Neural Connectivity of the Creative Mind

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Abstract

Human creativity contributes to the engagement, achievement, and subjective well-being of individuals. While historiometric and psychometric studies have defined multiple areas for creativity research, a neuroscientific understanding of how the human brain subserves creativity is only beginning to be realized. This chapter reviews the literature on the neuroscience of creativity, with special foci on how different components of creative cognition and domains of perception relate to the structural and functional connectivity of the human brain, and how these patterns of brain connectivity can inform interventions that foster creativity and innovation.

Keywords

Creativity, neuroimaging, structural connectivity, functional connectivity, creative cognition, perception, intervention

Introduction

What would the world be like without creativity? Surely, the fundamentally human drive to create something wholly new and useful has catalyzed great achievements in history. Creativity contributes to the adaptation, growth, and pleasure of communities, and plays an important role in the well-being of individuals. Creativity can allow us to lose ourselves in engaging activities, to achieve success by developing innovative solutions to problems, and to make social contributions that provide satisfaction and meaning in our lives. These ends—engagement, achievement, and meaning—are considered to be among the key components of the flourishing life (Seligman 2011). More specifically, research studies suggest that creativity may be positively correlated with measures of happiness and subjective well-being (Pannells & Claxton, 2008; Tamannaeifar & Motaghedifard, 2014). As positive psychology embraces the use of scientific inquiry to increase happiness and improve well-being, the movement would be incomplete without a thorough investigation of this core human strength (Seligman & Csikszentmihalyi, 2000; Simonton, 2002). In this chapter, we take a neuroscientific approach to identifying positive characteristics that generalize across creative individuals. With a focus on the neural underpinnings of creative thought and behavior, we hope to develop a more comprehensive understanding of the roots of creativity, so as to inform targeted interventions that would increase creativity, ultimately promoting greater well-being.

Approaches to Creativity

Defining Creativity

Creativity has been a topic in psychology since 1950, when Joy Paul Guilford espoused its importance in his presidential address to the American Psychological Association's annual convention. Despite several decades of study, however, a unanimous definition of creativity remains elusive. Some theorists suggest that this inconsistency impedes the field's progress, leading to confusion and contradictory findings in the literature (Parkhurst, 1999; Plucker & Beghetto, 2004; Simonton, 2013). Still, even as precise definitions differ, certain key themes unite research on creativity.

Researchers agree that for an idea or product to be considered creative, it must be original. For instance, we might say that a painter who convincingly replicates Van Gogh's Starry Night is quite skillful, but most of us would not call her work creative. Although seemingly straightforward, the criterion of originality does not specify who should be the judge of novelty. This concern has led some researchers to claim a distinction between psychological (or "P-") novelty and historical (or "H-") novelty. P-creative products are those that are novel to the individual creator, whereas H-creative products are novel in a historical context (Boden, 1991). Though historiometric approaches have been used to study eminent creators, most creativity research, inasmuch as it focuses on an individual's ability to create something new from her own perspective, focuses on P-creativity. In this chapter, we will reflect on the neural underpinnings of P-creativity, as well as potential factors that may be shared between P-creative and H-creative individuals.

While novelty is widely identified as a core criterion of creativity, it cannot be the sole criterion. Imagine that the captain of a college basketball team tells you his brilliant idea for a new play: he will pass the ball to his friend in the stands, and then his friend will attempt to shoot a basket. Though the play may indeed be original, we can hardly consider it creative, both because it violates the rules of the game and because it would likely be unsuccessful. Thus, to count as creative, products must also be in some way appropriate (useful, effective, or valuable: Boden, 1991; Stein, 1953; Sternberg, Lubart, Kaufman, & Pretz, 2005). Like novelty, appropriateness depends upon context. In its narrowest interpretation, this may mean that an act or product is truly creative only if perceived as a useful contribution from “appropriate experts” in the field (Csikszentmihalyi, 1997). Indeed, Csikszentmihalyi suggests that creativity is best understood as existing within a three-part system that includes the domain (e.g. mathematics; painting), the field (consisting of all experts or professionals in the domain), and the individual creator. In defining creative acts by their social reception, the construct of creativity becomes more objective, thereby facilitating measurement and study.

Some, but not all, researchers have also added a third criterion for creativity. This criterion has varied from “good” (Kaufman and Sternberg, 2010) to novel, appropriate, and “high in quality” (Sternberg, Lubart, Kaufman, and Pretz, 2005). While perhaps illuminating on their own, these quality-focused criteria may fall under the umbrella of “usefulness,” as the usefulness of a creative product often depends on its quality (Sternberg & Lubart, 1999). Though these nuanced definitions continue to be debated, most research maintains that creativity must be, at the very least, novel and useful (Runco & Jaeger, 2012).

Creativity and Mental Illness

While creativity is predominantly considered a positive trait, researchers and the popular media alike remain intrigued by its potential negative effects. Most hotly debated among these is the idea that creativity may be related to mental illness. Supporters of the association between the two constructs frequently cite an empirical study by Andreason (1987), in which 30 creative writers and their families demonstrated higher rates of mental illness, particularly of the affective and bipolar types, than controls. More recently, Kyaga and colleagues (2013) have replicated this finding about writers and suggested that scientists and artists may be more likely than those in non-creative professions to have first-degree relatives with psychiatric disorders. Furthermore, analyses of specific creative and personal output of great artists of the past, in light of the clinical psychology literature, suggest possible links between the artistic temperament and manic-depressive illness (Jamison, 1996). On the other hand, some argue that the methods used in these studies are weak and blindly overstated in popular discourse, casting doubt on the association altogether (Schlesinger, 2009; Waddell, 1998).

A more nuanced understanding of the connection between creativity and mental illness has emerged in recent years. Most research about the relationship between creativity and mental illness addresses only certain creative domains (most notably the fine arts) and certain mental illnesses (such as affective, bipolar, and thought disorders and substance abuse), suggesting that the association may be domain-specific (Silvia and Kaufman, 2010). Even within these domains, the strength of the putative associations appears to vary. In a study of 826 writers, Kaufman (2005) demonstrated that poets were more likely to exhibit severe mental illness than any other type of writer. Furthermore, direction of the association between mental illness and creative genius may be moderated by the degree of creativity: while creative people may demonstrate better mental health than non-creative individuals, exceptional creativity in the “mad-genius” may predict mental illness, such as in some individuals with autism or savant syndrome (Simonton, 2014; Pring, Ryder, Crane, & Hermelin, 2012; Mottron, Dawson, & Soulieres, 2009).

Types of Creativity

The construct of creativity can be divided into several subtypes. One popular framework for categorizing creativity is by the importance or impact of the creative product, i.e. the distinction between “Big-C” and “little-c” creativity (Csikszentmihalyi, 1997). Big-C creativity is eminent creativity that results in highly influential products. Big-C creators include artists and thinkers who change the direction of their disciplines, such as Albert Einstein, Ernest Hemingway, and

Steve Jobs. In contrast, little-c creativity is the “everyday” creativity that we all have the potential to experience. Though it may not change the course of history, little-c creativity encompasses the creative ideas, decisions and products that enable us to solve problems and to improve or enrich our daily lives. Distinguishing these types of creativity informs how we understand the implications of creativity research.

