, it might be advantageous to also study sex differences in its neural correlates as they relate to creativity – measured both as a trait as well as a state.

Sampaio, Soares, Coutinho, Sousa, and Gonçalves (2014) also investigated the relationship between the Big Five and stimulus-independent brain function at rest, with the difference that their data were collected using fMRI and that they focused on the contribution of the default mode network (DMN) to stable individual differences in personality in healthy adults ranging from 19 to 52 years of age (*N* = 49). They found that greater openness/intellect was associated with increased activity in the right inferior parietal cortex and with decreased activity in bilateral superior parietal cortex and in the left precuneus. It is unclear why resting-state activity in different regions of the parietal lobe was associated negatively and positively with openness/intellect scores, although the authors suggested that in part this might be due to the role of some regions of the parietal lobes in "processing more outward-directed social or contextual information" (p. 1920). This account remains to be verified.

Task-dependent Activity

DeYoung, Shamosh, Green, Braver, and Gray (2009) parsed out the differential contributions of openness versus intellect to brain function in the course of performing a difficult working-memory task. Specifically, the authors hypothesized that because of the greater loading of intellect than openness on working memory (see DeYoung et al., 2005), brain activity during engagement with a difficult working memory task would be correlated with individual differences in the former but not the latter aspect of the openness/intellect factor. This hypothesis was tested in a sample of neurologically healthy participants (*N* = 104) who completed the 3-back working memory task in the fMRI scanner. Their results demonstrated that intellect but not openness scores were correlated positively with accuracy-related brain activity in left lateral anterior PFC and medial frontal cortex – regions of the brain implicated in executive functions (including working memory). In addition, mediation analyses revealed that neural activity in the aforementioned regions mediated the link between intellect and working memory performance. This result suggests that these regions could reflect the "neural substrate of Intellect" (p. 883). This study represents an important theoretically-driven contribution to our understanding of the differential associations of each aspect of openness/intellect with brain function.

Functional Connectivity and Network Integrity

Recently, a number of noteworthy contributions to the literature were made by researchers who have used resting-state fMRI data to assess patterns of functional connectivity and network integrity in relation to individual differences in openness/intellect. Specifically, focusing on the Big Five, Adelstein et al. (2011) examined the contribution of each personality factor to resting-state functional connectivity involving two "hubs" that are known to exhibit connectivity with numerous regions in the brain – the anterior cingulate cortex (ACC) and the precuneus – in a sample of neurologically healthy adults (*N* = 39). The researchers' aim was to identify potentially dissociable intrinsic functional networks associated with each of the five factors. With respect to openness/intellect, the researchers found that the scores predicted resting-state functional connectivity with midline hubs of the DMN known to underlie internally oriented cognition, as well as with the DLPFC, a region associated with intelligence, executive functions and the intellect aspect of the openness/intellect factor. However, arguably, the most important finding of the study was that the observed pattern of resting-state functional connectivity was inconsistently observed across participants, such that "although a fundamental, core functional architecture is preserved across individuals, variable connections outside of that core encompass the inter-individual differences in personality that motivate diverse responses" (p. 1). This important set of findings suggests that individual differences in openness/intellect are a reflection of the combined contribution of common and unique patterns of resting-state functional connectivity across individuals.

In turn, Passamonti et al. (2015) investigated the relationship between openness/intellect and dopaminergic circuits. This investigation was motivated by the idea that individual differences in openness/intellect might be related to dopamine, known to play a role in adaptive behaviors, as well as the orientation of attention toward salient and/or rewarding stimuli (see DeYoung, 2010; DeYoung et al., 2005). Of particular focus were mesocortical midbrain structures that contain dopaminergic circuits. The hypothesis that there would be a link between individual differences in openness/intellect and brain function in mesocortical networks was tested using fMRI in three studies involving neurologically healthy participants ($N = 46$). The first study involved the collection of task-independent resting-state fMRI, whereas the last two studies involved tasks based on the presentation of pleasant odors and pictures of food. Focusing their analysis on the salience network, the authors found consistent evidence across all three studies to show that openness/intellect was associated positively with the functional connectivity between the right substantia nigra/ventral tegmental area – a major source of dopaminergic inputs in the brain – and the ipsilateral DLPFC – a key working memory region for encoding, maintaining, and updating information relevant for adaptive behaviors. Consistent with Feist's (1998, 1999) hypothesis that personality influences creativity by lowering the behavioral thresholds that make creativity more likely, Passamonti et al. (2015) reasoned that "increased dopaminergic inputs within the DLPFC reduce the threshold for information processing in open people and make them highly 'permeable' and receptive to relevant information" (p. 307). As such, their results provide important evidence regarding the ways in which openness/intellect might affect the gating of information in creative people (see also Jung et al., 2013).

Finally, Beaty et al. (2016) collected resting-state fMRI to determine whether the aspects of openness and intellect are differentially related to the global function of the DMN. Analytically, the authors used a graph-theoretic method to derive a measure of (global) network efficiency, considered to reflect the efficiency of information processing within a system. The results of Study 1 ($N = 68$) demonstrated that as openness/intellect scores increased, the DMN exhibited more efficient information processing (i.e., network efficiency). A follow-up analysis revealed that Intellect but not Openness was a significant predictor of network efficiency. In Study 2 ($N = 86$), from the Big Five traits only openness/intellect was a significant predictor of DMN openness/intellect network efficiency. The results of this study suggest that individual differences in openness/intellect affect the functional organization of the DMN – a large-scale brain network. In addition, the authors suggested that the functional role of the observed association between openness/intellect and greater network efficiency in the DMN might be that people with higher scores on this factor might be better at engaging the psychological processes associated with the DMN.

Summary

Historically, our understanding of creativity has benefitted greatly by knowledge gained from personality and the study of individual differences. One of the most robust findings of this area of research has been the discovery of the association between the Big Five factor of openness/intellect and creativity. The relatively small but rapidly growing domain of personality neuroscience has begun to enrich our understanding of the relationships among openness/intellect, brain characteristics, and creativity. An important problem while evaluating the available evidence concerns inconsistencies in the results across studies. As noted by DeYoung (2010), the inconsistencies largely stem from a combination of the use of relatively small sample sizes which are known to cause problems in detecting true statistical effects, and the fact that the traits under investigation are likely influenced by many factors, each of which accounts for only a small portion of the variance in the trait. DeYoung's (2010) recommendation for circumventing this problem is to conduct more theoretically oriented hypotheses: "These difficulties highlight the importance of testing reasonably focused hypotheses, rather than simply exploring associations with biological variables in the absence of any theory of the causal mechanisms that might underlie a given trait" (p. 1167). Indeed, recent contributions to the field involving functional connectivity and network efficiency reviewed above represent promising examples of such theoretically driven investigations into the neural bases of openness/intellect (e.g., Adelstein et al., 2011; Beaty et al., 2016; Passamonti et al., 2015). It is hoped that the continuation of research on the neural bases of openness/intellect will contribute to a more complete understanding of how this factor influences individual differences in creativity.

Despite the promises of this emergent domain of inquiry, some outstanding theoretical and empirical issues remain that require attention for moving the field forward. I will highlight two issues here. First, although numerous studies have focused on the association between regional brain volume and variation in openness/intellect, the specifics of how brain volume measures relate to brain function measures remains unknown (DeYoung et al., 2010). The resolution of this issue is necessary if one were interested in making inferences about function based on volumetric data. Second, a major recent development in the field of systems neuroscience has involved an appreciation of the contribution of large-scale brain networks to cognition and behavior. For example, in relation to internally-oriented cognition, Zabelina and Andrews-Hanna (2016) have recently outlined the contributions of seven such large-scale networks to external and internal attention, including dynamic control of attention. Recent research has focused on the dynamic interaction of large-scale networks in support of creativity (Beaty, Benedek, Kaufman, & Silvia, 2015), and it would appear that studying the role of openness/intellect in the modulation of such large-scale network interactions would be advantageous for our understanding of creativity.

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27 Creativity and the Aging Brain

Kenneth M. Heilman and Ira S. Fischler

Introduction

According to some researchers (e.g., Abra, 1989), there is a decrease in creativity with aging. There is some support for this claim; for example, Simonton (1994) reported that there are age-related changes in creative productivity, with a sharp increase in productivity between the ages of 20 and 30 years, peaking between the ages of 30 and 50, followed by declining creative production over the next several decades. Lehman (1953) reported that poets and mathematicians typically reach their creative peaks at the earliest age, while philosophers and novelists develop their peak creativity at a later age. Even within these broad trends, there is uncertainty about the strength of the relationship between age and creativity. According to Lehman, scientists do their highest-quality work before the age of 40, but Cole (1979) found that age had only a minor impact on scientific performance. For the most part, however, there has been little study of how creativity may change with age. Remarkably, the term "aging" doesn't even appear in the index of a recent handbook on creativity (Kaufman & Sternberg, 2010). In this chapter we will discuss how aging may influence creativity and the changes in the brain that may be responsible for these changes; but first we will discuss the definition of creativity, the stages of creativity and the component cognitive processes that may be critical for creative productions.

Definition of Creativity

The Merriam Dictionary (1988) defines creativity as the ability to make new things. Similarly, the Encyclopedia Britannica defines creativity as the ability to make or bring into existence something new. These definitions are, however, somewhat inadequate. Artists, writers, and scientists who mechanically record facts might be productive but are not creative. Conversely, typing a list of nonwords, colors randomly applied to a canvas, or a random list of variables may be novel or original, but not creative. Some definitions also mention utility or the production of useful object; however, an artist may paint a beautiful picture but never display this painting. Thus, it is not useful, but this painting can be very creative.

Bronowski (1972) defined creativity as finding unity in what appears to be diversity. We agree that finding unity appears to be a major element or theme of much creative achievement. For example, great artworks have a myriad of colors and forms/shapes, and great musical works have a large variety of melodies and rhythms, but in both paintings and symphonies the artist is able to develop a thread that unites diverse elements and display order. Creative scientists such as Copernicus with his heliocentric hypothesis was able to see the thread that united what previously appeared to be a disorderly planetary system, and Einstein was able to see the thread that united matter and energy. Thus, in the arts as well as the sciences, creativity may be defined as a new understanding or novel development and systematic expression of orderly relationships (finding the "thread that unites"; Heilman, 2005; Heilman, Nadeau, & Beversdorf, 2003).

Stages of Creativity

Classic accounts of the creative process (e.g., Helmholtz, 1826, as cited by Eysenck, 1995; Wallas, 1926) proposed that creativity has four stages: preparation, incubation, illumination, and verification. *Preparation* is the acquisition of the skills and knowledge that allows a person to create. For example, Einstein developed superb skills in physics and math before he made his great discoveries, and Picasso learned to draw forms and mix colors before he painted his masterpieces. The acquisition of knowledge and skill is dependent upon brain development, and different skills require the development of different brain networks. The second stage is *incubation*, and there are probably several forms of incubation. For example, Kuhn (1996) noted that many important discoveries are initiated by the observation of an anomaly, and many important scientific discoveries are made when a scientist perceives significance in apparently accidental occurrences, such as Fleming observing that when penicillin mold fell into a Petri dish with bacteria, this mold killed these bacteria. The scientists who make these types of discoveries, such as Alexander Fleming, must be prepared to understand the importance of these accidents. Although these discoveries are based on an anomaly, it is the “prepared mind” that enables creators to perceive the importance of the phenomenon they observed. Thus, it is highly probable that creative people such as Fleming were incubating ideas about the phenomena prior to their observations. The experience of buoyancy is not an accidental occurrence and therefore when taking a bath Archimedes’ discovery of the law of buoyancy was probably based on incubation. With discovery of this law Archimedes exclaimed “Eureka!” and others have called this burst of euphoria the “Aha!” experience. It is this “Aha’”’ experience or epiphany that Helmholtz and Wallas termed *illumination*. Subsequently, creative people such as scientists perform experiments that attempt to test their hypothesis. This is the process of *verification*.

The constructs of incubation and illumination have received much criticism. The debate about the nature of incubation has centered on the question of whether “subconscious” problem-solving may occur, or whether a solution is more likely after a period of rest because incubation reduces the need for inhibition (Koppel & Storm, 2014). Metcalfe and Wiebe (1987) demonstrated that the subjective feeling of knowing (illumination) did not predict performance on insight problems. Weisberg (1986) suggested that creativity rarely requires great leaps (e.g., illumination), and the processes that lead to many great discoveries might not be subconscious incubation, but rather a series of conscious steps. Even according to Helmholtz and Wallas, rather than being an independent factor, illumination appears to be the culmination of the incubation process. As there is no consensus on these stages of creativity, instead of discussing incubation and illumination as independent stages, in this chapter we combine these stages and will use the term “creative innovation.” In addition, innovators such as visual artists, composers, and authors do not verify theories but rather produce works of art. Therefore, in this chapter we call this last stage *verification–production*. Whereas verification–production are critical elements of creative achievement, these processes are specific to the type of creativity and they will not be further discussed in this chapter.

Neuropsychology of Creative Innovation

Creativity requires the novel understanding and expression of orderly relationships, and novelty requires that the creative person take a different direction from the prevailing modes of thought or expression, which is called divergent thinking. The concept of divergent thinking was put forth by William James (1890) who stated, “Instead of thoughts of concrete things patiently following one another in a beaten track of habitual suggestion, we have the most abrupt cross-cuts and transitions from one idea to another … unheard of combination of elements … we seem suddenly introduced into a seething caldron of ideas … where treadmill routine is unknown and the unexpected is the only law." Much of the empirical research on creativity since James' time has focused on divergent thinking as a critical element of creative innovation.

Frontal Lobes and Divergent Thinking

Denny-Brown and Chambers (1958) noted that all animals have two basic forms of behavior: approach and avoidance. With evolution of the brain, animals are able to perform a greater variety of behaviors, but many of these behaviors are still based on the approach–avoidance dichotomy. According to Denny-Brown and Chambers, whereas the frontal lobes are the part of the brain important in avoidance, the posterior temporal and parietal lobes are important for approach. To perform divergent thinking, a person has to disengage from currently known concepts and develop new ideas. Oliver Zangwell (1966) suggested that frontal lobe dysfunction would disrupt divergent thinking. Berg (1948) developed the Wisconsin Card Sorting test (WCS) in which participants are required to sort a deck of cards according to three main properties of images of objects illustrated on these cards (e.g., shape, color, and number). The subjects taking this test are not informed of the sorting principles (e.g., shape) but must deduce this from the response of the examiner after each sort. Throughout this test the sorting principles change (e.g., from shape to color) and the subjects must switch their strategy based on the responses of the examiner. Milner (1984) demonstrated that patients who had frontal lobectomies for the surgical treatment of intractable epilepsy were impaired at this test, suggesting that the frontal lobes might be critical for the ability to disengage and shift to new solutions. Cognitive perseveration, the inability to switch set or change the form of an activity, is often observed in brain-impaired individuals who have frontal lobe injuries. Luria (1969) demonstrated in a series of studies that patients with frontal lobe dysfunction are stimulus-(environmentally) dependent. For example, even on simple motor tasks ("When I put up one finger you put up two fingers and when I put up two you put up one") patients with frontal lobe injury have a propensity to produce behaviors that are entrained by the stimuli (a failure of disengagement) and therefore will put up the same number of fingers as the examiner.

William James (1890) suggested that the ability to switch strategies was important in divergent thinking. Converging evidence for the postulate that the frontal lobes are important for the ability to disengage and shift to new strategies (divergent thinking) comes from studies of regional blood flow in normal subjects who are performing the WCS or performing divergent-thinking creativity tests, similar to those described by Guilford (1967) and Torrance (1988). The dorsolateral prefrontal lobes were specifically more active during performance of the WCS than during a simple number-matching test, and the amount of increased activation correlated positively with WCS performance (Weinberger, Berman, & Zec, 1986). When creative subjects are providing alternative uses of bricks, their frontal lobes showed more activation than those who were less creative (Carlsson, Wendt, & Risberg, 2000).

While both studies of patients with frontal lobe lesions (Damasio & Anderson, 2003; Stuss & Knight, 2002) and functional imaging studies suggest that the frontal lobes are important for disengagement and developing alternative strategies (divergent thinking), the means by which the frontal lobes accomplish these functions remain unknown. The frontal lobes have strong connections with the polymodal regions of the temporal and parietal lobes (Pandya & Barnes, 1987). Perhaps these connections are important for inhibiting the activated networks that store semantically similar information while also exciting or activating the semantic conceptual networks that have been only weakly activated or not activated at all. Activation of these remote networks might be important in developing the alternative solutions so important in divergent thinking. Support for the postulate that the frontal lobes might be important in either activating or inhibiting semantic networks comes from a study using positron emission tomography (PET) that suggested different roles for medial and lateral rostral prefrontal cortex (Brodmann's area 10), with the former involved in suppressing internally generated thought, and the latter in maintaining these thought patterns (Burgess, Scott, & Frith, 2003).