The question of whether creativity is a core capacity that applies broadly across domains, or whether it is domain-specific, has challenged researchers for more than half a century. Though arguments have been made in support of each position, integrative theories suggest that creative expression may be the result of both domain-general and domain-specific creative capacities (Baer & Kaufman, 2005; Kaufman & Beghetto, 2009). Furthermore, whether creativity is found to be domain-general or domain-specific has depended upon the methods used to study it (Plucker, 2004). We will argue in this chapter that while heightened cognitive capacities may enable domain-general creativity, specialized perceptual skills and knowledge of a domain may enable domain-specific creativity. Thus, while each domain may be said to entail its own type of creativity, certain capacities may underlie creativity in all domains.

Models of Creative Thought

Much current research on creativity attempts to understand domain-general capacities and how they integrate to form an overarching process of creative thought. Perhaps the most widely recognized model describes creative thought as a process of divergent thinking following by convergent thinking. Divergent thinking contrasts with convergent thinking in that the former is the ability to generate many unique responses to an open-ended prompt, and the latter is the ability to determine the single “correct” answer to a problem. In 1960, Campbell published his theory of blind variation and selective retention (BVSR) to illustrate this two-stage process.

According to his model, creative thought can be understood to be akin to evolution by natural selection, which occurs when traits are first blindly generated within a population, and then selectively enhanced or diminished among offspring because they contribute differentially toward survival and reproduction. When applied to creativity, this suggests that creative thoughts occur when the mind first blindly (or randomly) generates new ideas, then assesses and selects the most appropriate and useful ideas for implementation. Though Simonton has spearheaded its defense and revision over the past two decades (Simonton 1999, 2011, 2013), the BVSR theory remains heavily debated (Dasgupta, 2011; Gabora, 2011; Sternberg, 1999).

While divergent and convergent thinking may factor importantly into creative thinking, creative achievement likely involves a confluence of several psychological factors. A multivariate approach to creative achievement conceptualizes the process as involving three types of abilities: cognitive abilities, domain-specific or task-related abilities (including knowledge and perceptual skills), and motivation (Amabile, 1996; Besançon, Lubart, & Barbot, 2013). Each factor is needed for creative ideas to be brought to fruition and accepted socially, and can be assessed separately with a variety of measures.

Methods in Creativity Research

Different types of creativity lend themselves to different forms of measurement. To study Big-C creators, some researchers have taken a historiometric approach of applying quantitative analysis to data concerning historical individuals (Simonton, 1990). Aside from Csikszentmihalyi's (1997) seminal study of 91 renowned, and still living, creators, research into Big-C creativity has needed to rely on less direct methods of gathering data. As it does not require the active participation of subjects, historiometry has allowed researchers to study variables systematically such as eminence, psychopathology, and leadership in the world's most eminent creators, alive and deceased (Simonton, 2014; Vessey, Barrett, Mumford, Johnson, & Litwiller, 2014). Although this approach relies on potentially inaccurate and necessarily subjective secondary source materials, and may be vulnerable to selection bias (Ligon, Harris, & Hunter, 2012; Rothenberg, 1985; Yammarino, Mumford, Serban, & Shirreffs, 2013), the appeal of studying historical creators is clear. Big-C creativity epitomizes the creative potential of humankind, and its study provides a window into the opportunities through which the rest of us can hope to enrich our own creative lives.

On the other end of the creativity spectrum, psychometric research aims to measure the mental processes that underlie the creative thought and production in little-c creativity. The most common of these psychometric approaches to creativity assesses divergent thinking, such as the Torrance Tests of Creative Thinking, or TTCT (Torrance, 1968). Developed by E. Paul Torrance, the TTCT comprise ten subtests that measure the generation of responses to both figural and verbal prompts. In one such subtest, the Unusual Uses Test, also called the Alternate Uses Task, subjects list as many possible uses for an object, such as a brick, as they can within a specific time frame. The answers are then judged on fluency, flexibility, originality, and in some versions, elaboration. While divergent thinking tasks have been widely used by researchers studying creativity, as well as educators admitting students into gifted programs (Hunsaker & Callahan, 1995), the past two decades have seen heavy criticism of their ubiquitous use. Criticisms include that measures of divergent thinking do not correlate well with measures of creative behavior, and that they resemble verbal fluency tasks too closely, thus calling construct validity into question (Silvia, Beaty, & Nusbaum, 2013; Simonton, 2003). In their defense, Cropley (2000) explains that divergent thinking tasks may better measure creative potential than creative achievement itself, as actual creative achievement requires additional factors such as knowledge of a field. As theories of the creative process suggest that creativity requires convergent as well as divergent thinking, these divergent thinking tasks capture only part of the creative process; nevertheless the part of the process that is captured could be fundamental or generalizable across multiple domains of creativity.

More direct measurements of creativity assess the creative merit of the subjects' actual products, or achievements. These include self-report, family- or teacher-report, and social consensus-based measures. The Creative Achievement Questionnaire (CAQ), one such self-report measure, asks subjects to report the number and eminence of their accomplishments in ten domains, ranging from music to science to the culinary arts (Carson, Peterson, & Higgins, 2005). Individuals score higher on the creativity scale if they report making major contributions to a field, rather than receiving minor or local recognition (Silvia, Wigert, Reiter-Palmon, & Kaufman, 2012). Another empirically validated method for determining an individual's creativity is the Consensual Assessment Technique (CAT). For this method, rather than asking subjects to self-report which of their achievements have been socially recognized, the experimenter asks subjects to create an item, such as a poem or a collage, and then has expert judges independently rate the item's creativity (Amabile, 1982; Baer & McKool, 2009). While perhaps less sensitive to the potential of young creators, these measures guarantee that only those novel products that are socially useful or valued are deemed creative.

As research technologies have advanced, so have our methods for measuring psychological traits such as creativity. In particular, the field of cognitive neuroscience has equipped researchers with novel tools, such as MRI, fMRI, and EEG, to achieve a deeper level of understanding. Certainly an understanding of mechanisms within the human brain that give rise to creativity can enrich our thinking by adding another dimension to our knowledge of its processes, personalities, and achievements, while potentially shedding light on some existing debates in creativity research. With many questions still unanswered, creativity researchers have begun to search for answers in the brain itself.

Approaches to Brain Connectivity

While this chapter offers a critical review of the literature on the patterns of neural connectivity that characterize the creative mind, in this section we provide an overview of the theoretical, biological, and methodological background needed to discuss brain connectivity as it relates to creativity. The past twenty years has seen an explosion of studies that use neuroimaging. A rapidly developing area in cognitive neuroscience is concerned with understanding patterns of brain activity, rather than responses of single regions. While patterns of brain activity can occur at many spatial and temporal scales, one general goal is to understand temporal correlations of brain regions, as well as structural connectivity between groups of brain regions. Conceptualizing the human brain as patterns of connectivity offers a more nuanced approach: on one hand to networks of regions, rather than individual regions, that might be affected in psychological disorders, on the other hand to understanding and potentially maximizing exceptional abilities.

The human brain is comprised of an estimated 10^{12} interconnected neurons, each of which receives electrical and chemical signals through dendrites, and transmits signals by firing action potentials down its myelin-wrapped axons. Studies that examine *structural* connectivity (or anatomical connectivity) in the human brain investigate the anatomical properties of groups of myelinated axons from neurons, forming axon bundles that connect neural cell bodies. In contrast, studies that investigate *functional* connectivity in the human brain capitalize on the co-occurrent, or correlated, activity of groups of neurons that can be measured with a variety of factors, such as electrical potential changes in EEG and oxygen level changes in fMRI that are dependent upon neural activity. Both have been used in creativity research.

Structural connectivity

From early days in neuroscience, studies of creativity and the brain have benefited from lesion analyses, such as of where lesions in the frontal lobe have been related to creative block (e.g. "writers' block") (Flaherty, 2005). With the use of neuroimaging, anatomical brain networks can be measured *in vivo* using a specific type of MRI known as Diffusion Tensor Imaging (DTI). DTI is a type of structural MRI that is tuned to the directional properties of white matter in the brain (Jones, 2008). Using the information obtained from the directional diffusion of water, one can make inferences as to whether specific regions are more likely to contain white matter (axons) or grey matter (neuronal cell bodies). Furthermore, one can get information regarding the principal directions in which each voxel diffuses. By connecting sequential voxels with similar principal directions, via the process of tractography, DTI algorithms can reconstruct streamlines that represent major white matter pathways in the brain.

While neuroimaging methods such as DTI are useful in visualizing structural connections in the brain, recent advances in network science have offered new ways to conceptualize brain connectivity. Network science is an interdisciplinary field that has given us graph theory – a broadly applicable set of descriptive models of social and biological networks, that can now be applied to the study of brain connectivity as it relates to concepts central to creativity. Using graph theory one can obtain network measures of each brain such as degrees (number of connection from each entity, or each node), clustering (proportion of connections that are also connected with each other, also known as "cliquishness"), and path length (mean number of connections between each pair of nodes). In a recent DTI study that used graph theory to approach creativity in the brain (Ryman et al., 2014), divergent thinking tests (Verbal and Drawing Creativity Tasks, Uses of Objects Test) were administered and DTI scans were obtained from 106 human subjects. Divergent thinking tests were scored by independent judges to yield a composite creativity score for each subject. DTI, tractography, and graph theory were combined. The resulting graph theory metrics were correlated with scores on the divergent thinking tests separately for males and females. Intriguingly, results showed a negative correlation between clustering and the composite creativity score in females but not in males: more creative females had less clustered brain networks. Further analyses showed many sex differences in correlations between graph theory metrics and creativity. While results are somewhat difficult to interpret at this point, given the large sample size in this study these differences in network metrics should be relatively stable and replicable, and may be suggestive of different patterns of neural connectivity that subserve the ways in which men and women approach creativity tasks such as divergent thinking tests.

Functional connectivity

In contrast to anatomical networks, functional networks of the brain can be estimated using functional MRI and electroencephalography (EEG). EEG methods make use of rapid changes in electrical activity, resulting from synchronous action potentials fired by populations of neurons. These electrical potential changes can be recorded on the surface of the scalp and can provide indices of neural activity with high temporal resolution. Event-Related Potentials (ERP) are a technique that uses averages of EEG recorded during repeated perceptual and/or cognitive events. One example of an ERP that has been related to creativity, specifically to solving insight problems, is the P300 waveform (e.g. Lavric, Forstmeier, & Rippon, 2000). The P300 is a positive waveform that occurs approximately 300 milliseconds after onset of a task-relevant stimulus. This waveform has been found to differ in amplitude and topographical distribution over the scalp during the performance of creative tasks such as solving insight problems (Lavric, Forstmeier, & Rippon, 2000), and is associated with frontal lobe function.

Another use of EEG data comes from time-frequency analyses that aim to extract frequency bands of electrical activity as recorded on the scalp. Since EEG was discovered in the 1920s, it was observed that specific brain states were associated with specific frequencies of EEG activity. For example, synchronous alpha band (8 – 12 Hz) activity across different parts of the scalp is related to drowsiness and/or relaxation, whereas beta band (12 – 30 Hz) activity is associated with wakeful alertness. Alpha band power, in particular, has been associated with creativity-related tasks and the originality of ideas (Fink & Benedek, 2012). Band power changes at specific frequency bands are an index of functional connectivity, similarly to resting state functional connectivity MRI as described below.

Functional MRI can include task fMRI and resting state fMRI. In task fMRI, individuals typically perform behavioral tasks in the MR scanner. The classic task fMRI analysis entails comparing MR signal between behavioral task conditions (e.g. doing a creative task versus resting / no task), resulting in a large number of univariate statistical comparisons (e.g. t-tests) where the clusters of activations that pass a significance threshold are projected as activations overlaid on an anatomical image. One example of univariate statistical design in a task fMRI experiment comes from an fMRI investigation of creative generation of stories (Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005). Subjects were given three words that were either semantically related or unrelated, and were instructed to generate creative and uncreative stories in response to the words. The stories were rated by independent raters as more creative when the instruction was to be creative; but more interestingly, the stories were also rated as more creative when the target words were unrelated. A univariate fMRI contrast between the creative and uncreative task conditions showed increased activity in the prefrontal cortex during the creative condition, providing support for the involvement of the prefrontal cortex in creative idea generation. Furthermore, an interaction between semantic relatedness and creativity showed activity in the right prefrontal cortex: subjects showed increased right prefrontal activation when trying to be creative with semantically unrelated target words. This finding adds support to the idea that prefrontal cortex in the right hemisphere is involved in forming the remote associations that relate divergence to creativity. This task fMRI experiment benefits from the two-factor design of the univariate statistical approach (i.e. a two-way ANOVA), in which statistical interactions can be assessed to answer questions that pertain to the conjunction, or interaction, of different factors influencing brain activity — such as creativity and semantic divergence.

In addition to the classic univariate task fMRI analyses, newer analyses of functional connectivity involve identifying patterns of simultaneous or correlated activity among different voxels throughout the brain. The assessment of functional connectivity is the main goal in resting state fMRI, which is a variant of fMRI in which the subject does not engage in any specific task. Instead, subjects are told simply to lie still in the scanner while multiple images of their brain are acquired over time. From resting state fMRI data, one identifiable functional network is the Default Mode Network (DMN), a set of regions including the medial prefrontal cortex (mPFC), the posterior cingulate cortex (PCC), and the lateral parietal cortex (LP) (Fox et al., 2005). The DMN is active during mind-wandering (day-dreaming, or stimulus-independent thought) (Mason et al., 2007), Christoff, Gordon, Smallwood, Smith, & Schooler, 2009), which may facilitate an incubation period that is necessary for creativity (Baird et al., 2012). In support of this idea, resting state functional connectivity from the mPFC, especially in its correlation with the PCC, was positively associated with scores on a divergent thinking task (Takeuchi et al., 2012): people who scored higher on a divergent thinking test showed a stronger DMN. These findings may provide a direct link between DMN and creativity. Further support for this link comes from a recent finding that scores on the Creative Achievement Questionnaire (Carson, Peterson, & Higgins, 2005) were positively correlated with grey matter volume in the ventromedial prefrontal cortex (vmPFC), a region within the DMN (Chen et al., 2014). Taken together, these results relate creativity to the default mode network, with mind-wandering as a possible mediator of this relationship.