Connectivity and the Cerebral Hemispheres

Creativity was defined in the beginning of this chapter as the new understanding or new development and expression, in a systematic fashion, of novel orderly relationships. Since the work of Paul Broca (1863) and using the lesion method, laterality studies such as dichotic listening and visual half-field, as well as electrophysiological (EEG) studies and functional imaging, it has been repeatedly demonstrated that the human brain is organized in modular fashion. Thus, the understanding, development, and expression of orderly relationships might require communication between these modules. Perhaps the strongest evidence for brain modularity is hemispheric specialization, the left hemisphere being dominant for language, even in the majority of left handed people (McGlone, 1984), dominant for motor control of skilled movements (Liepmann, 1920), and categorical processing (Kosslyn, 1998). In contrast, the right hemisphere appears to be important in spatial cognition (Benton, Hannay, & Varney, 1975), including spatial imagery (Butters, Barton, & Brody, 1970), face recognition (Benton, 1990), and coordinate coding (Kosslyn, 1998). The right hemisphere also appears to be important in emotional communication such as recognizing and expressing emotional speech prosody and emotional facial expressions (Heilman, Blonder, Bowers, & Crucian, 2000). The right hemisphere may also be dominant for mediating primary emotions (Heilman et al., 2000). Whereas the right hemisphere appears to have a global attentional perspective (Barrett, Beversdorf, Crucian, & Heilman, 1998; Robertson, Lamb, & Knight, 1988), the left hemisphere has a more focused attentional perspective. Many other right–left hemisphere dichotomies have been described that cannot be fully addressed in this chapter, but scientific or artistic creativity often requires that the creative person use the skills and knowledge mediated by both hemispheres. For example, the novelist who is writing about an emotional response of a character must use the knowledge of facial emotional expressions stored in their right hemisphere together with the verbal lexicon stored in their left hemisphere. The sculptor must imagine the rotation of spatial images such as a face where the representation is stored in the right hemisphere while she or he uses the motor skills mediated by the left hemisphere. The astronomer must combine the spatial computations mediated by the right hemisphere with arithmetic skills mediated by the left hemisphere. Thus, interhemispheric communication should be important for combining the knowledge and skills that are important for creative innovation.

William James (1890) suggested that creativity requires, "unheard of combination of elements and the subtlest associations." Spearman (1931) suggested that creative ideas result from the combination of two or more ideas that have been previously isolated. Because the right and left hemispheres store different forms of knowledge and mediate different forms of cognitive activity, different neuronal architectures probably exist within the association cortices of each of the hemispheres. A possible method of resolving a previously unsolved problem is to see this problem "in a new light" and a means of seeing a problem in a new light is to use the different forms of knowledge, and using cognitive strategies mediated by the opposite hemisphere may allow a person to gain this new insight. Although divergent thinking has been the main focus of research on creativity, the "convergent" thinking that the brain's connectivity allows – finding the thread that unites – has been seen as critical in many so-called "insight" tasks (e.g., Kounios et al., 2008).

The largest structure connecting these different hemispheric modular systems is the corpus callosum. Lewis (1979) administered the Rorschach test to eight patients before and after they had undergone a cerebral commissurotomy and reported that the disconnection of the two cerebral hemispheres "tended to destroy creativity" as measured by this test. It may be that because of its visuo-spatial nature, creative responses to this visually based projective test rely largely on right-hemispheric modules, while it would be these patients' left hemisphere that is responsible for the verbal responses. Bogen and Bogen (1988) noted that although the corpus callosum transfers high-level information, normally this interhemispheric communication is incomplete. Bogen and Bogen posited that incomplete interhemispheric communication permits hemispheric independence and lateralized cognition, and suggested that the momentary suspension of this partial independence could actually facilitate creative innovation. The Bogens, however, did not say what could account for this momentary suspension of partial independence.

The cerebral connectivity that is important for creativity might not only be interhemispheric, but also intrahemispheric. In addition to the myelinated axons that carry information between the hemispheres, there are myelinated axons that also carry information between cortical regions within the same hemisphere, as well as from the thalamus to the cortex, and from the cortex to the basal ganglia, thalamus, and brain stem. These intrahemispheric connections facilitate intrahemispheric communication that also might be important for creative innovation because widespread connectivity allows creative people to combine the representations of ideas that have been previously isolated.

Connectionist models, as well as parallel distributed processing models, suggest that the information stored in the brain is related to the strengths of connections between neurons and that a large number of units linked by a set of connections define a domain of knowledge from which any one of a large number of concepts can be generated. Psychological studies of priming effects on lexical decision latency provide a particularly clear demonstration of the capacity of this type of model to account for empirical results. In a lexical decision task, words or pseudo-words are flashed one at a time on a screen and the subject has to indicate, as rapidly as possible, if the word displayed is, or is not, a real word. In a priming paradigm, before the target word or nonword appears on the screen, a prime word appears. If the prime is strongly related to the target (e.g., the prime is *doctor* and the target is *nurse*), the response time is less than when the prime and target are unrelated (e.g., *doctor–zebra*). This is because, when a related prime appears, it generates a distributed concept representation that involves activation of many of the units that define the distributed representation of the target. To the extent that the target's neuronal representation is already activated when the target appears, response latency to the target is reduced.

We might look to these kinds of models for a more precise understanding of how connectivity might support creative thinking. There are two means by which connectionist architectures might account for creativity. Entities in the environment lead to activation of selected units, thereby leading to the generation of the patterns of activation that instantiate the concepts of these entities. There may, however, be the capacity for the discretionary–intentional activation, mediated by frontal executive networks, of selected units in a cognitive network, thereby producing novel patterns of activation corresponding to novel concepts. In this way, the network represents an internal model of some domain of knowledge, and the discretional ability to activate selected units corresponds to the ability to ask “what if” questions.

A greater measure of creativity might be achieved by using networks representing knowledge in one domain to help organize a different domain that might nevertheless share some attributes. Such “structural concept mapping” is at the heart of current approaches to analogical reasoning and metaphor comprehension, which one could argue are prototypical examples of creative thinking (Gentner & Bowdle, 2008; cf. Glucksberg, 2008).

Many different network architectures exist within the association cortices of the brain. This raises the possibility that this aspect of creativity might involve the recruitment of networks of substantially different architecture in order to escape the constraints of existing (learned) models represented in the networks previously used for reasoning in a particular knowledge domain. The manipulation of concepts in a network of a completely different architecture would allow the investigator or artist to ask novel “what if” questions. For example, both Einstein and Richard Feynman, the Nobel Prize-winning physicist, often began with visual–spatial representations of ideas, which they subsequently translated into mathematical terms. Apparently the architecture of the networks supporting these visual representations permitted them the manipulative freedom to escape conventional formulations, thereby providing the basis for creative innovation.

Mednick (1962) suggested that in generating associative responses to stimuli, creative individuals are characterized by a “flatter” associative hierarchy than are less-creative individuals – that is, the connectivity in the semantic networks to the most common associations may be relatively weaker, and/or the links to the more “remote” networks may be stronger and thus these remote associations may be more readily activated. Hence, creative people might have the ability to activate more highly distributed networks. Support for Mednick’s proposed theory, and partial support for the postulate that creative innovation is related to the recruitment of different networks, comes from EEG studies of normal subjects who, during creative thought, demonstrated an increase of anatomically distributed coherence of EEG oscillations (Jausovec & Jausovec, 2000; Kounios et al., 2008; Petsche,1996).

Changes in Creativity with Aging

As noted earlier, Simonton (1994) reported that creative productivity is a function of age, with the years of peak creativity varying widely across disciplines. Simonton (1994) suggests that “career age” (the number of years that a person has been creative in a domain) is an important factor in the reduction of creativity with aging because people simply run out of ideas. Although creative people’s decreased productivity with aging might be related to the exhaustion of new ideas, there are many changes that occur in the brain with aging, and thus changes in creativity might also be related to biological factors making the generation of new ideas more difficult. For the remainder of this paper, we will consider some of those potential neurological factors.

Changes in Intelligence with Aging

There are many definitions of intelligence. Some people who do not like the construct of intelligence define intelligence as the score a person obtains on a test of intelligence (IQ test). However, to many psychologists, intelligence is the measure of a person’s ability to acquire and apply knowledge. Sternberg and O’Hara (1999) suggested that, logically, there are four possible relationships between intelligence and creativity: (1) they are the same; (2) one is a subset of another (for example, creativity is a subset of intelligence); (3) they are unrelated; (4) they are overlapping but independent concepts. We would suggest a more complex and nuanced relationship: Whereas intelligence and creativity are independent concepts, creativity at the preparation stage requires the ability to acquire knowledge, and at the productivity stage to apply this knowledge. In addition, if intelligence is the measure of a person's cognitive ability to adapt, creativity is a gift that might allow one to better adapt, but this would only be true of certain forms of creativity.

One of the founders of intelligence tests, Alfred Binet, must have initially thought that creativity and intelligence were the same, or closely overlapping, because in the first intelligence test that he devised in 1896 he used inkblots to explore the imagination of children. Later, according to Sternberg and O'Hara (1999), he discontinued this inkblot test because he was unable to develop a means of scoring it.

The validity of many current tests of creativity and individual differences remains controversial. Whereas Guilford and Christensen (1973) suggested that creativity was a subset of intelligence, these investigators did attempt to develop psychometric tests that could measure creativity. These tests are similar to those developed by Torrance (1974) and primarily measure divergent thinking. One of the most widely adopted of divergent thinking tests assesses subjects' ability to develop novel uses of common objects (the Alternative Uses Test). For example, subjects would be asked to name, in a fixed time interval, the different ways in which they might be able to use a brick. Guilford found that students with low IQ consistently performed poorly on these tests, but for those students with high IQs, performance on creativity tests did not correlate highly with their performance on IQ tests. In an influential study, Wallach and Kogan (1965) compared the performance of a large number of school children on a battery of then-available tests of intelligence, and of creativity, including Guilford's Alternative Uses Test. Within each class of tests, correlations were strong, but overall, the correlation between intelligence and creativity tests was meager. After reviewing the relationship between intelligence and creativity, Torrance (1975) suggested that IQ and creativity are moderately related at best, a conclusion supported as recently as 2005 by a meta-analysis of an increasingly large literature (Kim, 2005).

Another means of studying the relationship between creativity and intelligence is studying creative peoples' intelligence. Barron and Harrington (1981) studied architects and found a weak relationship between the creativity of these architects and their IQ. They concluded that above an IQ of about 120, IQ does not predict creativity as much as it does if the IQ is below 120. These observations suggest that there might be an IQ threshold, such that a person needs to be above this threshold to have sufficient intelligence to learn the knowledge about the domain of their creativity and to acquire the skills needed to be creative in a domain. From this perspective, intelligence may be a necessary but not sufficient component of creativity.

Other investigators have also studied populations of known creative people and attempted to learn if there is a strong correlation between their estimated eminence as creators and their intelligence. Simonton (1994) and other investigators, such as Herr, Moore, and Hasen (1965), also found that the correlation between intelligence and creativity is weak. This weak correlation, however, might be related to the test that was used to measure intelligence.

Cattell (1963) posited that there are two types of intelligence, which he called "crystallized" and "fluid." Whereas crystallized intelligence is primarily declarative memories, such as knowing that Albany is the capital of New York State or lexical-semantic knowledge such as knowing what the word "impale" means, fluid intelligence is the ability to solve problems. Most modern intelligence tests, such as the Wechsler Adult Intelligence Scale (WAIS), test both crystallized (e.g., vocabulary definitions) and fluid intelligence (e.g., How are a fly and tree similar?). Cattell thought that while crystallized knowledge may be important in enabling creativity, it is fluid intelligence that determines creativity.

There may be different domains of fluid intelligence, such as the ability to solve a mathematical problem or a visuo-spatial problem. Nonetheless, the most recent work examining the relationship between intelligence and creativity has focused on tests of fluid intelligence and "executive functions," broadly speaking; and consistent with Cattell's view, these studies have found a much stronger relationship between creativity and intelligence than previously reported. For example, Silvia (2008), using a composite latent-variable measure of fluid intelligence, found it to be strongly predictive of performance in Guilford's Alternative Uses test. Lee and Therriault (2013) also used latent-variable measures, and found support (through structural equation modeling) for fluid intelligence being significantly predictive of both divergent thinking (as measured by a battery of tests including Torrance's) and convergent thinking (as measured by Mednick's Remote Association Test as well as two "insight" problems). The relationship between intelligence and creativity was strongest when modeled through the mediating variable of "associative fluency" (as measured by three different word-production tasks). In a similar study, we found that a composite intelligence variable, based on the Wechsler Abbreviated Scale of Intelligence (WASI), which has both crystalized (vocabulary) and fluid (matrix reasoning) components, was predictive of self-reported creative behavior, but was mediated wholly through performance on convergent (Remote Associations) rather than divergent (Alternative Uses) thinking (Lee et al., 2012). Silvia (2015) has reviewed this literature, and concluded that the link between intelligence and creativity is stronger than previously thought.

With aging there is a decrease in the performance IQ, suggesting that fluid intelligence might decrease with aging. Many of the tests in the performance IQ of the WAIS are timed, and as people get older they often get slower. This slowing is both electrophysiological (e.g., evoked potentials) and behavioral. Thus, some investigators have asked whether the lower scores on the performance IQ that is associated with aging is related to slowing. While allowing older subjects more time did improve their performance, even without time constraints the older subjects did less well than the younger subjects (Storandt, 1977). Thus, with advancing age there appears to be a continuing increase in crystallized intelligence, but a decrease of fluid intelligence (Ryan, Sattler, & Lopez, 2000). The decrease of fluid intelligence as a function of age appears to mirror the changes in creativity seen with aging, but this relationship is correlative, not explanatory.

The Aging Brain

With aging there are many diseases that may alter brain function, such as stroke and degenerative diseases such as Alzheimer's disease and Parkinson's disease; however, independent of the many diseases of the brain that are more common in older people, there are many biological changes in the brain that occur with normal aging. The brain decreases in both size and weight with aging. These involutional changes usually start at the age of 50, and there is about a 5% decrease with each subsequent decade. Quantitative anatomical studies of the aging brain in nondemented people, using neurostereology (Pakkenberg et al., 2003), have revealed that the difference in total number of neurons in the brain of people who ranged from 20 to 90 years old is, however, less than 10%. This would suggest that the loss of brain substance is not predominantly due to the loss of neurons.

Although there is only a small percentage of neurons lost with aging, many of the neurons that are lost are located in brain areas that might be critical to creativity, including the prefrontal lobe (e.g., Brodmann's area 10) and the inferior parietal lobe (including Brodmann's areas 40 and 39). With aging one can see, even in the absence of a clinical diagnosis of dementia, the histological changes that are often associated with Alzheimer's disease, including the deposition of amyloid as well as changes in the neurons, including neurofibrillary tangles, and a loss of dendritic branching or arborization. Thus, some neurons that are not lost might be "sick" and not properly functioning. With a loss of dendritic arborization these neurons are less connected to other neurons. Other changes include granulovacuolar degeneration (little vesicles or holes in the neurons' cytoplasm) and the deposit of lipofuscin (a form of pigmented fat).

Some physiological research that studied blood flow with PET or dominant EEG rhythms suggests that with aging there might be metabolic changes that reduce the overall activity of the brain. When subjects with medical diseases such as hypertension or diabetes were excluded from these physiological aging studies, there appeared to be no major difference in blood flow (Duara et al., 1983) or brain activity, as measured by EEG frequency (Duffy & McAnulty, 1988). Therefore, it is unlikely that the decreased creativity associated with aging is caused by metabolic abnormalities.

Many of the intra- and interhemispheric connections that we mentioned above are mediated by axons that travel in the subcortical white matter. Studies which have compared the loss of gray matter (primarily composed of neurons and their dendritic processes) versus white matter (primarily composed of myelinated axons and supporting structures) have revealed that most of the brain volume and brain weight that is lost with aging is related to loss of white matter (Tang, Whitman, Lopez, & Baloh, 2001). In addition, in contrast to the minimal loss of cortical neurons associated with aging, the total myelinated fiber length of axons decreases with aging (Pakkenberg et al., 2003).

The areas that show the greatest white matter loss are those which myelinate late in development, such as those in the frontal lobes. When older people obtain magnetic resonance imaging (MRI) or computer tomographic scan (CT) of their brain, there is often evidence of enlarged ventricles, and it is the loss of subcortical white matter that is responsible for the increases in the size of their lateral ventricles. In addition, many older people who undergo MRI show evidence of injury to the subcortical white matter. Neuroradiologists often call these changes "ischemic demyelination" or "leukoaraiosis." The cause of this loss and damage to the white matter is not entirely known; however, the change in the brain that is most likely to result in leukoaraiosis is a loss of myelinated axons.

Earlier in this chapter we discussed the important role of the corpus callosum, the major connection between the left and right hemisphere, in creativity. The corpus callosum is primarily composed of myelinated axons that travel from one hemisphere to the other. With the loss of the white matter associated with aging there is also a thinning of the corpus callosum (Hopper, Patel, Cann, Wilcox, & Schaeffer, 1994). In addition to the anatomic alterations with aging there is also evidence of a functional decrease in interhemispheric communication that is mediated by the corpus callosum (Reuter-Lorenz & Stanczak, 2000).

Gall, the founder of the pseudoscience of phrenology, posited that the brain is organized in a modular fashion and that the larger the module, the more superior its performance. Geschwind and Levitsky (1968), using unselected brains from post-mortem examinations and without knowledge of these peoples' hand preference or language laterality, found that in more than 60% of these brains, the planum temporale in their left hemisphere was longer than that in their right hemisphere. Subsequently, in patients who were being evaluated for epilepsy surgery, by using selective hemispheric anesthesia to determine language laterality (the Wada test) and MRI to determine brain morphology, we demonstrated that almost all subjects who had left-hemisphere dominance for language also had a larger planum temporale in their left than their right hemisphere (Foundas, Leonard, Gilmore, Fennell, & Heilman, 1994). We also demonstrated that portions of the left inferior frontal areas (i.e., Broca area) that are important in speech production are also larger on the left (Foundas, Faulhaber, Kulynch, Browning, & Weinberger, 1999). Several other right–left hemisphere asymmetries have been described, including: the termination of the Sylvian fissure being higher in the right than left hemisphere (Rubens, Mahowald, & Hutton, 1976) and the right frontal lobe being wider (distance between the lateral wall of the frontal horn of the lateral ventricle and the surface of the cortex of the frontal convexity cortex) than the left. It is possible that people who are creative not only have greater functional asymmetries, but also have greater anatomic asymmetries.