Cognition

Having reviewed the major methodological approaches for studying brain connectivity, as well as some applications towards understanding creativity, we now turn to review the core studies in the neuroscience of creative cognition. Three major areas of focus for neuroscience research on creative cognition are divergent thinking, the relationship between creativity and intelligence and working memory, insight and its subprocesses, and creative performance and improvisation. While studies in these areas have taken varied approaches, sometimes resulting in limited generalizability or comparability across studies, the field has nonetheless made promising strides toward a nuanced understanding of the cognitive components of creativity.

Divergent Thinking

Divergent thinking is the ability to come up with multiple possible solutions to a problem. Although not synonymous with creativity, divergent thinking is undoubtedly an important component of the creative process (Runco, 1991). As introduced in the previous section, divergent thinking may be associated with functional connectivity in the Default Mode Network (Beaty et al., 2014; Jung, Mead, Carrasco, & Flores, 2013; Takeuchi et al., 2012). Using resting-state fMRI, Takeuchi et al. (2012) observed a positive correlation between divergent thinking scores and functional connectivity between the mPFC and the posterior cingulate cortex, two regions within the DMN. Beaty et al. (2014) found an increase in functional connectivity of the left inferior frontal gyrus (IFG) with the entire DMN, and the right IFG with several regions associated with the DMN, in a high-creativity group compared to a low-creativity group as defined by divergent thinking measures. EEG studies showed alpha band activity in EEG while performing on divergent thinking tests, with increases in alpha band activity after a two-week training period in divergent thinking exercises, especially in alpha power over the frontal lobe (Fink, Grabner, Benedek, & Neubauer, 2006).

Although research on creativity has traditionally focused on divergent thinking, convergent thinking — the ability to come up with the ”correct” solution to a problem — is also an important component of creative thought (Lee & Therriault, 2013). Despite Guilford’s view that convergent thinking is antithetical to creativity, certain kinds of creative problem solving may be largely convergent (Cropley, 2006; Dietrich, 2004). For example, insight problems involve “thinking outside the box”, but do require converging at a single correct solution to a problem (Lee & Therriault, 2013).

Working memory and intelligence

There is also substantial evidence that working memory and fluid intelligence are linked to creativity (Nusbaum & Silvia, 2011; Vartanian, 2013). Dietrich (2004) suggested that all creative circuits include a working memory buffer, implemented in the prefrontal cortex, and Vartanian (2013) observed associations between working memory training and performance on divergent thinking tasks. While Lee and Therriault (2013) found no direct correlation between divergent thinking and working memory in a large-scale study (n = 265), they observed an indirect positive correlation mediated by intelligence and associative fluency. This finding relates to an important question in creativity research: how much intelligence, usually measured with tests of convergent thinking, relates to creativity (Sternberg, Lubart, Kaufman, & Pretz, 2005).

Jung and Haier's (2007) Parieto-Frontal Integration Theory (P-FIT) suggests a broad neural network underlying intelligence including the dorsolateral prefrontal cortex (dlPFC), the somatosensory and visual association cortices, and Broca's and Wernicke's areas. According to this theory, information moves through the parieto-frontal network in a seven-stage sequence of processing events. Beginning in the extrastriate cortex and fusiform gyrus, sensory information is processed through the network until it reaches frontal areas, where responses are selected and competing responses inhibited (Jung & Haier, 2007). The parieto-frontal network shares some brain areas with those activated in divergent thought. These areas appear to be involved in the activation and regulation of widespread neural activity connected to both divergent and convergent thinking (Jung & Haier, 2013).

Intelligence is thought to be comprised of crystallized intelligence (G_c — culturally derived, accumulated knowledge and skill) and fluid intelligence (G_f — the ability to respond efficiently and flexibly to new situations) (Horn & Cattell, 1967). Nusbaum and Silvia (2011) found an effect of G_f on creativity mediated by executive task switching, the participants' ability to move between conceptual sets within a task. Taken together, while there are some areas of overlap between intelligence and creativity in the brain, the effect of intelligence on creativity may be limited by an intelligence threshold. The threshold hypothesis states that above-average intelligence is necessary but not sufficient for creativity (Guilford, 1967). This hypothesis has garnered empirical support from psychometric testing, showing a significant association between intelligence and creativity only up to an I.Q. threshold of around 120 (Jauk, Benedek, Dunst, &

Neubauer, 2013). Neuroimaging of frontal and parietal lobe metabolism showed different relationships between neuronal integrity and creativity (as assessed using divergent thinking) in individuals with high and low verbal IQ, also providing support for the threshold theory (Jung et al., 2009).

Insight

An insight solution, sometimes called an aha! moment or a Eureka experience, occurs when a problem or concept has been unconsciously restructured, enabling the sudden realization of a solution from seemingly "out of nowhere." While of great interest to psychologists, insight events can be difficult to study because of their unpredictable nature. Investigators have had to develop a wide variety of testing paradigms, such as solving anagrams and riddles, to capture their target. For the most part, research has focused on identifying discrete brain regions associated with insight events. While insight and non-insight solutions involve largely the same problem-solving network, insight solutions may involve more activation of the anterior cingulate cortex (Kounios, 2006; Starchenko, Bekhtereva, Pakhomov, & Medvedev, 2003) and prefrontal cortex (Aziz-Zadeh, Kaplan, & Iacoboni, 2009; Bechtereva et al., 2004). Discrepancies among recent reviews (Dietrich & Kanso, 2010; Kounios & Beeman, 2014), however, suggest that overarching conclusions remain elusive.

Some steps have been made towards understanding neural connectivity as it pertains to insight. One study found that, whereas search processing is associated with left insula activation, insight solutions were associated with bilateral insula activation. The authors interpreted this finding as supporting a theory of interhemispheric transfer, or increased functional connectivity between the left and right hemispheres (Aziz-Zadeh, Kaplan, & Iacoboni, 2009). This finding of bilateral activation has been replicated in several additional studies (Bechtereva et al., 2004; Kounios, 2006; Luo & Niki, 2003) and suggests that while most problem solving recruits left hemisphere processes, the right hemisphere is additionally involved in insight problem solving, and intact connectivity between the two hemispheres is crucial for finding solutions to problems of insight specifically.

Although the idea of interhemispheric connectivity is attractive, few studies have directly investigated brain connectivity as it relates to insight. This may stem from the fact that fMRI, our key instrument for assessing structural and functional connectivity, lacks good temporal resolution, making it difficult to capture insight events. Temporal resolution is important for studying insight because insight events are thought to be sudden and fleeting. Without good temporal resolution, we may not know whether we are examining the insightful moment itself, or other cognitive and emotional experiences associated with problem solving. Insight events may be better understood by combining fMRI with EEG for optimal spatial and temporal resolution. One study used this combination of methods, to show that there is a burst of activity in the right anterior superior temporal gyrus – an area involved in semantic integration — right at the moment of understanding for verbal insight solutions relative to non-insight solutions (Jung-Beeman et al., 2004). Further research into the application of these methods to assess neural connectivity is warranted.