As mentioned, dividing the hemispheres by cutting the corpus callosum has been shown to reduce creativity (Lewis, 1979). Based on this observation it is possible that the degree of interhemispheric connectivity might be directly related to creative potential. However, the cerebral connectivity important for creativity might not only be interhemispheric, but also intrahemispheric. As noted earlier, these intrahemispheric connections facilitate intrahemispheric communication, which may also be important for creative innovation because, as we have mentioned, creativity may require widespread connectivity. Support for this hypothesis comes from the work of Takeuchi et al. (2010a), who used diffusion tensor imaging and a test of divergent thinking to investigate the relationship between creativity and structural connectivity. These investigators found that integrated white-matter tracts between the association cortices and the corpus callosum, which connect the networks that store different forms of information in distant brain regions, support creativity. The reduction of creativity with aging may, therefore, be in part related to the age-related loss of intrahemispheric as well as interhemispheric white matter connectivity.

Frontal Lobes and Aging

Injury to the frontal lobes or interruptions of its subcortical connections, with structures such as the basal ganglia or thalamus, impairs the functioning of the frontal lobes. Many of the neurobehavioral deficits associated with frontal lobe functions are called executive deficits. Several studies suggest that in older people the frontal lobes might not function as well as they do in younger people. For example, Mittenberg, Seidenberg, O'Leary, and DiGiulio (1989) compared older and younger subjects on tests designed to assess frontal, parietal, and temporal lobe functions. These investigators found that it was frontal lobe functions that best correlated with the subject's age.

As mentioned, Denny-Brown and Chambers (1958) noted that the frontal lobes are critical for avoidance and disengagement. One of the most common executive deficits associated with frontal lobe dysfunction is perseverative behavior on tests such as the WCS. Creative innovation requires that a person disengage from previously used ideas-concepts, strategies, and products and then develop new ideas-concepts, strategies, and products. If a creative person gets "stuck in set" their creative careers will come to an end. Ridderinkhof, Span and van der Molen (2002) tested a population of older subjects with the WCS test and found that they are more likely to get stuck in set than are younger subjects. Hence, the problem the older subjects were having on this task was not related to their inability to develop rules of sorting, but rather their reluctance or inability to shift strategy after they found a sorting strategy. This form of perseverative behavior might also be termed "cognitive rigidity."

The reason why some older people have a propensity to get stuck in set or have cognitive rigidity is unclear, but one possibility concerns decreases in dopamine levels. As we mentioned earlier, neurons communicate by releasing chemicals called neurotransmitters. One of the major neurotransmitters that appears to decrease with aging is dopamine. For example, Volkow et al. (2000), using PET, noted that with aging there was a decrease of dopamine, together with a decrease of frontal lobe activation. The cells that release dopamine are found in the midbrain and from there travel to both the basal ganglia and cerebral cortex. Patients with Parkinson's disease have a reduced level of dopamine and they also have evidence for frontal lobe dysfunction (Green et al., 2002). For example, patients with Parkinson's disease often perform poorly on tests such as the WCS, frequently getting stuck in set. Thus, another possible hypothesis to account for the loss of creativity with aging is the presence of cognitive rigidity that is induced by an age-related loss of dopaminergic neurons.

One of the best ways to assess the presence of cognitive rigidity is by use of divergent thinking tests such as the Alternative Uses Test. Takeuchi et al. (2010b) used voxel-based morphometry (VBM) to identify the gray-matter correlates of individual creativity as measured by the divergent thinking test. They found positive correlations between regional gray-matter volume and individual creativity in several regions such as the right dorsolateral prefrontal cortex and subcortical areas such as the substantia nigra and ventral tegmental area. According to these investigators, their findings suggest that creativity, as measured by the divergent thinking test, is mainly related to a decrement in the regional gray matter of regions in the brain known to be associated with the dopaminergic system.

As mentioned above, with aging there is a loss of or injury to subcortical white matter. Patients who have diseases that injure their white matter, such as multiple sclerosis or multiple small strokes of the white matter, frequently show evidence of frontal lobe dysfunction and hence perform poorly on tests such as the WCS because they get stuck in set, whereas to be creative one has to break out of a set and think divergently.

As mentioned earlier, one of the most popular means to test divergent thinking is the Alternative Uses Test, where participants are asked to describe alternative uses of common objects such as bricks and to select uses that are the most creative. We tested 30 older and 30 younger subjects using the Alternative Uses Task and found, unexpectedly, that the older subjects performed better than the younger subjects (Leon, Altmann, Abrams, Gonzalez-Rothi, & Heilman, 2014). We posited that perhaps the older subjects had more experiences with these objects than did the younger subjects. It is possible that the Alternative Uses Test assesses not only divergent thinking but also acquired knowledge, but this hypothesis needs to be further tested.

Right Hemisphere Deterioration with Aging

The right hemisphere appears to be more important for mediating global than local processing (Fink et al., 1997), and global processing is often important in finding the "thread that unites." The right hemisphere is also important in visual–spatial functions, and many extremely creative people such as Albert Einstein have reported using visual–spatial strategies to help find creative solutions. Thus, another hypothesis as to why creativity decreases with aging suggests that right-hemisphere-mediated functions deteriorate more than those of the left (Dolcos, Rice, & Cabeza, 2002). The right-hemisphere deterioration hypothesis of reduced creativity with aging is supported by studies that gave older and younger subjects the WAIS. The visual–spatial tasks (e.g., block construction) on the WAIS are part of the performance IQ, whereas the language tests (e.g., vocabulary) are part of the verbal IQ. Investigators have found that with aging there is greater deterioration of the performance IQ than there is of the verbal IQ. As the right hemisphere appears to be dominant for visual–spatial functions, one could interpret this age-related decrease of visual–spatial abilities to a loss of right-hemispheric function with aging.

There are, however, several confounds to this interpretation. For example, many of the spatial tests that are part of the performance IQ are timed, and with aging there is slowing of response times independent of task. In addition, the performance IQ is also more of a test of fluid that crystallized intelligence, and as mentioned above with aging there might be a greater decrement of fluid intelligence. However, many visual–spatial functions have been shown to deteriorate with aging even when using untimed tests (Koss et al., 1991). For example, when shown incomplete drawings of objects, older subjects have more trouble recognizing these objects (Read, 1988), or when older subjects have to find figures which are embedded in larger figures, they also perform more poorly than the younger subjects. Recognition with incomplete information or finding a meaningful stimulus in a noisy background is similar to finding the “thread that unites.” In contrast to the deterioration of spatial skills, as a function of age, the verbal IQ of older people appears to remain stable, and some studies even showed an improvement of verbal skills with aging. Whereas vocabulary seems to remain unchanged or even increase with aging, there are some suggestions that knowledge of grammar and syntax also appear to improve. Perhaps this is why novelists are more likely to remain creative to an older age than are mathematicians and theoretical physicists.

While the assessment of the right versus left hemisphere’s cognitive functional efficacy as we age remains to be fully determined, Gur and associates (1980) studied the ratio of gray to white matter in the left versus right hemisphere and found that there is more gray matter relative to white matter in the left than in the right hemisphere. This observation suggests that the left hemisphere primarily transfers information within or between contiguous regions of the left hemisphere and that the right hemisphere transfers intrahemispheric information across regions that are greater distances apart. Therefore, the normal functions mediated by the right hemisphere may be more dependent on long myelinated axons. Because with aging there is a greater loss of white than gray matter, the right hemisphere should be more affected by aging than the left hemisphere, and therefore the decrease of creativity with aging might be related to a decrease in the functions mediated by the right hemisphere. However, Gur et al. (1980) also measured gray-matter atrophy as a function of age and found that there was more gray-matter atrophy of the left than the right hemisphere, especially in men, a finding that would be in conflict with the right-hemisphere hypothesis for reduced creativity with aging.

Depth of Processing

Objects can have functional and associative relationships or they might have conceptual relationships. Finding the unity in what appears to be diversity is critical for creativity, and finding this unity would appear to be more dependent on determining conceptual than associative relationships. When subjects were asked to group objects, Denney (1974) found that elderly people are more likely than younger subjects to group these objects by associative relationships than by semantic-conceptual relationships. For example, if participants are given three objects, a rifle, a bow, and an arrow, and are asked to group the two objects that are most closely related, a person could select a bow and arrow based on their strong associative relationship, or a bow and rifle because these two objects have a closer semantic-conceptual relationship (weapons that emit projectiles). The means by which the brain develops associative versus conceptual relationships is unknown; however, grouping by associative relationships can be done based on sensory (iconic) memories. Hence, a person might be able to imagine a bow together with an arrow easier than she or he could imagine a bow together with a rifle, because the former two items are more often seen together than the latter two items. The grouping at the semantic-conceptual level is more abstract (less dependent on sensory associations) than grouping on an associative level. The term abstract comes from the Latin term abstractus that means to "draw away," and in order to group at the semantic-conceptual level a person must draw away from the sensory-iconic level of processing and group by functions or shared properties. Therefore, determining associative relationships can be performed within a modality, but determining conceptual relationships often depends on the activation of widely distributed networks, and older people may have a reduction in connectivity that impairs the communication between anatomically distributed conceptual-semantic networks.

Hormones and Aging

Serum levels of total and bioavailable testosterone gradually decrease with age in men, and this change is associated with changes in cognition. Cherrier and co-investigators (2001) examined the relationship between exogenous testosterone administration and cognitive abilities in a population of healthy older men. Circulating total testosterone was raised an average of 130% from baseline at 3 weeks and 116% at 6 weeks in the treatment group. Because of aromatization of testosterone, in the treatment group estradiol increased an average of 77% at week 3 and 73% at week 6. Significant improvements in cognition were observed for spatial memory (recall of a walking route), spatial ability (block construction), and verbal memory (recall of a short story) in older men treated with testosterone compared with their baseline evaluation and the performance of the placebo group; however, it is not known whether hormonal treatment with testosterone can restore any age-related decrease of creativity.

Oxytocin is another neurohormone that may decrease with age (see Huffmeijer, van IJzendoorn, & Bakermans-Kranenburg, 2013) and has been associated with creative performance. In a series of studies reported by De Dreu et al. (2014), administration of intranasal oxytocin versus placebo increased holistic processing (Study 3, response time to "global" versus "local" targets in Navon figures), improved divergent thinking (Study 5, all three dimensions of performance in the Alternative Uses Test), and led to more solutions of insight problems, which have been used as tests of convergent creative thinking (Study 6). As with testosterone, it is not known whether administration of oxytocin could restore any age-related decrements in creativity, or what other impacts such administration might have in the elderly.

Conclusion

In this chapter, we have attempted to define creativity, review the stages of creativity, discuss the possible neuropsychological mechanisms that are important in creativity, and consider how these processes and mechanisms might change with aging. Although it has been repeatedly claimed that with aging there is a decrease in creativity, the specific changes – for worse, or better – in creative abilities and performance that may be associated with aging have not been systematically examined, and the possible alterations in brain functions that may alter creativity with aging also have not been fully studied. Creativity is one of the most important of human attributes, but historically it has not generated as much interest as other domains of cognition such as memory and language. Therefore, there is a great need for research that will allow us to understand the brain mechanisms that allow humans to be creative, as well as how creativity can be developed and enhanced. We also need to learn more about the adverse influence of diseases and aging on creativity and how these can be modified and mitigated.

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Part VIII

Artistic and Aesthetic Processes

28 The Neuroscience of Musical Creativity

David Bashwiner

> When the faculty of creation is in full spate, ideas abound with unthinkable effortlessness … Under these circumstances it is a good idea to write them down (so as not to lose any part of them) … The ideas that occur to one in this way are usually rough diamonds that need to be polished later. When the mind is in this state, an electric current circulates in the veins.
>
> – Antoine Reicha (1824–1826)[1]

Introduction: What is Musical Creativity?

The question "What is musical creativity?" does not have a straightforward answer. The entire field of music is more-or-less creative – performers, conductors, teachers, analysts, even listeners all do important creative work. In this chapter, by necessity, I ignore these other manifestations of musical creativity, limiting my focus specifically to *the generation (and modification) of novel note-and-duration sequences*. This activity is common to composers and improvisers, as well as to songwriters, programmers of electronic music, arrangers, and so on. All trained musicians do it to some extent, and I take it to be the essential skill around which musical creativity is centered – although all creative manifestations in music are valuable and important.

Neurological Uniqueness of Musical Creativity

Before proceeding further, I would like to point out a few aspects of musical creativity which make it unique from other forms of creativity, and therefore of particular importance for situating this chapter within the larger volume. At first blush, music is an auditory phenomenon. This is largely the case from the listener's perspective, but from the performer's music is equally motoric, and ultimately it is not in either the individual auditory or the individual motor faculty that the essence of music lies, but rather in their integration. A performer has refined motor skills, but they are refined in relationship to the sounds they are able to produce. A listener uses his ears, and his higher-level auditory-cognitive capacities to make sense of large-scale organization in sound – but the more engaging the music is, the more likely he is to find himself tapping his foot, swaying in his chair, singing along (covertly or overtly), and even getting up to dance. Finally, a composer or improviser imagining a musical sound does so, experiments have shown, not merely through the use of the auditory regions, but also the motor regions (Herholz, Halpern, & Zatorre, 2012). The opposite is also the case: imagining motor patterns gives rise to auditory cortical activity. Trained musicians listening to unfamiliar music demonstrate (pre)motor-cortical activity consistent with the sounds produced (Bangert et al., 2006), and nonmusicians do this as well when trained to play the specific melodies heard (Lahav, Saltzman, & Schlaug, 2007). Thus music is highly auditory–motoric at its essence.

A second unique aspect of musical creativity is that it takes place extremely rapidly. This is particularly the case for improvisation, but all of the "great" composers – Mozart, Beethoven,

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[1] From the *Traité de haute composition musicale*, Vol. 2, p. 235 (in Bent, 1984, p. 50).

Bach, etc. – were great improvisers, and thus the generalization likely holds for both. Because the generation of novel note-and-duration sequences is a hugely complex process, and often takes place in a fraction of the amount of time that might be expected (Johnson-Laird, 2002), it seems certain that a great deal of highly complex processing must be going on at subconscious levels, in what Dietrich and Haider (2015) call the "implicit system." Indeed, explicit goals and analytical procedures are also strongly implicated. But perhaps more than any other type of creativity, musical creativity – particularly improvisation but also spontaneous or "all-at-once" composition – demands a profound degree of automaticity, i.e., of patterns having been "made motorically transparent through over-learning" (Pressing, 1998, p. 53). In addition to being fundamentally auditory–motoric, musical creativity – at least at its best – is foundationally grounded in the implicit system, the highly trained and automatized processes of working with notes and durations that composers and improvisers learn over time and work into their auditory–motor repertoire.

Third, as with all of the arts, music is largely abstract and nonfunctional. Creativity is often defined as the production of something both novel and useful (Runco & Jaeger, 2012), but this definition is problematic for art, given that art is frequently defined as the production of something that is *not* useful. Thus, composer Arnold Schoenberg writes,

> I believe that a real composer writes music for no other reason than that it pleases him. Those who compose because they want to please others, and have audiences in mind, are not artists (1975, p. 54; in Impett, 2009, p. 404).

This perspective is especially important when considering the nature of "evaluative processes" for music (and the other arts). Unlike in the hard sciences, evaluation in music is arguably based more on *liking* than on usefulness – i.e., on something irrational, something emotional and visceroreceptive, and potentially not available to conscious, explicit introspection.

In sum, this chapter need not be considered solely about "musical" creativity. More generally, it can be read as an investigation into creativity by means of a particular kind of faculty, which happens to be: (a) multimodal (auditory–motoric); (b) extremely rapid and yet complex, and thus largely a product of the automatic/implicit system; and (c) evaluated largely irrationally, based on liking rather than pragmatic use value.

Phases of the Compositional Process

While improvisation takes place all at once (for the most part), composition is a process, with multiple different phases.[2] The first can be called the "generative" phase. In the epigraph to this chapter, Reicha writes of a "faculty of creation," in which "ideas abound with unthinkable effortlessness," and which is characterized by the feeling of "an electric current circulat[ing] in the veins" (Reicha, 1824–1826, Vol. 2, p. 235; in Bent, 1984, p. 50). A not dissimilar picture is painted by Mozart, who states:

> When I am … completely myself, entirely alone, and of good cheer … it is on such occasions that my ideas flow best and most abundantly. Whence and how they come, I know not; nor can I force them … All this fires my soul, and provided I am not disturbed, my subject enlarges itself, becomes methodized and defined, and the whole, though it be long, stands almost completed and finished in my mind … All this inventing, this producing takes place in a pleasing and lively dream (Holmes, 2009, pp. 317–318; in Wiggins, 2012, p. 234).

Brahms too describes an "inspired" state of a similar nature, in which compositions would be

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[2] While in the abstract this is more or less true – sensible with respect to *onstage* improvisation – it should be noted that improvisation requires a significant amount of *offstage* practice as well, and thus, like composition, improvisation too has multiple stages (which could be called generative and transformational as well).

"revealed" to him "measure by measure." In such a state, he elaborates,

> the best ideas flow from the hand or mind without any particular effort. Most of the time you have to be, or will be, in a semi-trance condition to get such results – a condition when the conscious mind is in temporary abeyance and the subconscious mind is in control, for it is through the subconscious mind … that the inspiration comes (Abell, 1955, p. 6).

Brahms cautions, however, that inspiration is not the whole of the compositional process:

> Structure is just as consequential, for without craftsmanship, inspiration is a "mere reed shaken in the wind" or "sounding brass or tinkling cymbals" … My compositions are not the fruits of inspiration alone, but also of severe, laborious and painstaking toil … A composer who hopes to write anything of lasting value must have both inspiration and craftsmanship (p. 59).

Koch (1782), too, stresses that while the generative phase is "chiefly the preserve of the inspired genius," a second phase – which I will call the "transformative" phase – "is more the object of taste, though at the same time the higher mental faculties, namely intellect and power of judgment, must manifest their efficacy" (Vol. 2, p. 98; in Bent, 1984, p. 36).