Cognitive Styles and Personality

In contrast to creative achievement, which is defined by the originality and usefulness of the output, the creative personality can be viewed as a disposition that differentiates people who frequently show creative behavior, even if only at a small scale (Eysenck, 1997). As creative achievement depends on cognitive variables such as intelligence, knowledge, technical skills and talent, as well as environmental variables and personality variables of internal motivation, confidence, nonconformity, and creativity, the personality trait of creativity is a necessary but not sufficient condition for creative achievement (Eysenck, 1993) The creative personality is characterized as introverted, open to experience, uninhibited, and (especially in the case of artists) anxious and high on neuroticism. The latter two characteristics suggest that one end of the spectrum of creative personality might be related to psychopathology, with some correlation between creativity and psychoticism – or at least the susceptibility to developing psychotic symptoms.

In hypothesizing a causal link between genetic determinants and creative achievement, Eysenck (1993, 1997) posits that cortical arousal, mediated by the influence of dopamine and serotonin on the hippocampal formation, leads to the decrease of cognitive inhibition which leads, on one hand, to psychoticism, but on the other hand to the trait of creativity and ultimately to creative achievement. Although not based specifically on neuroanatomy, this model presaged more neuroimaging-based theories of creativity in important ways. Firstly, Eysenck's model attempts to explain creativity as a lack of inhibition, which is echoed in the Frontal Disinhibition (F-DIM) model of creativity (Jung & Haier, 2013). The F-DIM model states that the lack of inhibition, specifically from the frontal lobe towards other areas of the brain, gives rise to creativity (Jung & Haier, 2013). As the processes of inhibition and disinhibition within the brain rely on intact connectivity between its regions, the F-DIM model and Eysenck's model can both be seen as connectivity-based theories. Secondly, the Eysenck model of creative achievement relates psychoticism to the creative personality, while still maintaining a clear differentiation between the two constructs. This idea of shared susceptibility between creativity and psychoticism is echoed later by the model of shared neurocognitive vulnerability (Carson, 2013), in which creative ideation shares genetically influenced neurocognitive features with some forms of mental illness, such as mood disorders, schizospectrum disorders, and substance abuse.

Improvisation

Improvisation is a creative act that is spontaneous, but requires complex cognitive functions that result from training and expertise. These characteristics enable the creative act to be performed in a laboratory setting, in a time frame suitable for neuroscientific research (McPherson & Limb, 2013). Though every creative work is distinct, the process of improvisation is, in this sense, replicable (McPherson & Limb, 2013).

Ecological validity may be of particular concern in studies of such complex phenomena as improvisation (Limb & Braun, 2008). Designs that seek to recreate improvisatory brain activity with simplified tasks might produce patterns of activity critically different from those found in improvisation. In addition, studies on improvisation use a range of participants, from the musically untrained, to professional jazz and classical pianists, to freestyle rappers. The pattern of dissociated frontal lobe activity found by Liu et al. (2012) and Limb and Braun (2008) in a population of trained improvisers (freestyle rap and jazz piano, respectively), may represent a learned cognitive approach to improvisation distinct from the approach of untrained or classically trained participants.

There is disagreement on the extent to which improvisation critically requires cognitive control. While some characterize improvisation as a creative task in which high cognitive control enables deliberate and analytical processing (Ellamil, Dobson, Beeman, and Christoff, 2012), others describe it as occurring beyond volitional control (Limb and Braun, 2008). Empirical studies contribute to this debate: in one study, classical pianists were presented with a visual score and asked to improvise on the presented melody (Bengtsson, Csikszentmihalyi, & Ullen; 2007).

Brain activity for improvisation was contrasted against activity for trials in which the pianists were asked to reproduce a previous improvisation. Results for improvisation showed significant activation of the dlPFC, a brain region involved in cognitive functions such as rule-based processing and executive control. In contrast, Liu et al. (2012) and Limb and Braun (2008) studied extended free style rap improvisation and jazz piano improvisation, respectively, using the performance of an over-learned, original composition as a comparison task. Their results showed activation in the mPFC, with correlated deactivation of the dlPFC. Specifically, Liu et al. (2012) found a pattern of activity in which the mPFC bypassed normal mediation by the dlPFC, suggesting the down-regulation of cognitive control. In another study, pairs of jazz pianists improvised passages in alternating four-measure segments, and showed activation in language areas including inferior frontal gyrus (IFG) and superior temporal gyrus (STG). These authors suggested that the discrepancy with earlier research may be explained by the social demands of partnered improvisation, and the particular importance of responding to preceding musical material in this context, increasing demands on working memory associated with dlPFC activation (Donnay, Rankin, Lopez-Gonzalez, Jiradejvong, & Limb, 2014).

Neuroscientific research may have important implications for the use of improvisation in both therapeutic treatment and positive interventions. Improvisation has long been an important ingredient in many music therapy models, such as Creative Music Therapy, which uses improvisatory music as the exclusive means of communication in the client-therapist relationship (Brown & Pavlicevic, 1996). Researchers have also noted similarities between musical improvisation and meditation, perhaps mediated by deactivation by the lateral prefrontal regions (Limb & Braun, 2008), and between improvisation and flow states (Csikszentmihalyi, 1996).

Flow

Flow is a state of optimal experience in which a person performing a skilled activity (such as musical improvisation) is fully immersed, single-mindedly focused, in a state of deep enjoyment, and being challenged while deriving intrinsic reward from the activity (Csikszentmihalyi, 1991). Understanding the neural underpinnings of flow would be of the utmost importance to the neuroscience of creativity, as it is often during this state of flow when great works of artistic and scientific creativity are born. However, few neuroscience studies have attempted directly to investigate the neural substrates of flow. This may stem from the relative difficulty to conduct a well-controlled neuroscientific study on this topic for two reasons. First, difficulty arises from designing a neuropsychological test for the flow experience, as taking the test itself would disrupt the flow experience. Second, challenges arise from applying neuroscientific methods (e.g. EEG, fMRI) to the individuals in flow while respecting the original definition of flow, which is defined as a domain-general concept that spans multiple areas of expertise. To obtain neuroimaging data during the state of flow, while different individuals are performing their distinct activities, would result in confounds that arise from differences in motor movement and perceptual and cognitive demands that result from performing the task at hand, rather than from the experience of flow per se.

Confronted with these challenges, researchers have attempted to circumvent the first difficulty by using the experience sampling method (described in the previous section on mind-wandering) (MacDonald, Byrne, & Carlton, 2006), and the second difficulty by limiting studies to a single domain. In that regard, helpful conclusions come from studies of jazz improvisation (reviewed above) and the musical *groove* (Stupacher, Hove, Novembre, Schutz-Bosbach, & Keller, 2013). Groove is the pleasurable state of optimal auditory-motor entrainment, also known as action-perception coupling or sensorimotor synchronization (Novembre & Keller, 2014), and theoretical and empirical work on this phenomenon posit that being in the groove requires the interfacing or connectivity between the auditory system and the motor system (Janata, Tomic, & Haberman, 2012; Novembre & Keller, 2014; Stupacher, Hove, Novembre, Schutz-Bosbach, & Keller, 2013). This idea of sensorimotor synchronization converges well with the general theme of neural connectivity subserving creative experiences such as the flow experience. However, being in a state of flow requires that the individual be pushed to the edge of their ability (Csikszentmihalyi, 1991), whereas the same is not required of a groove experience (Janata, Tomic, & Haberman, 2012). It could be that the requisite difference of being pushed to perform at the edge of one's ability, in whichever domain at which one excels, is what distinguishes the true flow state of generating uniquely creative output from simply having an enjoyable experience.

Domains of knowledge and perception

Perception and creativity

While many may think of creativity as mostly an internally generated (or self-generated) cognitive capacity, creativity relies heavily on perception, which is a relatively externally generated, or environmentally driven, source of knowledge and information. Fundamentally, the act of perception entails the identification and experience of sensory information in a changing environment, including the detection of patterns and the interpretation of sensory stimuli (Arnheim, 1966). In the context of perception, creativity may entail a readiness to receive new information, or to accept old information from new vantage points (Smith & Amner, 1997). This flexibility in shifting perspectives may lead creative perceivers to withhold judgment and to entertain multiple hypotheses when confronted with ambiguous sensory stimuli.

This hallmark of flexible perceptual decision-making may underlie artistic creativity. In a classic study, a set of cards with figures was presented to artists and non-artists. Subjects' task — known as the Welsh Figure Preferences Test — was to sort these cards into stacks of "liked" and "disliked" cards according to their own aesthetic preference. Results from factor analysis showed that artists preferred asymmetrical and complex figures, whereas non-artists preferred symmetry and simplicity (Barron & Welsh, 1952). Although these results do not show a direct link between being perception and creativity, one may infer that artists – or people in the creative industries more generally – are more ready to arrive at different aesthetic decisions given the same sensory stimuli, due to their flexibility in accepting and even preferring unusual perceptual experiences.

Perceptual tests of creativity

In addition to the Welsh Figure Preference Test, other tests have been devised to assess perception as a gateway to creativity (Smith & Amner, 1997). The Multidimensional Stimulus-Fluency Measure (MSFM) (Wallach & Kogan, 1965) contained a perceptual subtest that was used in preschool children to assess original thinking (Moran, Milgram, Sawyers, & Fu, 1983). In this test, children were presented with square cards with visual patterns, and had to provide possible interpretations of the simple patterns. While children who were more creative offered more possible interpretations of the patterns, results also showed behavioral dissociations between original thinking and intelligence as assessed by other psychometric tests. The MSFM was also administered to adults in art classes (Sawyers & Canestaro, 1989), where a positive correlation was observed between MSFM and achievement in design coursework. Finally, the Creative Functioning Test (CFT) is a psychophysical test where a series of ambiguous visual displays were presented for different durations, and subjects' task was to generate as many interpretations of each stimulus as possible (Smith & Danielsson, 1976, as cited in Smith &

Amner, 1997). Robust correlations were observed between CFT performance and quality of output among artists and architects (Smith, Carlsson, & Andersson, 1989).

While these tests have some overt differences in stimuli and task instructions, they share the common steps of presenting subjects with an ambiguous visual stimulus, followed by the task of interpreting or evaluating the stimulus. Thus, the tests used to assess perceptual creativity typically entail visual perception, engaging the visual system in stimulus processing followed by potentially domain-general creative processes, such as the divergent and convergent thinking processes reviewed earlier. In the visual system, stimulus processing passes through the crucial way station of the primary visual cortex in the occipital lobe, followed by the "what" and "where" pathways of the occipital, temporal, and parietal cortices. While these primary and association areas are recruited in sensory processing, they also have connections via white matter pathways into the prefrontal cortex, which subserves personality and cognitive mechanisms in a top-down manner. Thus, the prefrontal-dependent processes of the divergent and convergent thinking exert top-down influence upon each of these sensory processing regions and bottom-up pathways. Such influence may be in the form of neural inhibition as well as excitation, enabled by structural and functional connectivity between frontal lobe and other subsystems of the human brain.

Domains of perception

Although most tests of perceptual creativity rely on visual perception, perceptual creativity is certainly not limited to vision, but manifests itself in other modalities as well. Creativity in gustatory perception, for instance, may distinguish exceptional culinary artists from everyday cooks, whereas creativity in auditory perception may characterize the full range of musicians from classical composers to jazz improvisers to rappers. In this regard, studies on jazz improvisation (Bengtsson, Csikszentmihalyi, & Ullen, 2007; Limb & Braun, 2008; Pinho, de Manzano, Fransson, Eriksson, & Ullen, 2014), freestyle rap (Liu et al., 2012), and musical aptitude (Hassler, Nieschlag, & de la Motte, 1990; Ukkola-Vuoti et al., 2013) are some exemplars of relatively domain-specific and perceptually dependent forms of creativity. As the perceptual requirements for culinary and musical artists differ – for example, a master chef may have a poor ear for music, but must have a discerning sense of taste – so too do the neural requirements for exceptional ability in these domains.

Domain-specific exceptional ability

If exceptional ability in the creative arts is tied to perceptual skills, then exceptional perceptual behavior with known neural underpinnings may inform our understanding of the neural substrates of artistic creativity. Synesthesia and absolute pitch are two forms of exceptional perceptual skills/behavior that are common among artists and composers, and are subserved by specific, well-identified neural markers. Synesthesia is a neurological phenomenon where the stimulation of one sensory modality triggers the concurrent, automatic, and involuntary sensation of another modality (Cytowic & Eagleman, 2009). For instance, individuals with music-color synesthesia perceive colors as triggered by musical stimuli (pitches, timbres, chords, melodies, etc.) Synesthesia is eight times more common among people in the creative industries (Ramachandran et al., 2004), and some synesthetes report that they use their synesthetic experiences as a source of artistic inspiration (Cytowic & Eagleman, 2009). Neural theories posited for synesthesia share some parallels with the theories of creativity (e.g. Jung, Mead, Carrasco, & Flores, 2013), in that it posits a combination of increased connectivity and disinhibition, and are validated by DTI, fMRI, and small world network analysis of cortical thickness data in grapheme-color synesthesia (Hanggi, Wotruba, & Jancke, 2011; Pariyadath, Plitt, Churchill, & Eagleman, 2012; Rouw & Scholte, 2007; Zamm, Schlaug, Eagleman, & Loui, 2013). Formal psychometric testing for creativity among synesthetes showed that while synesthetes did not differ from controls on the Alternate Uses Test, they did outperform controls in the Remote Associates Test (Ward et al., 2008), again suggesting a neurological connection between synesthesia and creativity (Mulvenna, 2007).

Absolute pitch (AP) is another form of exceptional perceptual ability that is common among superbly creative individuals and has known neural correlates that may be informative of the neural substrates of creativity. AP is the ability to identify pitch classes of any given tone without a reference (Ward, 1999). Its possession among historically distinguished musical talents such as Mozart has led some to suggest that AP is a form of perceptual talent (Ward, 1999). Although supposedly rare, affecting less than 1% of the general population (Ward, 1999), AP is disproportionally found among musicians, especially composers and musical improvisers (Loui, 2014). The neural correlates of AP consist of increased structural and functional connectivity, with the posterior superior temporal gyrus (auditory association cortex) as the hub of a hyper-connected network that relates the perception and categorization of musical pitch (Loui, Li, Hohmann, & Schlaug, 2011; Loui, Zamm, & Schlaug, 2012).