The application of "taste," in my opinion, is preferably relegated to a separate phase, or more accurately a phasically active "process," which I will refer to as "the evaluative process." Most writers on creativity caution that evaluative processes must be deactivated during the generative phase – this suggests a possible grounding in anticorrelated networks, a matter to be addressed later (see also Beaty, Benedek, Silvia, & Schacter, 2016). Within the transformative phase, evaluative processes are likely active, but in my estimation they may turn on and off phasically within extended transformative stretches – evaluating which transformative avenue to take, for instance (e.g., whether the motive should be sequenced this way or that way), and then whether the result of the transformative process completed is as aesthetically pleasing as was anticipated.

Thus, in sum, three compositional phases can be identified: a *generative phase*, typified by a trance-like state of consciousness and the effortless flow of musical ideas; a *transformative phase*, characterized by craftsmanship, labor, and toil, and the recruitment of the higher mental faculties; and an *evaluative phase*, or more accurately *phasic evaluative processes* (alternating especially with transformative processes), characterized by reflecting upon one's internal and largely irrational emotional/hedonic response to the material created and transformed in the first two phases (and to simulations of future creations/transformations).

Neuroscientific Studies of the Creative Process

Preliminaries

Neuroscientific research expressly focused on understanding compositional and improvisational processes is in its infancy. Tables 28.1 and 28.2 present those studies on the subject known to me. The earliest is that of Petsche (1996), an EEG study involving seven composers; another early study is that of Brown, Martinez, and Parsons (2004), a PET imaging study using vocalists. The remaining 17 studies were published within the last decade, during which time there has been a steady flow of research productivity, and productive discourse among researchers.

Despite this growing body of research, however, it is neither advisable nor possible at present to draw bold conclusions with respect to the extant findings, for several reasons. First, the imaging methods are diverse, with most studies using fMRI but others using PET, sMRI, EEG, and genetic linkage analysis. With respect to EEG analysis, Rahman and Bhattacharya (2016) perform fine-grain source localization, Petsche

Table 28.1 *Structural and functional imaging studies of musical creativity (sMRI, fMRI, PET, EEG).*

Author (date)	**Imaging method; subjects**	**Task**
Bashwiner, Wertz, Flores, & Jung (2016)	sMRI (cortical surface area, subcortical volume); $N = 239$	Questionnaire: self-reported comp./improv. activity
Bengtsson, Csíkszentmihályi, M., & Ullén (2007)	fMRI; 11 concert pianists	Improv based on visually displayed melody; 12-note keyboard, right hand only
Berkowitz & Ansari (2008)	fMRI; 13 classically trained pianist undergrads	Rhythmic vs. melodic improv; 5-key piano keyboard, right hand
Berkowitz & Ansari (2010)	fMRI; 12 musicians (classically trained pianists), 12 nonmusicians	Rhythmic vs. melodic improv; 5-key piano keyboard, right hand
Brown, Martinez, Hodges, Fox, & Parsons (2004)	PET; 10 musician undergrads	Vocally harmonize with a presented melody according to the rules of tonal harmony
de Manzano & Ullén (2012a)	fMRI: 15 classical pianists	Melodic vs. rhythmic improv; one-octave keyboard, right hand
de Manzano & Ullén (2012b)	fMRI; 18 classical concert pianists	Piano keyboard (2, 6, or 12 notes; right hand); improv. vs. pseudo-random vs. note-reading
Donnay, Rankin, Lopez-Gonzalez, Jiradejvong, & Limb (2014)	fMRI; 11 professional jazz pianists	Trading fours with experimenter (with accompaniment), compared to memorized melody or scales; 35-note keyboard (right hand)
Limb & Braun (2008)	fMRI; 6 professional jazz pianists	Improv vs memorized 12-bar blues w/accomp.; 35-note keyboard, right hand only

Findings				
Motor control	**Auditory regions**	**Default mode regions**	**DLPFC and FPCS**	**Limbic/ paralimbic**
Bilat dPMC, SMA, pre-SMA; left PT	Left PT, right TP, MTG	Bilat dMPFC; right TP, MTG		Bilat OFC/antINS; right TP; left amygdala
Right pre-SMA; bilat dPMC; left pSTG/TPJ; complexity of improv: right pre-SMA	Left pSTG/TPJ	Left pSTG/TPJ	Right DLPFC (BA 9)	–
Both: left RCZ, ACC, IFG/vPMC, bilat dPMC		Melodic: ↓bilat PCC, ↑right AG, ↓right SMG, ↑left SMG rhythmic: left IPL Musicians: ↓right TPJ/AG (improv minus patterns)	Melodic: ↓right MFG, SFG (BA 10) rhythmic: left SPL	
Bilat MC, IFG (44/45), putamen, cereb; right SMA,	Bilat STG/STS (21/22), PP/TP (BA 38); right SAC (42); left PAC (41)	Right PHG	(Below threshold DLPFC activation)	Right GP, midbrain, PHG, ACC (32); left insula
Melody: left dPMC, pre-SMA rhythm: left pre-SMA; greater FC between pre-SMA and cereb				
Right ACC, bilat IFG, pre-SMA, cereb		Left dMPFC		Right ACC, bilat INS, cereb
Bilat Broca's Area (BAs 44 and 45), bilat SMA; FC: ↑lft IFG ⇔ rIFG; ↓bilat IFG ⇔ STG ↓left IFG ⇔ bilat AG	Bilat Wernicke's Area (pSTG, BA 22); greater pSTG activity on right	Bilat SMG/IPL bilat ↓AG	Bilat DLPFC, SPL; ↓SFG/MFG	↓HF+, ↓PHG, ↓PCC, ↓TP
Left Broca's area (BA 44/45); right vPMC; bilat dLPMC, SMA, dMC; left ACC/CMA; right cereb	Bilat aSTG, aMTG, aSTS	Bilat ↑aMPFC, ↓dMPFC, ↑SMG, ↓PCC, ↓AG	Bilat ↓Lat PFC (DLPFC–LOFC), ↑SPL	Bilat ↓amyg, ↓EC, ↓TP, ↓PCC, ↓PHG, ↓HF+, ↓Hypothal, ↓BG (put, caud, striat), ↓INS

(*continued*)

Table 28.1 (*cont.*)

Author (date)	**Imaging method; subjects**	**Task**
Liu et al. (2012)	fMRI; 20 freestyle rap artists	Improvise freestyle rap over instrumental track (compared with performing a memorized rap)
Lu et al. (2015)	fMRI; 17 composition students	Mentally compose for unfamiliar instrument given a single detailed measure
McPherson, barrett, Lopez-Gonzalez, Jiradejvon, & Limb (2016)	fMRI; 12 prof. jazz pianists	Improv based on emotion in photo (pos, neg, ambig); right hand, 35-key piano
Pinho, de Manano, Fransson, Eriksson, & Ullén (2014)	fMRI; 39 pianists with more vs. less improv experience	Free improv; 12-note keyboard, right hand
Pinho, Ullén, Castelo-Branco, Fransson, & de Manzano (2016)	fMRI; 39 pianists	Improv based on a pitch set (ps) or emotion (em); 12-note keyboard, right hand
Rahman & Bhattacharya (2016)	EEG; 8 classical pianists	Improv based on complex excerpt; full-size piano, both hands
Villarreal et al. (2013)	fMRI; 24 subjects with greater or lesser creativity	Improv on rhythmic fragments; response box with single key, right hand

Findings				
Motor control	**Auditory regions**	**Default mode regions**	**DLPFC and FPCS**	**Limbic/paralimbic**
Left IFG; left CMA, pre-SMA, dPMC, BG (caud, GP); right cereb	Left MTG, STG, STS; innovative quality: post-mid MTG/STS, left MPFC (esp. BA 9)	MPFC from FP to pre-SMA; left-lateralized; innovative quality: left MPFC (esp. BA 9), PCC; FC from MPFC: *neg*: DLPFC, IPS; *pos:* IFG, CMA/ACC, pre-SMA, dPMC	↓Right DLPFC; neg. FC from MPFC	FC to left amyg: left IFG, CMA, pre-SMA; FC from left amyg: right IFG, IPL; bilat antINS
FC decreased *within* motor network, but FC increased from ACC to bilat SFG (dPMC and SMA/pre-SMA)		FC increased from ACC to right AG and bilat SFG (incl. dMPFC)		
All: left Broca's area (BA 45), ↓mid cing pos: dPMC, cereb neg: SMA amb: SMA, cereb, left MC	Neg and amb: bilat MTG amb: right pSTG/TP (BA 21, 22, 38), bilat PAC (BA 41)	All: ↓AG, ↓precun, ↓vMPFC/FP (most deactiv. in AG and precun for pos) neg and amb: right IPL (BA 40) neg: left AG/SMG, right hipp	All: ↓DLPFC (BA 9) (most deactivation for pos)	All: ↓OFC/FP pos: left hipp/amyg, right PHG; ↓hipp, cereb neg:bilat ↓hipp, INS, right ACC, amb: right ↓hipp
↓Right IFG; inc. FC from DLPFC to motor regions (dPMC, preSMA)		↓Right AG (IPL)	↓Right DLPFC; inc. FC with dPMC and preSMA	↓Right antINS
ps: right dPMC, em: left dPMC	ps: inc FC of right DLPFC with rSTG em:	ps: bilat SPL em: left dMPFC; inc. FC of DMN with rDLPFC	ps: right DLPFC (inc. FC with PREMOT, rSTG); em: ↓right DLPFC (inc. FC with DMN)	em: bilat INS/amyg
↑rt dPMC/preSMA ↓left dPMC/preSMA ↓left BA 45/46		↑Left IPL/SMG	↓Left DLPFC	
Right vLPFC (BA 45) (Broca's Area)			Left DLPFC	Right insula

Table 28.2 *EEG power/coherence and genetic studies of musical creativity.*

Author (date)	**Imaging method; subjects**	**Task**	**Findings**
Dikaya & Skirtach (2015)	EEG Power and Coherence; professional and amateur musicians, $N = 136$	Listen to short sequences (major or minor), mentally compose a variant (to be written down afterward)	– All musical activities relative to rest: • higher delta-band power in left frontal regions – Composing relative to other musical activities: • higher delta power in left posterior temporal regions • increased short-range coherence (delta and theta frequencies) between right prefrontal, central, and left parietal regions • higher beta-band power in right frontal and left occipital – Professionals relative to amateurs (composing) • short-range interhemispheric coherence in the delta band for homologous leads throughout the brain; • long-distance intrahemispheric and interhemispheric coherence increases in the beta band, particularly between right frontal and left posterior regions (“the creativity axis”). – Major vs. Minor (positive vs. negative emotion): • Major: • increased power and short-range coherence in left anterior regions; • Minor: • increased power in right frontal and temporal regions, • short-range coherence prominent at low frequencies • long-distance coherence prominent at higher frequencies.
Petsche (1996)	EEG Coherence; 7 composers	Mentally compose a short work for piano (to be written down afterward)	– Listening (relative to rest): • cortico-cortical coherence in left hemisphere • cross-hemisphere cooperativity across the frontal lobes – Composing (relative to listening): • greater whole-brain coherence generally in all frequency bands but delta, within and across hemispheres • decreased coherence in delta band both intrahemispherically and interhemispherically, particularly in frontal lobes • coherence increase was smallest in the temporal lobes • coherence decreased strongly between right-temporal and left-frontal regions
Oikkonen et al. (2016)	Genetic; 577 subjects (474 belonging to 79 families; 103 unrelated)	Questionnaire: self-reported composition, arranging, musicianship	– Composing (4q22) linked with • previously identified for musical aptitude, music perception, and performance • overrepresentation of cerebellar long-term depression pathway (synaptic plasticity) • AMPAR receptor in this pathway, also linked with arranging and (in other studies) with divergent thinking • Schizophrenia – Composing and arranging linked with intelligence – Creativity even when nonmusical linked with intelligence and musical aptitude – 4q22 in other studies (by same authors) one of most upregulated genes during listening to and performing music – Composing creativity more common in males

(1996) focuses strictly on coherence, and Dikaya and Skirtach (2015) consider both coherence and power.

Second, subjects and tasks differ markedly across studies. Subject pools in some cases included both musicians and nonmusicians (Bashwiner et al., 2016; Berkowitz & Ansari, 2010; Oikkonen et al., 2016). In other cases they contrasted professional and amateur musicians (Dikaya & Skirtach, 2015), included music students generally (Brown et al., 2004), addressed specifically professional and student composers (Lu et al., 2015; Petsche, 1996) or professional freestyle rap artists (Liu et al., 2012), or compared professional pianists with varying degrees of classical vs. jazz training (Donnay et al., 2014; Limb & Braun, 2008; Pinho et al., 2014; Rahman & Bhattacharya, 2016) or musicians with more vs. less creative flexibility (Villarreal et al., 2013).

The tasks employed have been similarly diverse. In some cases no task was employed, as in studies by Bashwiner et al. (2016) and Oikkonen et al. (2016), which used questionnaires to gather information. Studies by Petsche (1996), Dikaya and Skirtach (2015), and Lu et al. (2015) employed mental "composition" tasks, while the remainder employed a form of "improvisation." There is a great degree of overlap between these types of behaviors, but the main difference for present purposes is that composition tasks involved purely mental creation in the absence of motor execution, while the improvisation tasks additionally involved (and were constrained by) motor execution.

With respect to improvisation specifically, the tasks differed in a number of notable ways: in some cases subjects improvised unaccompanied, while in others cases they were accompanied by a recording (Brown et al., 2004; Limb & Braun, 2008; Liu et al., 2012), and/or a fellow musician (Donnay et al., 2014). In some cases, improvisation tasks were "structurally" focused, as when the set of pitches or rhythms to be used was determined by the experimenters (Berkowitz & Ansari, 2008, 2010; de Manzano & Ullén, 2012a,b; Pinho et al., 2014, 2016), while in other cases subjects were given freer rein to improvise in a genre-specific way (Limb & Braun, 2008), or according to an emotion specified by the experimenter (McPherson et al., 2016; Pinho et al., 2016). With respect to composition, tasks also differed: for instance, whether a composition was to be written for a familiar (Dikaya & Skirtach, 2015; Petsche, 1996) or unfamiliar instrument (Lu et al., 2015).

Finally, the ecological validity of the task and experimental apparatus varied across studies. In all but one of the piano-improvisation studies, only the right hand was used – a situation that is uncommon in real-world contexts and that has important implications for lateralization and connectivity. Equally notable, only one of these studies (the same one, Rahman & Bhattacharya, 2016) used a full-sized piano keyboard, with the remaining studies using smaller keyboards of 35 keys (Donnay et al., 2014; Limb & Braun, 2008; McPherson et al., 2016), 12 keys (Bengtsson et al., 2007; deManzano & Ullén, 2012a), five keys (Berkowitz & Ansari, 2008, 2010), or one key (Villarreal et al., 2013).

Structural and Functional Studies

Acknowledging this appeal to caution, a few consistencies can nevertheless be observed in the data. They concern (a) the consistent implication of motor-control regions, particularly the higher-cognitive motor-control regions of the prefrontal cortex; (b) a less consistent but nevertheless evident involvement of non-primary auditory regions; (c) a somewhat puzzlingly inconsistent involvement of default-mode regions; (d) an equally puzzling inconsistency of dorsolateral prefrontal cortex (DLPFC) recruitment; and finally (e) relatively (but not completely) consistent involvement of limbic and paralimbic structures. Table 28.1 offers an overview of the structural and functional studies. Most are concerned with improvisation and thus that is the dominant focus of this section. The EEG and genetic studies will be briefly discussed in a following section.

Motor-control Regions. The vast majority of functional and structural studies of improvisation implicate the motor-control regions. Notably, only two implicate primary motor cortex (MC) itself (Brown et al., 2004; McPherson et al., 2016). This is not surprising given that most comparisons were not with a rest condition but with some other form of musical performance, such as playing a memorized rather than newly invented melody. Nevertheless, the motor *planning* and *sequencing* regions are consistently implicated, suggesting a crucial and foundational role for them in musical improvisation. The most consistently implicated regions of this sort are the prefrontal cortical motor-control regions: premotor cortex (PMC), the supplementary motor area (SMA), the presupplementary motor area (preSMA), and posterior inferior frontal gyrus (pIFG) – this latter being equivalent to Broca's area, centering on BAs 44 and 45, and often including the ventral premotor cortex (vPMC) as well. Additional regions included in this putative motor-planning-and-sequencing network are the putamen and the cerebellum.

PMC exerts top-down control over motor cortex (MC), with vPMC controlling more of ventral MC, and hence controlling both the articulatory apparatus and the fingers (Barbas & Pandya, 1987; Zatorre et al., 2007; Zatorre & Zarate, 2012). In contrast, dorsal premotor cortex (dPMC) correlates more with foot and trunk movements, consistent with its reported involvement in beat-tracking and the more abstract aspects of auditory–motor mapping (Chen, Penhune & Zatorre, 2008a, 2008b; Chen, Zatorre, & Penhune, 2006; Zatorre et al., 2007; Zatorre & Zarate, 2012). Adjacent to the vPMC is the remainder of the pIFG, notably BAs 44 and 45. This larger Broca's area region is strongly associated with auditory working memory and cognitive control (Slevc & Okada, 2015), with keeping track of syntactic build-up in music and speech (Koelsch, 2013; Koelsch et al., 2009), and in the construction of temporal event-hierarchical representations generally (Fitch & Martins, 2014). Together with the dPMC, the putamen is selectively active when a beat is present in a musical stimulus, while the cerebellum is involved in motor fine-tuning, apparently irrespective of whether a beat is present or not (Brown et al., 2006; Grahn & Brett, 2007). Notably, this entire system of motor-control regions is active not only during the performance of music, but also during its perception. It is thus best understood as the motor portion of a highly integrated auditory–motor system, rather than a distinct system.[3]

Auditory Regions. As with the primary motor cortex above, the primary auditory cortex is also not frequently implicated in studies of improvisation when a control task involves a comparable amount of sound. It is not perception that changes, one can assume, but planning and execution. Nevertheless, consistent with the picture portrayed thus far of highly integrated auditory and motor systems, planned (and executed) motor output commands of a musical nature do tend to manifest *as sound* in auditory regions, by way of efference copies being sent predictively from one set of regions to the other (Dietrich & Haider, 2015; Koelsch, 2013, pp. 194–199; Rauschecker & Scott, 2009; Zatorre & Zarate, 2012). The sending of efference copies is a characteristic of the implicit system – the "procedural-memory" or "skill-based" system – and is fundamental to understanding creativity with respect to imagining and predicting upcoming acts and their sonic consequences (to be discussed in the concluding section; Dietrich & Haider, 2015; Wiggins, 2012).

A number of nonprimary auditory regions are implicated in Table 28.1, which can be grouped according to whether they lie posterior or anterior to primary auditory cortex (PAC) on the

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[3] The reported prevalence of mirror neurons in both the PMC and pIFG is further evidence for the integration of the two systems (Koelsch, 2013, pp. 187–189; Lahav et al., 2007; cf. Fitch & Martins, 2014).

superior temporal gyrus (STG). At the posterior end of the STG is the region called the planum temporale (PT), which is considered to be a foundational link in the auditory–motor translation process (Zatorre et al., 2007; Zatorre & Zarate, 2012). In the left hemisphere, this region tends to be larger in musicians with more training and/or with absolute pitch (Elmer, Hänggi, Meyer, & Jäncke, 2013), as well as in subjects with Williams syndrome who have particularly strong musical skills (Martens, Reutens, & Wilson, 2010). Our research group (Bashwiner et al., 2016) similarly found greater surface area in the left PT for subjects reporting more experience being musically creative. A number of additional studies in Table 28.1 similarly report increased activity in this area (Bengtsson et al., 2007; Brown et al., 2004; Donnay et al., 2014; McPherson et al., 2016).

The region anterior to PAC on the STG is the planum polare (PP, or aSTG), and is associated with categorical aspects of musical sound processing (Warren, Uppenkamp, Patterson, & Griffiths, 2003). While the pSTG region described above (PT) forms the base of the dorsal pathway to the frontal cortex and is more affiliated with dorsal premotor cortex, the PP forms the base of the ventral pathway and is more associated with vPMC/pIFG. Limb and Braun (2008), notably, report activity broadly throughout the anterior temporal lobe region, as well as activity in the bilateral vPMC, the left pIFG, and the bilateral dPMC. Further anterior in the temporal lobe is the temporal pole (TP), which is often considered a limbic structure (Koelsch, Fritz, Müller, & Friederici, 2006), but was suggested by Brown et al. (2004) to be "tertiary auditory cortex," selectively engaged when subjects improvised a vocal harmonization to a piano melody. Bashwiner et al. (2016) similarly found enhanced surface area in this region correlating with self-reported creativity, but two functional imaging studies (Donnay et al., 2014; Limb & Braun, 2008) reported reduced task-related activity in TP – along with other limbic/paralimbic deactivations (to be discussed below).

Default Mode Regions. While the above discussion presents general consensus with respect to (pre)motor and auditory involvement, less consensus is to be found with respect to default-mode involvement. Regions in the default mode network (DMN) are those that tend to be more active when a subject is at rest ("in default") than when the subject is engaged in a task (Raichle et al., 2001). However, this is the case only for specific types of task, namely those with exogenous focus (Fox et al., 2005). Tasks that promote endogenous focus, such as self-reflection, episodic memory recall, and emotional reasoning, evoke DMN activity. Thus, DMN activity seems to be consistent with two types of condition, only somewhat overlapping: a defocused or mind-wandering state (Andrews-Hanna, 2012; Martindale, 2007), and a state of internally directed focus (Fox et al., 2005; Raichle, 2010, 2015).

The DMN has been frequently implicated in creativity, particularly in divergent thinking and otherwise "generative" behaviors (Beaty et al., 2014; Jung, Mead, Carrasco & Flores, 2013). Therefore, a role in musico-generative processes, such as improvisation, would be expected, and a number of studies support this expectation. Three DMN regions were found to be larger in surface area in musically creative subjects in the study by Bashwiner et al. (2016), namely dorsomedial prefrontal cortex (dMPFC), lateral temporal cortex (LTC), and TP. These regions represent three of the four members of the dMPFC subsystem identified by Andrews-Hanna, Reidler, Sepulcre, Poulin, and Buckner (2012), associated predominantly with self-focused, present-directed thought – and thus conceivably at work in evaluative-type processes (see Ellamil et al., 2012 for a corroborating perspective). Many of the improvisation studies in Table 28.1 similarly report increased dMPFC activity (de Manzano & Ullén, 2012a; Liu et al., 2012; Pinho et al., 2016) or increased dMPFC functional connectivity (from the anterior cingulate, for instance, in Lu et al., 2015). Notably, in the study by Pinho et al. (2016) contrasting "structural" with "emotional" improvisation, dMPFC activity increased only for the emotional condition – and numerous DMN regions (including but not limited to dMPFC) showed increased functional connectivity (FC) with DLPFC (to be discussed below). Other DMN regions for which greater activation or connectivity are reported in Table 28.1 include: the inferior parietal regions (Bengtsson et al., 2007; Berkowitz & Ansari, 2008, 2010; Donnay et al., 2014; Limb & Braun, 2008; Lu et al., 2015; McPherson et al., 2016; Rahman & Bhattacharya, 2016), the parahippocampal gyrus (Brown et al., 2004), and the hippocampus (McPherson et al., 2016).

Nevertheless, despite the high number of reports of *increased* DMN involvement in improvisation, there is a nonnegligible number of reports of *decreased* DMN involvement as well, sometimes from the same studies (Berkowitz & Ansari, 2008, 2010; Donnay et al., 2014; Limb & Braun, 2008; McPherson et al., 2016, all tasks; Pinho et al., 2014). The reason for this is explored below.

Dorsolateral Prefrontal Cortex. Just as DMN activity is inconsistent across studies, so too is DLPFC activity. A recent study by Pinho et al. (2016) elegantly suggests a linkage between these two phenomena, as a function of the variety of task employed. The DLPFC is consistently implicated in executive functioning, thus with higher-cognitive faculties, cognitive control, and the "explicit system" (see Introduction). If generative behaviors can be expected to depend more on default-mode involvement – Brahms' "semi-trance condition," for instance, or Mozart's "pleasing and lively dream" – then for reciprocal reasons "transformative" behaviors – Brahms' "craftsmanship," Koch's "intellect and power of judgment" – can be expected to recruit DLPFC activity. Should improvisation be considered "generative" or "transformative"? In other words, should one expect to find DMN involvement or DLPFC involvement during improvisation?

The reported findings effectively divide down the middle, with five studies reporting *increased* DLPFC activation during improvisation (Bengtsson et al., 2007; Donnay et al., 2014, Pinho et al., 2016, pitch-set condition, Villarreal et al., 2013; below-threshold activation in Brown et al., 2004), and five reporting *decreased* DLPFC activation during improvisation (Limb & Braun, 2008; Liu et al., 2012; McPherson et al., 2016; Pinho et al., 2014; Rahman & Bhattacharya, 2016).

Hypothesizing that DLPFC involvement might vary as a function of the particular nature of the task – whether the task demanded greater top-down, executive control, for instance, or rather allowed for more bottom-up freedom – Pinho et al. (2016) contrasted DLPFC involvement in two different improvisatory conditions, one in which the experimenters prescribed the set of pitches the improviser was to use, and another in which the experimenters instead prescribed the emotion to be portrayed (happy or afraid). As hypothesized, it was found that the more structural-cognitive task (the pitch-set condition) recruited greater DLPFC activity, while the more emotional task recruited less. Corroborating these results, in an experiment contrasting improvisational responses to different affective pictures (positive, negative, and ambiguous), McPherson et al. (2016) found reduced DLPFC activity for all emotional conditions – but particularly for the positive emotion condition.[4]

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[4] The authors (McPherson et al., 2016) note that hypofrontality is characteristic of flow states generally (Dietrich, 2003; Dietrich & Kanso, 2010), and thus that positive-emotion improvisation might be more evocative of flow states than negative or ambiguous improvisation. Nevertheless, it should be noted that music of a positive emotional valence (usually in a major key) is often structurally simpler than negatively valenced music (usually in a minor key): the former tending to have fewer dissonances, fewer borrowed (nondiatonic) notes, reduced chordal vocabulary, and even a reduced number of notes in its scale (Meyer, 1956, pp. 214–232; see also Huron, 2006). Minor key music (associated with negativity) thus might simply evoke greater DLPFC activity because of its structural complexity (in an information-theoretical sense), rather than because of its emotionality.

Limbic and Paralimbic Regions. All improvisations are not created equal. Some improvisations may be more top-down in their control, others more bottom-up; some more cognitively controlled, others more spontaneous; some more structurally cognitive, others more emotionally inspired. Just as DMN and DLPFC activity differs across studies, so too does limbic/paralimbic (L/P) involvement. In many cases, DMN and L/P activity correlate with one another, while DLPFC and L/P activity anticorrelate. But this is not always the case.

Of the 16 studies in Table 28.1, seven report greater L/P involvement for improvisation/creativity, three report reduced involvement, one reports some of both, and the remaining six report none. Because music is considered to be enjoyable, and because many studies of music perception do demonstrate L/P involvement for well-liked music (e.g., Blood & Zatorre, 2001; Koelsch et al., 2006; Salimpoor, Benovoy, Larcher, Dagher, & Zatorre, 2011; Salimpoor et al., 2013; reviewed at length in Bashwiner, 2010), most researchers into musical improvisation seem to have expected to find limbic involvement. Many do, no doubt, but those that find reduction in L/P activity are particularly notable. Limb and Braun (2008) and Donnay et al. (2014) both report reduced activity in numerous L/P regions – parahippocampal gyrus (PHG), hippocampal formation (HF), TP, and posterior cingulate cortex (PCC), for instance – and these studies appear similarly to have been the most demanding in their cognitive task demands. Interestingly, they also appear to be the most typical of real-world improvisational settings. In a live jazz performance, therefore, when the cognitive demand of an improvisational task may be extremely high, it may be common, contrary to expectation, for L/P regions to be *down*regulated rather than the reverse. Nevertheless, concerts do not consist entirely of fast music played virtuosically – ballads are similarly common, they are slower and more lyrical, and hence they might be expected to elicit more L/P participation. The complexity of findings in Table 28.1 – demonstrating both increased and decreased activity in different L/P structures, as well as varying patterns of both increased and decreased functional connectivity with motor-control, auditory, DMN, and DLPFC regions – attests to the wonderfully complex nature of emotion's contribution to creative musical experience.

EEG Coherence and Power Studies, and a Genetic Study

While the above studies (Table 28.1) present largely a region-focused approach to understanding musical creativity, I present briefly in this section three additional studies using two different methodologies: a pair of studies using EEG coherence and/or power analysis, and one using genetic linkage analysis. To invoke Fink and Benedek (2014) in their review of alpha power EEG in creativity studies, "there are so many different measures or parameters," for studying analyzing EEG activity that it is "notoriously difficult to compare and integrate findings across different studies" (p. 112). The same is the case here, and thus I offer more of a factual report of each study's findings, rather than attempting any form of synthesis.

An early study by Petsche (1996) examined EEG coherence in composers ($N = 7$) while (a) resting, (b) listening to music, or (c) composing a short piece (to be notated afterward). While listening (relative to rest) correlated predominantly with cortico-cortical coherence in the left hemisphere and cross-hemisphere coherence across the frontal lobes, composing correlated with much greater whole-brain coherence generally (i.e., including the right hemisphere as well), with particularly pronounced increases in long-distance and cross-hemispheric coherence. With respect to individual frequency bands, coherence increases were found for all bands but delta, in which coherence decreased – particularly in the frontal lobes, both intra- and interhemispherically. Interestingly, while long-range coherence increased in both hemispheres for all other frequency bands, coherence increase was smallest in the temporal lobes – with coherence decreasing particularly between right-temporal and left-frontal regions. According to Petsche's interpretation, long-range coherence increases indicate the cooperation of far-distant regions of cortex, while short-range coherence decreases – particularly those seen in the frontal lobes – suggest interaction with subcortical structures and hence "greater functional parcellation" (p. 157; Thatcher et al., 2005 offer a similar interpretation with respect to intelligence and resting-state EEG).

A more recent EEG study with a similar paradigm was conducted by Dikaya and Skirtach (2015), in which listeners (both professional and amateur musicians, $N = 136$) were presented with short chord progressions in major and minor keys, subjects being instructed to (a) listen, (b) mentally recreate what they heard, or (c) mentally compose an improvisation on what they heard (to be written down afterward). Compared with rest, all musical activities were characterized by higher delta-band power in left frontal regions. For mental-composition relative to the remaining musical activities, higher delta power was found in left posterior temporal regions; short-range coherence increases (at delta and theta frequencies) were found between right prefrontal, central, and left parietal regions; and higher beta-band power was found in right frontal regions and left occipital regions. For professionals relative to amateurs (mentally composing), short-range interhemispheric coherence was found in the delta band for homologous leads throughout the brain; and long-distance intra- and interhemispheric coherence increases were found in the beta band, particularly between the right frontal and left posterior regions (which the authors call "the creativity axis," citing Sviderskaya, 2011). Finally, with respect to mode, mentally improvising in major (which the authors associated with positive emotion) correlated with increased power and short-range coherence in left anterior regions; in contrast, mentally improvising in minor (associated with negative emotion) correlated with increased power in right frontal and temporal regions, with short-range coherence prominent at low frequencies and long-distance coherence prominent at higher frequencies. The authors point out the consistency with the association seen in the emotion literature linking positive emotion with left-brain activity and negative emotion with right-brain activity (e.g., Davidson, 1992).

Finally, the genetic study by Oikonnen et al. (2016) found correlations between self-reported composing and a region on chromosome 4 (4q22) which had been previously linked with musical aptitude, music perception, and performance. Notably, composing was strongly associated with the cerebellar long-term depression (LTD) pathway, with 17 of the 141 total genes associated with this pathway (across 10 genomic regions) linked to composition. LTD, the authors write, "facilitates the acquisition of novel information or elimination of previously learned information, which is compatible with the cognitive function needed in composing" (p. 13). The cerebellum itself, furthermore, is implicated in many different aspects of musical behavior, including motor and cognitive control, but also emotional response. Composition was also linked with intelligence and with schizophrenia, and was more common in males than females.

Conclusion: The Compositional Process Revisited

The Question

By way of conclusion, I would like to return to the topic introduced at the beginning of this chapter: that of compositional process. In particular, I would like to focus on the generative phase, and on the peculiar nature in which this phase is described by the composers quoted in this chapter's introduction. All the surveyed composers speak, more or less, of a transformative phase, in which the conscious mind is active, the techniques learned in the course of one's education are applied, and the process feels like work, i.e., like "severe, laborious, and painstaking toil" (according to Brahms; Abell, 1955, p. 59). That they do so is not surprising. The teaching of composition is effectively the teaching of these transformational processes.

What is surprising (to me, in any event) is the equally consistent mention of the generative phase, and a number of peculiar features of it that are nevertheless common across the descriptions. The first concerns the feeling tone of this phase: Mozart compares it to "a pleasing and lively dream," Brahms to "a semi-trance condition," Reicha to "an electric current circulat[ing] the veins." A second notable feature is its "effortless" nature, in which ideas seem to generate *themselves*, sometimes forming complete compositions apparently on their own. Most significant, however, is *the high quality attributed to these spontaneously generated musical materials*: for Brahms and Mozart, these are "the best" ideas; for Reicha, they are "rough diamonds" in need of a mere polish.

The question I wish to ask, then, is this (divided into two parts). First, how is it possible for musical ideas to be generated spontaneously *at all*? Second, what might account for such spontaneously generated ideas being *preferable* to those generated voluntarily and consciously? The answer I offer is speculative, but I propose that merely asking the question, and entertaining a possible answer to it, is worthy progress on a topic which, if someday understood, might yield a powerful new perspective on creativity in music specifically and perhaps creativity in the arts (and even the nonarts) more generally.

Spontaneous Generation

To reiterate the first question: how is it possible for ideas to be generated in the subconscious mind *at all*? I believe some traction can be gained on this question by considering how spontaneous content is generated in another familiar – if nevertheless bizarre – context: that of the dream. To begin with the obvious, Mozart outrightly compares his own musico-generative state with that of "a pleasing and lively dream," and Brahms describes his as a "semi-trance condition," which seems equally not far off. Brahms in fact cautions against losing consciousness completely, as in such cases "the ideas escape" (Abell, 1955, p. 48). He also stresses the importance of "not [being] interrupted or disturbed," as "the Muse is a very jealous entity … and she flies away on the slightest provocation" (p. 60). Virtually all of the writers I surveyed (with the exception of Mozart) also stress the importance of writing down the generated ideas immediately, so that, in Brahms' words, they "are fixed and cannot escape" (p. 49). In musical inspiration as in dreams, content is "notoriously difficult" to recall (Hobson, Pace-Schott, & Stickgold, 2000, p. 805).

Outwardly, then, inspired composing and dreaming seem passably similar. It is the inward experience of the two states, however, that motivates the comparison. In dreams as in musical inspiration, "ideas" or "images" arise spontaneously, in a bottom-up manner. Moreover, unlike bottom-up perception in the waking state – which is dominated by perception of content that is *exogenous* in origin – in dreaming and the musico-generative state, the origins of perceived bottom-up content are *endogenous*. Understanding how bottom-up ideas/images are generated endogenously in dreams might therefore help to explain how they can be generated in musically inspired states as well.

Hobson's activation–input–modulation (AIM) model (Hobson, 2009; Hobson et al., 2000) will serve as our neurological reference. The model plots REM consciousness, non-REM consciousness, and waking consciousness ("wake") on a cubic surface, with three axes for its dimensions: activation, input, and modulation. Both REM and wake are high in activation (reflected in rapid firing rates in the ascending reticular activating system, and high EEG energy at high frequencies and low energy at low frequencies). REM and wake differ, however, along the other two dimensions: the mode of "input" to the neocortex, with respect to perceived phenomena, is predominantly internal in REM but predominantly external in wake; furthermore, with respect to "modulation," REM is characterized by predominantly cholinergic modulation, while wake is characterized by predominantly aminergic modulation, particularly serotonin and norepinephrine.