Taken together, such exceptional populations as synesthetes and absolute pitch possessors are models of how unusual patterns of brain connectivity may give rise to behavior that is positively exceptional. While the same patterns of hyperconnectivity in the brain may characterize people with exceptional creativity more generally, it is important to recognize that AP and synesthesia may be a more homogeneous sample than the diverse populations of creative people, especially as the necessary and sufficient criteria for identification of creative individuals is still a matter of debate.

Reception of artistic creativity

Variation exists in how creative individuals perceive influence from social and environmental factors. Some artists, such as Van Gogh and Milton Babbitt (Babbitt, 1958), notably disregarded or even rejected the need for public recognition, believing instead that truly original and important work should be isolated from the "common practice" public opinion. On the other hand, some theorists espouse the need for social reception from an audience, stating that the aesthetic experience depends on alignment between creator and audience – a sympathetic activation or embodied imagination that exists between creator and receiver (Joy & Sherry, 2003; Lerdahl, 1992). Creativity research has agreed with the latter in stating that a social-psychological approach to creativity incorporates response generation, sympathetic resonance, and validation from the social context, in addition to the already-recognized components of domain-relevant skills, creativity-relevant skills, and task motivation as components of creative performance (Amabile, 1983).

The idea of sympathetic resonance has some support from neural theories and findings, notably coming from the new literature on an action observation network, similar to the putative mirror neuron network in humans (Calvo-Merino, Grèzes, Glaser, Passingham, & Haggard, 2006). Increased activity of the action observation network was seen in fMRI while watching dance performances that were aesthetically pleasing (Cross, Kirsch, Ticini, & Schutz-Bosbach, 2011). This provides a link between aesthetics and social-emotional perception through neural resonance in an action observation network of the brain, which encompasses perception areas in association cortices as well as action production or motor planning regions, notably the premotor cortex in the frontal lobe. This model of aesthetic creativity agrees well with the neurological theme of functional and structural connectivity between top-down (domain-general) functions in prefrontal areas and bottom-up (domain-specific) integration of sensory pathways. The success of creative aesthetic output, then, may depend on an embodied and socially contextualized experience that requires resonance with others, both at a social level and at a neural level.

Interventions: Fostering creativity through neuroplasticity

"We desperately need a positive psychology that provides us with information about how to build virtues like creativity, hope, future-mindedness, interpersonal skill, moral judgment, forgiveness, humor and courage…" (Gillham & Seligman, 1999).

At its core, the positive psychology movement aims to help us cultivate and strengthen the virtues of human flourishing. Though attempts to foster creativity certainly predated the formal establishment of positive psychology as a field of study, recent growth in public interest towards creative interventions has mobilized researchers and educators alike to deepen their efforts.

To understand the role of intervention in creative growth, it can be helpful to distinguish among creative potential, creative accomplishment, and creative talent. At the center is creative potential, which refers to one's latent ability to produce novel and appropriate work (Besançon, Lubart, & Barbot, 2013). In this respect, some are more gifted than others. Winner describes gifted children as possessing a particular precocity, an insistence upon learning in their own way, and a rage to master their domain (Winner, 1996). In other words, by learning in creative ways at such young ages, gifted children demonstrate a heightened potential to generate creative output later in life. Creative accomplishment then refers to this body of creative output, which has been deemed appropriate in the social context, and creative talent refers to the tendency to produce such accomplishments over time. Interventions and educational programs in creativity aim to enable creative accomplishment and talent by enhancing creative potential.

Such interventions take various forms. As there is some general agreement that creativity is at least partly domain-general and componential (Besançon, Lubart, & Barbot, 2013; Plucker & Beghetto, 2004; Vartanian, 2013; but see Baer, 2008), researchers are developing interventions to increase creativity overall by targeting the specific skills and mental processes which make it up. For instance, cognitive training has been shown to enhance working memory capacity (Klingberg, 2010) indicating, in light of the link between working memory and creativity, that such training may transitively increase creative ability. Other interventions take a more holistic approach, immersing subjects in a specific creative domain or setting. For example, a study that compared young children enrolled in traditional schools and Montessori schools demonstrated that the Montessori setting increased creativity in children, as measured by two divergent thinking and two integrative measures of creative thinking (Besançon, Lubart, & Barbot, 2013), while another study found that a drama program increased creative thinking and storytelling ability (Hui & Lau, 2006).

Studies of brain connectivity, and neuroplasticity more generally, can support both types of efforts to increase creativity by mapping and confirming training effects. The assumption is that if behavioral and neurological interventions are to alter creative potential tangibly, they should have a measurable effect on the neural substrates of creativity. By looking more deeply at these substrates, we can hope to enhance our inferences to a causal level.

Cognitive Growth

As cognitive capacities contribute significantly to creative ability, cognitive growth may be one of the most promising avenues for fostering creativity. Indeed, cognitive training and idea production have shown to be more effective at eliciting creativity than some commonly applied training strategies such as imagery training (Scott, Leritz, & Mumford, 2004).

One heavily studied example of cognitive training is working memory training. Working memory training often involves the repetition of working memory tasks, such as the n-back task. In the n-back task, subjects are asked to recall whether or not the image currently shown was also presented a specified number (n) of images before. Studies suggest that working memory training can improve working memory function, even on working memory tasks that differ from the training task (Holmes et al., 2010; Klingberg, 2006, 2010; Oleson, Westerberg, & Klingberg, 2004). In a review of ten fMRI studies of training by repeated performance of working memory tasks, Klingberg (2010) suggests that the improvements in working memory may be associated with patterns of coordinated activation in the frontoparietal network.

Studies also suggest that working memory training can extend to improve fluid intelligence (Au et al., 2014). In one study, four similar experiments were conducted, each requiring subjects to participate in several demanding working memory training sessions consisting of a dual n-back test. Standardized measures of fluid intelligence were administered before and after each experiment, which differed in the number (ranging from 8 to 19) of sessions between pre- and post-testing. Results suggested that training on a demanding working memory task could transfer to measures of fluid intelligence, and that the degree of gain in fluid intelligence is positively associated with the number of training sessions.

Recent research has demonstrated that improved effective connectivity may underlie some of working memory's transfer effects. In their EEG study, Kundu, Sutterer, Emrich, and Postle (2013) suggested that working memory training may have transfer effects on memory and attention which are mediated by increased effective connectivity across the frontoparietal and parietooccipital networks. Though the current body of research has not yet examined whether increased connectivity underlies the transfer from working memory training to measures of fluid intelligence, this finding suggests that such a connection may be likely.

Cognitive stimulation, through exposure to other people's ideas, is another type of cognitive training that may boost creativity (Fink et al., 2010; Wei et al., 2014). In one three-part study, creativity scores, as measured by the TTCT, and data from a resting-state functional magnetic resonance imaging (Rs-fMRI) scan were gathered for 269 subjects (Wei et al., 2014). Thirty-four subjects from this group were then randomly selected to participate in a cognitive stimulation task, followed by a post-task Rs-fMRI scan. In the first stage of the task, the "no-cue condition," subjects were asked to report as many novel and unusual uses of 10 objects as they could in a set time period, while in the second stage, the "cue condition," subjects were asked to do the same thing following six seconds of exposure to external ideas. The results for originality were higher for the 34 subjects in the cue condition than in the no-cue condition, suggesting that the task does increase creativity. More intriguing were the findings that this increase in creativity may be mediated by resting state functional connectivity (RSFC) in the medial prefrontal cortex. Specifically, pre-task creativity scores were positively correlated with pre-task RSFC between the medial pre-frontal gyrus and medial temporal gyrus, and RSFC between these areas significantly increased following cognitive stimulation.