Both of these latter two factors – input and modulation – may therefore be relevant to understanding not only dream consciousness but also "musico-generative" consciousness. In the inspired musical state, the source of content is largely internal rather than external. Indeed, and quite fascinatingly, a study of shamanic trance by Hove et al. (2016) found that the repetitive drumming eliciting the trance state ultimately led not to increased bottom-up auditory perception (as might be expected, given its sonic nature), but the reverse: functional decoupling at multiple levels of the auditory pathway, from brainstem to neocortex. Trance induction, in other words, appears to correlate with an attenuation of bottom-up *exogenous* perception, potentially to make way for bottom-up *endogenous* perception. Furthermore, as Hobson et al. (2000) note, the cholinergic system preferentially arouses subcortical and limbic cortical regions, while deactivating lateral regions (p. 809). It is well known that DLPFC activity is profoundly reduced during dreaming (Dietrich, 2003), as well as during creative states; and that the DMN is more active during dreaming and certain creative states as well (Desseilles, Dang-Vu, Sterpenich, & Schwartz, 2011). With respect at least to the internal–external "input mode" of perception, then, the parallel between the dreaming and the inspired musical state seems so far convincing.

However, what about the generation of "fictive visual and motor data" that is found in dreams (Hobson et al., 2000, p. 834)? Is this parallel to the generation of fictive *musical* data – i.e., fictive auditory–motor patterns – in musical inspiration? What gives rise to this fictive generation in dreams, and how can this be adapted to music? In Hobson's model, this fictive internal content generation appears to be a product of pedunculopontine–geniculate–occipital (PGO) waves that are characteristic of REM, and are elicited via cholinergic cortical modulation. Together with such bottom-up pseudo-perceptual arousal, the massive down-regulation of locus coeruleus activity and subsequent noradrenergic modulation of the cortex results in much-increased flexibility of cognitive thought: according to Heilman, Nadeau, and Beversdorf (2003), high cortical norepinephrine results in a "suppress[ion of] intrinsic excitatory synaptic potentials relative to the potentials elicited by direct afferent input" (p. 376). Thus, reduced cortical norepinephrine may be a mechanistic cause underlying the internality of dream content as well as its bizarreness.

The Best Ideas

We turn now to the second question: what can account for spontaneously generated ideas being preferable (aesthetically speaking) to those generated through deliberate conscious processes? Again I will suggest that pursuing a parallel with dream consciousness can yield traction on this slippery question. As stated, dream consciousness is characterized by reduced DLPFC activity, and this latter is similarly associated with "bizarre cognition" (Dietrich, 2003; Hobson et al., 2000, p. 809). Although highly speculative, my proposal is that the "bizarreness" of the musical ideas generated in the inspired state may be a primary source of their unique allure. Consistent with the model proposed by Dietrich and Haider (2015), ideas generated spontaneously by the "implicit system" – in this case the procedural memory system for music, i.e., the auditory–motor apparatus with particular focus in dPMC, (pre)SMA, and pIFG, together with the basal ganglia and perhaps also the cerebellum – are not likely to be "random," but can rather be schematically normative, at least at the more atomistic levels. Nevertheless, the "bizarreness" of dream-like, trance-like cognition manifests in unusual associative connections, which do form "randomly" in a way between the atomistic schemata that manage to find themselves promoted into dream consciousness. As mentioned, norepinephrine "makes responses more stereotypic," and "blocking adrenergic beta receptors increases creative flexibility" (Flaherty, 2011, p. 138; see also Heilman et al., 2003). Similarly, serotonin modulation is believed to be the means whereby psychedelic drugs modify consciousness, often making it more dreamlike (Baggott, 2015). Even subtly evoking a "trance-like" state, therefore, if it were to upregulate the cholinergic system and thereby downregulate the aminergic system, might have an indirect but still noticeable effect upon cortical norepinephrine and serotonin concentrations, and hence upon cognitive flexibility, divergent thinking processes, and perhaps the "bizarreness" of associative cognitive processes.

Conclusion

Musical creativity is unique and complex. It is also hugely diverse, inspired by – and able to inspire – the whole gamut of human feelings. To equal degrees frustrating and fascinating, the vast majority of this "extraordinary machine" is subcutaneous, subcogitative, subliminal. Its system is not that of the explicit, consciously accessible, verbally scrutable apparatus, but rather that of the implicit, unverbalizable, procedural memory apparatus – which, in the hands of a John Coltrane, can compose at the same lightning speed at which it performs (Johnson-Laird, 2002). Its workings too rapid to perceive in real-time, too ineffable and irrational to reward much in the way of after-the-fact reflection, musical creativity has been stubbornly inscrutable to science throughout their otherwise hoary and rather chummy past. This has begun to change in recent years with the rapidly increasing publication rate of neuroscientific studies addressing composition, improvisation, and other forms of musical creativity. While this new endeavor is still nascent enough to warrant genuine caution in the face of bold conclusion-drawing, a number of consistencies have begun to emerge in the collective findings – and even more fascinatingly, a number of the *in*consistencies that have emerged have begun to be resolved. As a result, new perspectives on musical creativity are being forged at an inspiring rate – and ages-old questions, some long forgotten, are now being asked once again, in inspiringly creative new ways.

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29 Artistic and Aesthetic Production: Progress and Limitations

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Introduction

Art is ubiquitous to every culture in the world (Cross, 2008; Ramachandran & Hirstein, 1999). Yet, from a neuroscientific perspective, an operational definition of art and its functions remain elusive. Art is difficult to define for several reasons. There are many domains of artistic expression – music, visual, dance, and poetry, among others. Any definition of art would need to encompass the various modalities through which art, as an object or performance, is created. In addition, there are culturally specific interpretations of art. Art may serve diverse functions in different contexts, and media or forms of expression that may be identified as art in one culture may serve a strictly ritual function elsewhere.

Definitions of art can generally be broken down into two categories: functional, and procedural. Functional definitions of art often center on aesthetics. Art as an object or occurrence can create an aesthetic experience, an experience of something being beautiful (Davies, 1990; Dissanayake, 1992; for a review of the field of aesthetics, see Gaut & Lopes, 2013). There are numerous theories of aesthetics; several claim that aesthetic preference is determined by features such as symmetry or perceptual grouping (the process of binding distinct features of a stimulus together), both of which might cause humans to find pleasure in certain kinds of stimuli (Enquist & Arak, 1994; Ishizu & Zeki, 2011; Ramachandran & Hirstein, 1999). Others posit that aesthetic experiences arise as artworks undergo various stages of information processing (e.g., perceptual, mnemonic) in the brain (Leder, Belke, Oeberst, & Augustin, 2004). Beyond aesthetics, functional definitions of art relate to the social role of art. Through shared aesthetic experiences, art may engender social understanding and cohesion (Cross, 2008). Alternatively, art can be designated by the means used to produce or evaluate it. For example, in Western visual arts, critics, museums, and historians can decide whether a particular creation deserves merit and praise as art (Davies, 1990, 2010).

Like "art," "creativity" is difficult to define. Creativity can generally be thought of as meeting two criteria: creativity produces something that is novel, and creativity must result in something that is useful or appropriate for a given context (Sternberg, 1999). "Context" could refer to an explicit or implicit set of rules or standards (for example, certain types of musical creativity are more appropriate in a classical context relative to a rock or jazz context), or a social or professional setting where particular behaviors or ideas are valued and evaluated. Because both the originality and appropriateness of art can be difficult to evaluate, particularly in a laboratory setting, creativity has only recently become a topic of serious scientific inquiry.

The multiple ways to define and characterize art and creativity open up a broad scope of potential research programs for understanding the neuroscience of art. Given that art is an integral part of all cultures, neuroscientists have begun to examine the neural systems that underlie both artistic production and perception. To date, there have been two principal approaches used to examine art in the brain. One is to study the neural responses to perceiving art. The other is to examine the neural processes responsible for creating art. These two approaches fall on either side of the definitional divide, but are complementary (Tinio, 2013). Studies of artistic perception address the functional definition of art by examining how humans process or respond to different artistic cues, develop preferences for certain kinds of stimuli, and have aesthetic experiences. Studies related to artistic creativity address the procedural definition of art by examining the processes through which people create art.

Although a deeper knowledge of how art is perceived or experienced is crucial to understanding art more generally, the present chapter will focus only on the procedural aspects of art by exploring the following questions: What neural processes are involved in creating art? What challenges arise when studying these processes scientifically? Is there evidence that the neural processes involved in artistic creation are distinct from creativity in other domains, such as science, technology, or literature? Despite the theoretical and technical difficulties involved in studying art and creativity, some headway is being made in understanding how the brain creates art and music. Numerous challenges have fragmented the research on artistic creativity. There is much need and possibility for further work.

Examining Artists and Artistic Creativity in the Brain

The current discussion of the literature will focus on the last 15 years of development in the study of artistic creativity within the field of cognitive neuroscience. It will review progress made using several neuroimaging techniques. EEG (electroencephalography) measures fast changes in electrical and magnetic fields within the cortex. PET (positron emission tomography) can measure the use of radioactive labeled chemicals. MRI (magnetic resonance imaging) and fMRI (functional MRI) can be used to examine soft-tissue structure and blood flow in the brain, respectively. MRI and fMRI have been the most broadly used methods to study creativity.

To understand the impact of artistic creativity on the brain, studies have taken one of two approaches. The first means of examining creativity is to study the long-term effects of artistic/creative training and expertise on the gross anatomy of the brain. These anatomical studies comparing artists and non-artists can be used to identify areas of the brain that differ after years of extended training in a creative domain. The second means of studying creativity is to examine the brain while it is creating. Due to the time constraints inherent in all methods of neuroimaging, improvisation, the spontaneous generation of a piece of art without prior planning or preparation, has been the main focus of most studies of creativity. This second approach can provide an understanding of the immediate brain networks involved in creative activity (specifically, improvisation).

The majority of studies investigating the effects of artistic training on brain structure have involved musicians. There are several practical reasons for this. Professional musicians generally begin their training at an early age, when brain plasticity is likely most robust, and train intensely into adulthood (Münte, Altenmüller, & Jäncke, 2002). The training and practice that professional musicians must undergo is largely consistent between individuals (Manturzewska, 1990). Musical proficiency requires a specific set of skills – fine motor coordination and repetition of precise movements, in addition to the honing of auditory perceptual skills. The longevity, intensity, and specificity of musical training make it an ideal model domain for examining the effects of extended training.

Musical training has been linked to gross anatomical change in various areas of the brain. Studies have found differences in brain volume in the cerebellum (Hutchinson, Lee, Gaab, & Schlaug, 2003), for example, an area known for motor coordination. These results were only seen in the male musicians (and not the group of female musicians who were studied), and were correlated with practice intensity over the musicians' lives. Other studies have shown structural differences between the primary motor areas of musicians and nonmusicians, and often these differences are linked to changes in primary auditory areas. For example, a 2003 study by Gaser and Schlaug found evidence of increased gray matter volume in professional musicians, compared to amateurs and nonmusicians, in primary motor and somatosensory areas, premotor areas, and Heschel's gyrus (the primary auditory area) (Gaser & Schlaug, 2003a). The data suggest that in addition to increased cortical gray-matter volume in auditory and motor areas in musicians, there is increased structural and functional connectivity between motor and auditory areas in musicians compared to non-musicians (Bangert et al., 2006; Baumann et al., 2007; Lahav, Boulanger, Schlaug, & Saltzman, 2005; Zatorre, Chen, & Penhune, 2007). This may be related to the auditory–motor synchronization necessary for musical performance.

Functional neuroimaging studies of creativity offer increased understanding of what areas of the brain are active during creative tasks. The neuroscience of artistic creativity is an emerging field – it is only in the past 10 years that technological advances have made it possible to examine the brain during creative acts. Similar to anatomical studies, creativity has primarily been studied in musicians, specifically, jazz pianists (McPherson & Limb, 2013). This is largely due to the physical constraints placed on subjects when their neural activity is being recorded. Methods such as EEG enable some freedom of movement, and can provide precise temporal information about neural activity. EEG, however, cannot always accurately identify the origin of the measured electrical responses. Methods such PET and fMRI require that the motion of experimental subjects be restricted. While this constrains the types of tasks that can be performed in the scanner, these methods provide data with fine spatial resolution in the brain, albeit with temporal resolution that lags by several seconds (orders of magnitude greater than the individual spikes of neurons). Notwithstanding these challenges, several researchers have been able to use fMRI to examine musicians, mainly pianists, while engaging in creative activities.

Studies have taken various approaches to isolate different elements of musical creativity. For example, several experiments have examined improvised versus memorized retrieval of prelearned melodies (Bengtsson, Csíkszentmihályi, & Ullén, 2007; Limb & Braun, 2008; Liu et al., 2012). A number of patterns have emerged. When compared to performing memorized music, improvisation seems to engage premotor and supplementary motor areas, as well as areas of the inferior frontal gyrus (IFG), parts of which are involved in language generation. Musical creativity (improvisation) requires precise motor planning and preparation – perhaps more so than memorized (noncreative) tasks. These studies have shown different effects of improvisation on activity in the prefrontal cortex. While Liu et al. (2012) and Limb and Braun (2008) found deactivation across the dorsolateral prefrontal cortex (DLPFC), and activation in the medial prefrontal cortex (mPFC), Bengtsson et al. (2007) found activation in the mPFC and DLPFC. These differences may be due to the slightly different task constraints between the studies. Specifically, Limb and Braun (2008) and Liu et al. (2012) had subjects memorize music or rap verses before being scanned, whereas Bengtsson et al. (2007) had subjects remember and perform previous improvisations from the scanner during their memory retrieval controls.

Other studies have examined melodic compared to rhythmic improvisation, or random motion (Bengtsson & Ullén, 2006; Berkowitz & Ansari, 2008; de Manzano & Ullén, 2012a, 2012b). These reveal how the specific modality of improvisation (melodic vs. rhythmic or random) influences the neural systems involved in creativity. Their manipulation showed differential recruitment of the premotor system during melodic improvisation compared to rhythmic improvisation. Across these studies, despite the varying control and test conditions, the presupplementary motor area (preSMA) was observed to be more active during rhythmic improvisation, whereas the premotor cortex was generally more active during melodic improvisation. These results suggest that the motor output necessary for improvising may be mediated through different premotor planning systems depending on whether the improvisation is primarily rhythmic, compared to rhythmically steady and melodically creative.

A single study has examined the influence of interaction within a social context on creativity – Donnay, Rankin, Lopez-Gonzalez, Jiradejvong, and Limb (2014) asked pianists to "trade-fours" during the scanning sessions. "Trading fours" is a common improvisational technique during which jazz musicians exchange improvisational ideas in four-measure segments. This study found that, compared to a memorized exchange, trading fours improvisation resulted in increased activation in left IFG and posterior superior temporal gyrus (STG), both of which are areas involved in language production and comprehension. These regions are often collectively called the perisylvian language regions, due to their proximity to the Sylvian fissure separating the temporal and frontal lobes of the cortex. These results suggest that musical improvisation, especially within a social context (trading fours), relies on similar brain circuitry as verbal communication. Two other studies have examined verbal creativity – one using freestyle rapping and fMRI (Liu et al., 2012), and another comparing the generation of melodies and sentences, and using PET scanning (Brown, Martinez, & Parsons, 2006). Both studies revealed (unsurprisingly) that perisylvian language areas were active during language-generation tasks. Brown and colleagues also found significant overlap between the areas responsible for melodic generation and those active during sentence generation. All three studies (Brown et al., 2006; Donnay et al., 2014; Liu et al., 2012) reported activations in the preSMA. Taken together, they indicate that similar motor and language-processing resources are shared between different modalities of creativity – linguistic and musical.

A distinction needs to be made between the existing studies of creativity that were tightly controlled and those that allowed unconstrained improvisation with a more realistic experimental setup. For example, several experiments have used five-button response boxes to study piano improvisation (Berkowitz & Ansari, 2008, 2010). Several other experiments used slightly larger keyboards (12 keys), but studied classical musicians (Bengtsson et al., 2007; de Manzano & Ullén, 2012a, 2012b). Classical pianists are highly trained, but their training does not focus on improvisation (Dolan, Sloboda, Jensen, Cruts, & Feygelson, 2013). It is possible that the classical pianists tested in these creativity studies were not comfortable with improvising. Researchers have tried to overcome these matters by studying professional jazz pianists or freestyle rappers in more realistic contexts (including, for the pianist, a 35-key keyboard with full-size keys) (Donnay et al., 2014; Limb & Braun, 2008; Liu et al., 2012; McPherson, Barrett, Lopez-Gonzalez, Jiradejvong, & Limb, 2016). There is a division between the results of these two types of studies – generally speaking, studies that have been more tightly constrained have observed activation in the prefrontal cortex during improvisation, whereas studies that have been more loosely constrained have observed deactivation in the prefrontal cortex during improvisation. It is possible that prefrontal cortex engagement is necessary when an experimental task is tightly controlled and requires more cognitive effort to complete, whereas when the task is less restrictive (and arguably more ecologically valid), deactivation in the prefrontal cortex reflects a decrease in cognitive control.

The first decade of fMRI and PET studies of improvisation and creativity (beginning around 2006) revealed that task constraints and experimental demands can greatly influence the observed neural patterns during improvisation. Research in creativity has therefore begun to explicitly examine the influence of both task demands and training on the observed results during neuroimaging studies of creativity. A 2015 study showed that task constraints (a free emotion expression improvisation vs. a pitch-controlled improvisation) can also influence neural responses (Pinho, Ullén, Castelo-Branco, Fransson, & de Manzano, 2015). In particular, the free improvisation task resulted in more widespread deactivation in the DLPFC compared to the more tightly constrained improvisation task.

A study that examined expression of emotion (happy/ambiguous/sad emotions) through music has found similar results – the extent of deactivation in the DLPFC is highly modulated by the task, in this specific case, the emotional intent (McPherson et al., 2016). Musicians were asked to improvise compositions in response to images of an actress expressing a happy, sad, or ambiguous emotion. The deactivation of the DLPFC was more widespread during improvisation performed in response to happy emotions compared to sad emotions or ambiguous emotions. However, the same basic network of activations in language areas and the SMA, and deactivations in the DLPFC, angular gyrus, and precuneus, was observed throughout all emotion conditions. The angular gyrus and precuneus, along with the DLPFC, are generally considered to be part of the default mode network (DMN), which is more active when the brain is at “rest,” or during internally focused attention (Buckner & Carroll, 2007). This engagement of the DMN suggests that improvisation may require self-referential, internally directed attention.

In addition to task constraints such as emotional state or pitch controls, it appears likely that training influences neural responses during musical improvisation. In 2014, Pinho and colleagues examined the effects of different training levels and constraints on neural activity during piano improvisation (Pinho, de Manzano, Fransson, Eriksson, & Ullén, 2014). This study found that improvisation training influenced the neural responses during improvisation compared to rest. Total hours of improvisation training were correlated with a reduction in prefrontal cortex activity during improvisation. Increased functional connectivity was also observed between bilateral DLPFCs, premotor cortices and preSMAs in more highly trained improvisers compared to those with fewer hours of training. The authors suggested that these findings reveal that improvisational training can lead to an automation of the improvisation process (i.e., lower prefrontal activity), and potentially more efficient connectivity between regions crucial for improvisation (e.g., DLPFC, and premotor areas). A critical finding was that these results were independent of hours of classical music training – changes in functional connectivity and activity patterns were correlated with the musicians’ experience *improvising*, not simply playing the piano. From these results, it appears that there is a dissociation between the physical skills needed to perform music, and the skills needed to perform music creatively – to improvise freely.

Evidence about artistic creativity in domains outside of music is relatively sparse. EEG evidence suggests that visual artists have significantly different patterns of cortical synchrony when they perceive visual art, when compared to non-artists (Bhattacharya & Petsche, 2002). It is unclear what specific advantage this increased synchronization confers to artists. Likewise, it has been shown that dancers have increased alpha patterns in EEG responses, specifically at frontal and right parietal areas, when asked to visualize and create a novel dance (Fink, Graif, & Neubauer, 2009). Alpha power is generally thought to correspond to mental effort; it is possible that creativity in dancers is related to increased activity in prefrontal and parietal areas, rather than decreased activity (as often seen in musicians). Consistent with the finding of increased frontal cortex activity during creativity, a study of creative writing by Shah and colleagues (Shah et al., 2013) observed increased activity in the IFG (language areas) and orbitofrontal cortex during creative brainstorming, suggesting effortful generation of novel content. Two studies of visual creativity show contradictory results relating to prefrontal activation or deactivation during creative activities. A 2009 study of visual artistic creativity indicated that creative training could lead to a unilateral (rather than bilateral) activation of the prefrontal and parietal cortices (Kowatari et al., 2009). This result suggests that artistic training can result in a decrease in prefrontal and parietal responses during creativity. Similarly, a study by Saggar et al. (2015) showed that drawing (in a Pictionary game-like setting) led to a decrease in activity throughout the DMN, as well as the DLPFC, compared to a zigzag drawing control. This result was found in subjects who did not have explicit artistic training.

Although the results between the existing studies of musical creativity and creativity in other domains do not always cohere, a somewhat consistent neural network has begun to emerge. Musical improvisation (and in some cases, visual artistic creativity; Saggar et al., 2015) leads to increased activity in language and motor-planning areas compared to nonimprovisatory tasks. More notably, improvisation is correlated with deactivation throughout the prefrontal cortex. In particular, a marked decrease in overall activity of the DLPFC often occurs during more ecologically valid improvisation tasks, studied in improvisation experts. This decrease in the DLPFC is often concurrent with deactivation throughout the DMN (and increased functional connectivity between the DLPFC and areas of the DMN).

The suppression of DLPFC activation has previously been linked to states of flow (Dietrich, 2004). States of flow are characterized by a total and positive immersion in an activity (Csikszentmihalyi & Csikszentmihalyi, 1992). The DLPFC does not receive direct sensory input – it is generally involved in top-down inhibition of inappropriate actions, which may help account for its suppression during states of flow. It is often tempting to ascribe causality to the results from neuroimaging studies; however it is worth emphasizing that the current literature does not necessarily prove that flow is a prerequisite for creative thinking, even though suppression of activity in the DLPFC is seen in a large number of studies. It is possible that certain types of creativity (perhaps including artistic creativity) are dependent on deactivation in the DLPFC, or activation throughout the prefrontal cortex. Certain types of creativity may require the ability to enter a flow state, while other types of creativity require focused attention and cognitive effort (Dietrich, 2015). Existing studies of artists and artistic creativity, however, strongly suggest that artistic creativity may be mediated through the suppression of a diverse network of brain areas. The full function of this deactivation is yet to be elucidated.

Challenges and Limitations

The scientific discourse about the neurobiological foundation of creativity is expanding. Nonetheless, there are problems with the current body of research. Several considerations are important when attempting to synthesize and draw strong conclusions from both anatomical and functional studies of musicians and other artists.

Interpreting the results of studies that examine the anatomical differences between highly trained artists and non-artists is difficult. It is not clear whether the observed differences are the result of training, or the result of innate differences that predispose certain people to artistic proficiency. There are strong correlations between certain anatomical changes and amount of practice, which suggest that many of the observed changes are the result of repetitive use (Gaser & Schlaug, 2003b; Hutchinson et al., 2003). It is also not clear how anatomical differences correspond with perceptual or behavioral differences between experts and nonexperts. For example, musicians have improved pitch perception thresholds in both musical and nonmusical tasks when compared to nonmusicians (Boebinger et al., 2015; Chartrand & Belin, 2006; Kishon-Rabin, Amir, Vexler, & Zaltz, 2001; Marques, Moreno, Castro, & Besson, 2007; Tervaniemi, Just, Koelsch, Widmann, & Schröger, 2005). These increased perceptual abilities, however, are not necessarily dependent on the increased gray-matter volume in the auditory cortices of musicians (Pantev et al., 1998; Schneider et al., 2002).

Another underlying difficulty with interpreting many of these results, especially when looking for evidence relating to the ability to be creative through different artistic media, is that there are many skills associated with artistic expertise that may not directly contribute to creative ability. The motor coordination needed to be a professional dancer and musician may be a prerequisite for success in the highly competitive industries of music and dance. This does not necessitate a causal relationship between increased motor and perceptual skills in artists (or increased gray-matter volume in auditory or motor areas), and the ability to be creative.

The majority of evidence about networks of the brain responsible for artistic creativity comes from functional neuroimaging data, rather than structural data. While these studies have begun to reveal a core network that appears to be responsible for the motor generation, interaction/expression, and flow that generally typify creativity, several limitations prevent definitive conclusions from being drawn. As discussed above, there are an abundance of different methodologies that have been used among studies, especially as they relate to musical creativity. Task constraints, whether they arise from the technological limitations of fMRI-compatible keyboards, or are imposed by researchers, influence experimental results. Some of these constraints call into question the premise of many of the existing studies of creativity – with so many constraints, are the subjects being tested truly able to be creative? It can readily be argued that the improvisations or freestyles of experimental subjects are both novel and appropriate for the given context (and therefore are, by definition, creative), yet there may be different degrees of creativity that are not captured within the constraints of any particular experiment.

Three further considerations make drawing of broader conclusions from the existing literature problematic. First, the current literature focuses almost exclusively on highly trained experts. Anatomical studies of musicians strongly suggest that years of training can lead to cortical reorganization. There is strong reason to assume that functional activations and connectivity within the brain would also be altered by training and expertise. The existing studies may show how *experts* create, but they may not accurately reflect creativity in amateurs, or creativity under more general conditions. Second, music is the only artistic domain that has been consistently studied. Music requires a separate set of skills from tasks such as writing poetry, painting, dance, etc. Musical creativity may be different from creativity in other artistic domains, calling into question generalizations about creativity that have been made based on the few existing studies of musical creativity. A third, more general concern is that artistic and aesthetic creativity may not be unique – there may be a common network responsible for creativity regardless of the domain (scientific, artistic, athletic, etc.). Drawing a distinction between artistic and aesthetic production and other forms of creativity, especially when most of the data supporting that distinction come from the single domain of music, makes it possible to miss nuances of task demand and expertise. While it is likely that there are different degrees and modes of creativity, a distinction between "artistic" and other forms of creativity may not be valid. Artistic creativity may not hold a privileged place in the brain after all (Dietrich, 2015).

Conclusions and Future Directions

Despite the many challenges in studying creativity and interpreting the existing results, the field has made significant progress. Although existing studies have used varied approaches and placed relatively severe experimental constraints on the subjects, a somewhat consistent image of the neural systems involved in artistic (specifically musical) improvisation is emerging.

The progress made so far points to three primary directions of further inquiry as neuroscientists attempt to better understand the neural basis of artistic endeavor and creativity. First, direct comparison between different forms of artistic creativity is necessary to determine whether there exists a single set of neural systems responsible for producing art. If there is a pattern of neural activity that typifies artistic creativity, compared to, for example, scientific or mathematical creativity, this suggests that the ability for divergent or creative thinking arises differently depending on the domain in which somebody gains expertise. It may not be valid to consider artistic creativity as something quantitatively and qualitatively different from creativity in other nonartistic domains, so direct comparisons between artistic creativity and other forms of creativity outside of the arts are also necessary. Second, studies showing the effects of development and training on artistic creativity are crucial avenues for future study. If, for example, it were shown that a different pattern of activity is observed in children who are being creative versus trained adults, this might suggest that training changes the way that the brain is creative. Alternatively, if deactivation in the DLPFC were observed in children during a creative task, as it has been shown in adults, this might suggest that hypofrontality and flow are crucial parts of creativity, regardless of training level. Third, there is scope for continued research into the factors that influence creativity – what task demands or constraints are responsible for engaging the underlying systems involved in creativity? By determining how the neural systems responsible for creativity are modulated, it might be possible to understand how diverse areas of the brain can work together during creative expression. Deriving answers to these questions, although difficult, will provide exciting insights into the fundamental human urge to create art.

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30 Polymathy: The Resurrection of Renaissance Man and the Renaissance Brain

Claudia Garcia-Vega and Vincent Walsh

Introduction: Whatever Happened to Renaissance Man?

When people are asked to say what they consider to be the best example of human creativity, there are two common strands of responses. The first is to name the giants of history – Picasso, Beethoven, Shakespeare, etc. – who changed the world in a particular way, usually in the direction of an artistic domain, but this can apply to all fields, and Einstein and Newton sometimes get a look in. The second is to give a sigh and say something like "Well, people are not as creative as they used to be; will there ever be another Leonardo?" In preparation for this chapter we shifted our focus and canvassed people for their best examples of living polymaths, which we loosely defined as people who have made significant contributions in diverse fields of endeavor. The pickings were remarkably slim and we noticed two trends in their answers. Either our respondents found it difficult to name people, or they would argue that in the modern, highly specialized world in which we live it is not possible to master more than one field, and that such opportunities for polymathy were a thing of the past. These views are important to us because the scientific consideration of creativity not only depends on the current ways in which we parse the cognitive functions of the brain, it also influences how users of cognitive science (educators, policy makers, sports and business people, and the person surfing the net for information and inspiration) will interpret what is possible based on the research we present in the public domain.

Of course, we also canvassed our scientific colleagues through the existing literature and asked two questions: What does current research on creativity tell us about polymaths? And, how does our current conceptualization of brain function influence how we might approach a cognitive neuroscience understanding of domain-general creativity?

The state of play in cognitive neuroscience in general is reflected in the literature on creativity: we do not merely speak of "functional specialization" and "domain specificity"; rather, they are part of the intellectual fabric of our discipline. Modularity is more than a heuristic, it is something of a creed. Neuroscience has, however, made fundamental contributions to discussions revolving around different facets of creativity, including visual artistic creativity (Heilman & Acosta, 2013), problem-solving and creativity (Kounios & Beeman, 2009), literary creativity (Wise & Braga, 2014), dance (Fink, Graif, & Neubauer, 2009), and a whole host of divergent thinking and insight problem tests (Arden, Chavez, Grazioplene, & Jung, 2010). The science is often excellent, but we have to face the limitation that creativity is not a moment, and even in capturing the elements of it that can be operationalized in the lab, we will leave much behind. Everyone reading this chapter, and everyone who has contributed to this volume, will know the creative process subjectively, but will also recognize that an idea can take days, weeks, or months to develop and that doing something about that idea can take equally as long. Studying the elements of creativity is a natural place to begin, but understanding the long-term processes involved in how creativity unfolds over time is no more guaranteed than is an understanding of art by extension of our knowledge of the visual system (Zeki, 1998, 1999). Our problem here is to approach the question of whether creativity is domain-specific through the methods of a field which is itself domain-obsessed. We are not the first to identify the problem; Arden et al. (2010) stated this as their first recommendation for advancing the study of creativity: "Goal: discover whether creative cognition is domain-specific. Action: test people phenotypically across many domains of creative production to quantify the common variance" (p. 12). We can identify several components of creativity and try to answer these individually in the context of polymathy. If we consider that creativity demands domain-specific knowledge, domain-general abilities, and the personality characteristics needed to motivate the persistence required, two areas on which to focus our questions present themselves for discussion: domain-general abilities, and personality characteristics.

The Continuing Existence of Renaissance Man

Before making our case for the neuroscience of polymathy, we should establish its existence and puncture the cultural and relatively recent view that it is either dead or indeed a deficiency. Carl Djerassi (himself a Nobel laureate and reputable author) termed polymaths "dabblers" and preferred the term for himself of "intellectual polygamist" (cited in Carr, 2016). Moreover, A. Robinson (2006), writing about Thomas Young, even puts a date on the extinction of the *Homo polymathyi*, entitling his book *The Last Man Who knew Everything* with the wonderful subtitle, "Thomas Young, the Anonymous Polymath Who Proved Newton Wrong, Explained How We See, Cured the Sick and Deciphered the Rosetta Stone." But whatever one wants to call them, however much one wants to romanticize the past, and in spite of the constant claims that people who know a lot about a lot are an endangered species, polymaths are not hard to find today.

No list would exclude Noam Chomsky or deny his contributions to cognitive science, philosophy and politics, or James Lovelock (engineer, inventor, and environmental intellectual), or the sometimes ignored extraordinary case of F. Story Musgrave, who, apart from having the shared record of six spaceflights as an astronaut, has six academic degrees and has worked at a very high level throughout his life as physicist, surgeon, marine, aviation electrician, aircraft crew chief, mathematician, experimental parachutist, National Heart institute fellow, professor of physiology and biophysics, literary critic, and photographer (Story Musgrave Biography – Academy of Achievement, 2016). And we shouldn't limit ourselves to intellectual pursuits. Arnold Shwarzenegger became a body-building legend, propelling the sport to a world profile, but he was also the world's highest-grossing actor in his heyday and governed one of the world's 10 biggest economies (as a Republican while married into the Kennedy-Shriver clan – now *that's* creative) (Schwarzenegger, Ptre, & Dürr, 2012). Further, Hugh Laurie, at one point the highest-paid actor on American TV, is also an accomplished writer, comedian, and musician (Bunko, 2011). There are many people out there who have made world-class contributions to different fields of endeavor. Polymathy is alive and well in the twenty-first century. Thomas Young's achievements and characteristics are certainly humbling, but their spirit is far from extinct (Martindale, 2001).

Here we need to take down a second major fallacy in the post-mortem reports of the polymath. It is often claimed that as the circle of knowledge gets wider, it becomes less and less likely that anyone can encompass a large enough area of it. Martin Rees, ex President of the Royal Society, states the fallacy perfectly: “The frontier of knowledge is getting longer. It is impossible now for anyone to focus on more than one part at a time” (Carr, 2016). However, this assumes that everything that is published matters (or that it even qualifies as knowledge). Our contention is that as knowledge accrues, so does our means of accessing it, and so too do our generalizations and understanding of general principles. As we will explain in later sections, conditions today encourage polymathy. There is no reason to fear that today’s Leonardos are weeping in their rooms wishing that there wasn’t so much to learn.

The Brain and Psychology of Renaissance Man

Studies of cognitive functions have proceeded successfully by adopting modular approaches to cognition and brain organization (Barrett & Kurzban, 2006; Cowey, 1979; Mahy, Moses, & Pfeifer, 2014; Moscovitch, 1995). There are many indications, however, that some organizational principles of the brain are domain-general. Domain-generality has been proposed in fluid intelligence (Chiappe & McDonald, 2005; Gray, Chabris, & Braver, 2003), learning (Chein & Schnieder, 2005), development (Kirkham, Slemmer, & Johnson, 2002), language skills (Saffran & Thiessen, 2008; Smith, 1999), musicianship (Bashwiner, Wertz, Flores, & Jung, 2016), and mathematics (Holloway & Ansari, 2008; Walsh, 2003). We can see a clear pattern when we look at the brain areas involved in domain-general processing. Independent of whether it is general intelligence, language, skill learning, music, literature, or mathematics, we see common areas of the brain implicated repeatedly in these diverse functions: dorsomedial and dorsolateral prefrontal cortex, middle temporal gyrus, temporal pole, posterior parietal cortex, and cingulate cortex appear as significant contributors to creativity in all these domains. What is significant is that these regions capture the core of the default mode network, DMN (Fransson & Marrelec, 2008; Greicius, Supekar, Menon, & Dougherty, 2009; Tryon, 2014). The DMN has been proposed as a domain-general super-hub in many different functions including literary creativity, based on studies of comprehension and narrative production (Binder, Desai, Graves, & Conant, 2009; Buckner & Carroll, 2007; Wise & Braga, 2014). Mirroring these functional findings, Bashwiner et al. (2016) noted structural changes within the DMN, which they associated with musical creativity. The story is strengthened in the music domain by several imaging studies (Beaty, 2015; Beaty & Silvia, 2012a, 2012b; Beaty et al., 2014; Beaty, Silvia, Nusbaum, & Jauk, 2014) which have shown DMN activity during musical improvisation.

The increase in DMN gray matter and its ubiquity in a wide variety of tasks give us some insight into its role in creativity. DMN activity is associated with many characteristics of creativity – mind-wandering (Andrews-Hanna, 2011; O’Callaghan, Shine, Lewis, Andrews-Hanna, & Irish, 2015), theory of mind (Buckner & Carroll, 2007), and simulation of future events (Schacter et al., 2012). All of these are elements in any of the longer-term processes that underlie creativity. One specific suggestion about its role is that DMN activity during artistic production is evidence of internally generated, self-referential mechanisms (Limb & Braun, 2008). The same authors go on to suggest that DMN activity is associated with the ability to supress voluntary self-monitoring in order to achieve flow. It is difficult to think of any domain of creativity which would not draw upon mind-wandering, self awareness, internal motivation and, in some circumstances, an appreciation of how others might see things. One could say, then, that the DMN is beginning to look like a solid platform on which to build the skills for polymathy.

We now have a neural basis to use as an anchor for polymathy. Mind-wandering, future simulation, and flow are not specific to any particular creative domain. If the DMN is necessary for more than one form of creativity, then the question arises of whether, in the course of acquiring expertise, it becomes functionally associated with one skill set and relatively inhibited for others. There are two classes of predictions we can make for the future:

1. DMN becomes associated with specific skill sets. If this is the case, then domain-general processes may not be that general. Once a chain of preference has been set in train (say, as one devotes 10 years to scratching a violin), it may be harder to divert DMN resources from one form of creativity to another. The analogy would be with muscle: athletes who have developed physiques for one specialization (say, upper body strength to optimize total power in BMX racing), may not be able to transfer to a similar-looking sport –cycling – where strength to weight is more apt than total power. An extreme form of this prediction is that the DMN in highly creative individuals may be relatively supressed for tasks outside their domain of creativity. This is logically possible, but seems to us unlikely.
2. DMN is equally activated in making a creative effort irrespective of expertise. To test this prediction, one would have to look at DMN activity in experts producing in their creative domain, and also making an equal effort in an area in which they do not excel (or are less adept). The presence of DMN activity in so many tasks in the literature suggests that the activity would be equal across efforts to the extent that the task involved components such as forward-thinking and divergent thinking.

Our own prediction, partly because the literature already points in this direction if we interpret the studies of DMN and creativity *post hoc*, is that DMN activity would not show any evidence of domain preference.

There are other equally fundamental reasons to believe that the brain has the capacity for polymathy. Paradoxically, the fact that individual brain cells are unintelligent makes them a super foundation for domain-general processing. The brain solves many problems – vision, audition, and touch as examples – and it uses the same strategies over and over again. The brain constructs visuotopic maps from retinal input, tonotopic maps from auditory input, and somatotopic maps from tactile input. It does so according to rules of columnar and laminar organization, and it produces these maps without any regard for the origin of the input (Shamma 2001; Sur, Gerraghty, & Roe, 1988). For example, a developing "auditory" cortex receiving input from the visual thalamus will construct visuotopic maps (Sur et al., 1988). This is not to say that the brain is domain-general or equipotential; rather, that it has few strategies at hand with which to solve problems and that good solutions will be recycled in different domains. In the extension from domain-specific creativity to polymathy, we suggest that the DMN occupies a functional position akin to that of making maps. Where the sensory networks create sensory maps, the DMN can be called upon to recreate conceptual maps and activate the component functions common to all aspects of creativity. We would consider this the deep structure of creativity that is the basis for our conclusion that the rarity of polymaths is a function of how we educate our brains and what we expect and believe of them, rather than a function of the brain's limited capabilities.

The brain imaging and physiology literature discussed above has allowed us to overlay a neuroscience onto ideas articulated by Root-Bernstein (1984, 1989, 2003), Amabile (1982, 1983, 1996), and Conti, Coon, and Amabile (1996). Root-Bernstein (2003), for example, describes psychological components of artistic and scientific creativity that read very much like the bread and butter of the DMN. He offers four routes for transfer between arts and sciences: invention or observation of the novel or anomalous; analogies and models; communication and articulation skills; and the "generation of possible worlds." He goes on to say that the fourth route "is the one most often over-looked and of the widest application to understanding innovative thinking in general" (p. 267).

There are two other areas of cognitive neuroscience that can help us to understand the possibilities for polymathy: developmental cognitive neuroscience, and social psychology. In the social domain we need do no more than remind ourselves that our brains develop in a social matrix. Amabile and Pillemer (2012) reviewed 35 years of the social psychology of creativity and give us insights, which have not yet been scaffolded by cognitive neuroscience. The long-term drive and resilience to produce ideas or to bring ideas to completion as final products (much more difficult) remain to be addressed by neuroscience. Bashwiner et al. (2016) point toward this in their finding of increased gray matter in orbitofrontal cortex, temporal pole, and amygdala of musicians. For our purposes, we would note that none of these areas is associated with domain-specific behaviors: if you have developed the capacity to be motivated and moved by one sphere of activity and learning, it seems reasonable to suggest that the capacity would be transferrable to others. Indeed, much of our education system (or at least its beliefs, if not practices) is predicated on this ability to transfer learning principles. There is good evidence that this is the case in self-regulation (Baumeister, 1998; Baumeister & Tierney, 2011) and, after a rocky start, evidence is emerging of the transfer of skills in brain training domains (Connolly et al., 2012; Fischer, Kubitszki, Guter, & Frey, 2007; Glass, Maddox, & Love, 2013; Green & Bavelier, 2007). Conceptually, then, we have already opened the door to general skills through transferable skills.

Other important findings from social psychology are that creative habits can be learned, and that our day-to-day environment influences creative behaviors. Unless we believe that intrinsic motivation is a fixed trait, then here is another component of creative behavior that we can look at and suggest, "we can produce that in our children by thinking about how we teach them in school" (Lee, Reeve, Xue, & Xiong, 2012; Oudeyer & Kaplan, 2007; Reeve & Lee, 2014).

Given that the brain has the machinery for domain-general creativity, that our creativity is affected by the environment we live in, and that none of the components of creativity are fixed traits, we can look at the developing brain in our search for polymathy. The most-watched TED talk on the Internet (seen by over 38 million people to put our h-factor obsessions into perspective) is Ken Robinson's (2006) "Do Schools Kill Creativity?" It is a fair question. One hundred years of psychology have given us a sound understanding of how people learn (Brown, Roediger, & McDaniel, 2014), are motivated (Dweck, 1986), self-regulated (Baumeister, 1998) and develop the confidence to face failure and persist (Duckworth, Peterson, Matthews, & Kelly, 2007; Dweck, 1986, 1999, 2006). As psychologists we know that we can get much more from new generations by giving them an education based on what we know about how people learn and how they are motivated to succeed. Our obsession with developing exam monkeys encourages a domain-specific, overspecialized view of the world and of children – conditions that limit the emergence of polymaths.

Big-P, Little-P, and P-Hunting in Everyday Life

We have so far willingly committed the sleight of hand of almost all creativity papers: we have talked about the greats, the game changers, the Big-Polymaths (and will do so again in the next section for the same reasons). We all do this because we assume some kind of linearity between the kinds of creativity we wish to understand – the Big-Cs –and the kinds we can access in group studies – the Little-Cs. In this chapter, we assume the same continuity between Big-Ps and Little-Ps. Big-P is hard to study because the few Big-Ps around are probably busy, and there is a drive toward larger group studies (but see our final section, "Challenges"). If we relax the criteria for polymathy, however, we see that it is an everyday occurrence. One rung below the game-changers are people who have excelled in one career yet proven themselves at something else: Brian May, for instance, has a PhD in astronomy as well as plays in a rock band; Wladimir Klitschko has a PhD as well as world title belts; and Douglas Hofstadter weighs in with a Pulitzer prize, a chair in Cognitive Neuroscience, several languages, and a PhD in Physics. In universities a PhD is merely an entry ticket, but it still ranks as an achievement that >98% of the population have not reached. If we relax the criteria more we all know people who are polyglots, good at sport and who can play a musical instrument at a party without embarrassing themselves. They may never translate Tomas Tranströmer, play for Manchester United or join Crazy Horse, but in the realms of Little-P they demonstrate mastery of skills that require years of learning, motivation, and domain-specific skills. What the existence of the Little-Ps tells us is that, in principle, polymathy is entirely possible. This raises some tractable questions for research. If we take our polyglot, soccer-playing, guitar-playing subjects (subjects rather than friends: even though we recognize their achievements, we are still at liberty to envy these people) and subjected them to structural and functional imaging experiments, there are a series of obvious questions: will the DMN be structurally different in Little-Ps compared with Non-Ps (Bashwiner et al., 2016); will Little-Ps show different domain-general learning activations than Non-Ps (see Chein & Schneider, 2005); if tested on tasks that are components of creativity, will Little-Ps show different DMN activity in tasks of mind-wandering?

With Little-P to give us laboratory and group access to polymathic subjects, any question that can be legitimately asked of domain-specific creativity can also be asked of domain-general creativity – polymathy – given that we are aware that the subjects under consideration are Little-Ps and not Big-Ps.

The Constraints on Polymathy

One might ask at this stage whether we have been avoiding the critical question of time and capacity. What can we say that will get around the brute fact that becoming an expert in anything takes years of effort and that, even with Google to replace our failing memories, we simply cannot, as Martin Rees argued, keep pace with it all? And how do we counter the possibility that there are capacity limits on creativity? After all, there are capacity limits on our senses, memory, motor production, and learning, so how can creativity be any different? We would argue that the time problem is one of our own making and the capacity problem is one of our own expectations. To return to Root-Bernstein (2003), it may be the case that creativity is more often than not born of polymathic roots. Taking Santiago Ramon y Cajal as an example, he notes that Cajal was a man of wide interests and considerable artistic skill (Ramon y Cajal, 1989). The idea that people had more time to explore the lesser knowledge back then simply doesn't hold water. Preparing brain samples and drawing them from primitive microscopic slides was as time-consuming as anything we now have to do. Also, the idea that the knowledge base was meaningfully smaller for Ramon y Cajal is somewhat naïve. When working at the limits of knowledge, something with which every contributor to this volume has experience, it is remarkable how much we forget or choose to ignore. The problem that attracts us is never the result of some logical process of knowledge accrual. Isn't it more often the case that the irrational attraction we feel toward a problem is some other expert's articulation about something outside our current area of achievement? The capacity required by a modern Ramon y Cajal is perhaps less rich than that required by him and others in less information-rich environments. In his address "The role of imagination in science," J. H. Van't Hoff (1967), the first Nobel laureate in Chemistry but also a musician and a poet, argues for the importance of imagination when it comes to scientific research, and gives examples of famous scientists who also had remarkable avocations in the arts, such as Charles Richet (Nobel laureate in medicine and playwright), Kepler (scientist and musician), Galileo (artist), Davy (poet), and Pasteur (artist). The list goes on and includes figures such as Max Planck (Nobel laureate and pianist), who also emphasized the importance of the "*artistic* imagination" in science (Planck, 1949, p. 14).

It is true that one could find many examples of scientists and artists who are not polymaths, and we have selected our examples to suit our case (we will atone in our final section), but unless we wish to subscribe to a fixed view of human potential, we view it as, at the very least, psychologically and philosophically healthy to believe that we have not yet produced all the Ramon y Cajals, Keplers, Plancks, or van't Hoffs it is possible to produce.

The Necessity of the Renaissance Brain

Our understanding of brain mechanisms of behavior necessarily runs behind our understanding of the behavior in question: social psychology is, as usual, ahead of neuroscience in conceptualizing and describing behavior, and in this case so too is society. In the previous section we discussed and dismissed some of the notions that have bolstered the fancy that "it was easier back then." Perhaps it is easier now to be a renaissance man than it was during, well, the renaissance or the seventeenth century (Grayling, 2016).

When we think of the modern world and the ways in which the brain has to respond, we sometimes read of information overload, social isolation, rewiring the brain, and "unnatural" modes of thinking – all delivered in alarmist language (Carr, 2016; Greenfield, 2015; Turkle, 2013). However, if we look at how technology, mobility, and education are changing the world, we can see that we are entering the Age of the Polymath. If your great, great grandparents were reading this chapter (if indeed they had had the opportunity to learn to read), they would not see much of a need for Little-Ps in their world. They would be doing pretty much the same job as their parents, living in the same town, and would expect to do so until they retired and died. Life was more predictable. Any undergrads or postgrads reading this chapter are already likely to be away from their hometown, have no idea what career they will enter – a career that will almost certainly not be a job for life – and they will probably have to retrain for several jobs throughout their life. They will also have to work longer than previous generations before they retire. There are some similarities with earlier generations – we all die – but the landscape of life has changed. This is being recognized in education (Long Lingo & Tepper, 2013a, 2013b), Government policy, and by a breaking down of disciplinary barriers. That entitles Root-Bernstein (2003) to say "I told you so." Embracing creativity in our education system has, in a rare alliance, two enemies – administration and faculty. At the top of our education tree we have to build on the grade-obsessed education system that confuses passing exams with learning. We also need high-quality faculty members willing to accept the changes in knowledge access and acquisition. Anyone going to university before 1998 would not have had access to Google; now a student can access all the knowledge of their Professors' lectures prior to the class. The challenge is "What can universities teach students that they can't look up on Google?" It is not just the students who need to engage their renaissance brains to survive, it is also their Professors.

The emergence of the renaissance world may be a completion of how things always seemed to some. In his 2003 review, Root-Bernstein argued that:

> no distinction exists between the arts and sciences at the level of the creative process itself (see also Koestler, 1964; Bronowski 1965; Root-Bernstein, 1984, 1989). The ways in which artists and scientists discover and invent problems, experiment with ways to come to grips with them, and generate and test possible solutions is universal. In fact, most of the greatest innovators in every discipline have been polymaths. Thus, I propose that creative people are generally creative, and their general creative ability comes from mastering a common set of thinking tools. … All real-world innovation is a process that involves the elaboration through fantasy (sometimes called imagination) of many possible solutions to any given problem, and the use of the widest range of mental and physical tools to constrain and evaluate which of these possibilities is most adequate to any given need. In this sense, all innovation is a process of survival of the fittest in which multiple variations of ideas are selected by social, economic, cultural and other factors. (p. 267)

There are challenges here, however. In our need to parameterize creativity for the laboratory, we have converged on different forms of insight, problem-solving, skill execution, and divergent thinking, but not everyone will recognize these as capturing the essence of creativity. Don Paterson, one of the English language's most important living poets, gives a view that leaves the lab mind reeling. He argues that poets often do not seek resolution in their creative output. In discussing Emily Dickinson's poetry, he emphasizes the importance of not knowing where your work is going, something he describes as "questing towards something she doesn't fully understand" (Paterson & Chiasson, 2012). The point for us as scientists is to remind us that we do not have a taxonomy of creativity that everyone will recognize. This is not the same as physicists having a description of matter that would not be useful to the average carpenter. Because we are dealing with an everyday human activity which occasionally extends to the exceptional, the face validity of our venture is important (unless one is happy with a description of creativity that is not understood or recognized by the Big-P creatives in our society).

Polymathy is fast becoming the modus vivendi of modern life. MIT's Media Lab has recently launched a new journal, *The Journal of Design & Science* (*JoDS*). The focus is antidisciplinary and in an inaugural essay, Neri Oxman (2016) states the "Antidisciplinary Hypothesis: that knowledge can no longer be ascribed to, or produced within, disciplinary boundaries, but is entirely entangled." The antidisciplinary approach is not mere posturing, and gives us a problem in thinking about domain-specific and domain-general creativity. In an Age of Entanglement that doesn't recognize old domain boundaries, the norm may well be Little-P.

Challenges for the Scientific Study of Polymathy

We have argued that the human brain is capable of polymathy; that polymathy is more prevalent than is usually assumed; that our education and expectations curtail it; and that polymathy is a necessary feature of modern life. Having made this case, it is clear to us that any neuroscientific account of creativity will be incomplete even in conception, let alone conclusions without taking polymathy into account.

The challenges, however, do not seem to us to be special. The study of creativity has matured. Arden et al. (2010) have made the case for clearer psychometric testing of creativity in conjunction with imaging studies, and we agree with all eight of their recommendations. Another major route is to consider the resurrection of single case studies. We are aware of the seductive qualities of storytelling and cherry-picking, but the history of modularity is built on studying the remarkably adept and the remarkably impaired. Face perception, memory, topographic organization, skill learning, and language, have all benefitted from examining people whose abilities lie at the extremes. There is a case to be made for revisiting this approach in parallel with large group studies. Rose (2016) delivers a timely reminder that no individual ever measures up (or down) to the mean of a population. Perhaps a jewel of information is buried in the structure–function relationships of a Big-P brain; it may be that there are many routes to Little- and Big-P behavior depending on the etiology of one's learning history. Perhaps our schools, having been built on the damaging foundations of Taylorism and Thorndyke's psychology, will benefit if science can show them examples of how they can promote polymathy. In 1912 John Rockerfeller funded the General Education Board and in an early vision statement wrote that schools should "not try to make these people or any of their children into philosophers, or men of learning or of science … not to raise up from among them authors, orators, poets or men of letters (nor) search for embryo great artists, painters, musicians" (the list of what education is *not* to achieve goes on; Yochum & Fosdick 1963, cited in Rose, 2016, pp. 50–51). Neuroscience has made no contribution to education to date, but if we can show what the brain (meaning people) can achieve, and give some direction as to how to reach those goals, we may contribute to the production of a new generation of necessary and attainable renaissance minds.

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