In addition to behavioral methods for altering cognitive function, researchers are exploring non-invasive brain stimulation (NIBS) techniques, such as transcranial direct current stimulation (tDCS) and transcranial random noise stimulation (tRNS), as potential tools for targeted modulation of neural networks. For example, in one study, creative thought (as assessed by the remote associates test) was found to increase following anodal tDCS over the left dorsolateral prefrontal cortex, but not its right-hemisphere analog, suggesting that tDCS was able to increase the excitability of the left dorsolateral prefrontal cortex (Cerruti & Schlaug, 2008; Kundu, Sutterer, Emrich, & Postle, 2013). The effects of NIBS may be especially positive when combined with behavioral interventions, such as cognitive training (Cohen Kadosh, Levy, O'Shea, Shea, & Savulescu, 2012). One cognitive training study, carried out in conjunction with anodal tDCS, comes from patients with aphasia who had disrupted language functions as the result of a stroke. Following a week of randomized, sham-controlled melodic intonation therapy, patients who received therapy coupled with anodal tDCS showed greater gains than those receiving therapy coupled with sham stimulation (Cerruti & Schlaug, 2008; Vines, Norton, & Schlaug, 2011). This converges with the finding that tRNS coupled with intensive cognitive training in a paradigm involving approximate number sense (ANS) resulted in greater and longer-lasting ANS improvement than either tRNS alone or cognitive training alone (Cappelletti, 2013). Crucially, the intervention also led to a transfer of improvements in other parietal lobe-based quantity judgment tasks, but only in the coupled condition. While evidence does suggest that functional connectivity may increase following tDCS (Antonenko, 2013; Polania, Nitsche, & Paulus, 2011), no studies to our knowledge have examined functional connectivity as a possible means by which NIBS may increase cognitive functioning.

Music Training

While musical performance does not necessarily entail creativity—one can imagine a musician who reads and plays music well, without contributing novelty to the work—music is one domain of potential creative accomplishment (Carson, Peterson, & Higgins, 2005). In our quest to understand how different interventions, mediated by brain plasticity, can improve creative potential, studies on music training prove to be particularly enlightening. The musician's brain is a good model of neuroplasticity because musicians have had extensive exposure to music training, a complex stimulus that engages motor, auditory, and multimodal skills (Munte, Altenmuller, & Janke, 2002; Shlaug, Norton, Overy, & Winner, 2005). In addition, research suggests that music training is correlated with a variety of enhanced mental functions, such as verbal memory (Chan, Ho, & Cheung, 1998) and intelligence (Schellenberg & Moreno, 2010). With brain imaging methods, researchers can examine how neural structure and activation may underlie music training's observed effects on mental processing. While several studies suggest that music training is correlated with changes in brain structure and function, we have seen a recent increase in attempts to establish the causal direction of this relationship. For example, one longitudinal study examined structural brain and behavioral changes in children receiving 15 months of musical training compared with children receiving no musical training (Hyde et al., 2009). Children who received music training showed structural changes following the training period in motor regions (such as the right precentral gyrus and corpus callosum), auditory regions, and bilateral frontolateral and frontomesial regions and a left posterior pericingulate region. These changes were correlated with improvements in motor and auditory behavioral skills.

In light of growing appreciation for network-based approaches to studying mental functioning, researchers are beginning to examine the effects of music training on white matter and patterns of brain activity. One longitudinal study of weekly instrumental music training in five- to seven-year-old children compared the size of the corpus callosum (CC), the main interhemispheric tract in the brain, among high-practicing subjects, low-practicing subjects, and controls before and after a 29 month training period (Schlaug et al., 2009). At baseline the three groups showed no differences in CC size, but after training the size of the CC was positively correlated with total weekly music exposure, supporting the hypothesis that music training can significantly impact neural connectivity. Another recent study examined whether gray matter increases attributed to music training are accompanied by changes in intrinsic functional connectivity, mapped from resting state fMRI (rsfMRI) data (Fauvel et al., 2014). Comparing rsfMRI data from 16 musically trained adults and 17 untrained controls, musically trained adults exhibited significantly strengthened connectivity between the left superior temporal gyrus and language-related areas, as well as between the right inferior frontal gyrus and areas involved in binding sensory and motor information. As the study design precludes definitive conclusions about the direction of causality, further investigation is needed to confirm that the enhanced functional connectivity in musically trained adults results from, rather than predates, musical training.

Transfer effects

The question remains as to whether or not arts interventions, such as music training, transfer to other domains such as creativity. In a comprehensive review of the effects of arts education on creativity, Winner, Goldstein, and Vincent-Lancrin (2013) found some evidence supporting assertions that theater and dance increase creativity. However, they found little evidence supporting a link between multi-arts or visual arts education and creativity, and no studies examining whether music education transfers to creativity. Importantly, the authors noted several possible reasons for this dearth of findings, including that the measures of creativity may be too limited. Again, we find that tests such as the TTCT, which primarily measure divergent thinking as a component of creativity, have been interpreted as singular measures of creativity itself. Further studies are needed to deepen our understanding of the connection between arts interventions and the development of creativity.

Other research has focused on the transfer of music training to other domains, such as intelligence and executive functioning. One study compared 144 six-year-olds randomized to four training groups: two intervention groups (keyboard and voice lessons) and two control groups (drama lessons and no lessons) (Schellenberg, 2004). With no significant differences pre-training, the combined intervention group demonstrated significantly higher post-training overall intelligence than the combined control group. In another study examining the effects of an interactive computerized training program, four- to six-year-old children were randomly assigned to either the music version or the visual art version of the program (Moreno et al., 2011). Following 20 days of training, only the children who participated in the music version demonstrated significantly better verbal intelligence, as measured by the vocabulary scores of the Wechsler Preschool and Primary Scale of Intelligence study. These changes were related to changes in brain plasticity induced during an executive functioning task, suggesting some transfer of music training to both verbal intelligence and executive functioning. Though caution should be taken not to overinterpret correlational results which link music training to executive functioning (see Mehr, Schachner, Katz, & Spelke, 2013), these results are suggestive of a domain-general (or transferable) impact of musical training.

Interestingly, certain interventions may have social transfer effects to qualities such as empathy. Musical group interaction (MGI), a setting in which two or more individuals play music together, was the focus of one such study. Investigators developed and implemented an MGI program, which aimed to maximize empathy-promoting musical components, such as movement and imitation with eight to eleven year old children over the course of one year. The results showed that children who received the program performed significantly better after the intervention than before, and performed significantly better after the intervention than children who did not receive the training (Rabinowitch, Cross, & Burnard, 2013). Results suggest that domain-specific interventions, such as music training, could result in gains that are not limited to auditory, motor, or executive functioning, but may generalize towards social effects as well.

Conclusions

In this chapter, we provided a neuroscientific overview of creativity research especially as it relates to the psychology of human strengths. We began by defining creativity and its subtypes and component processes. This was followed by a review of methods in neuroscience research, especially as they apply to creativity. Then we reviewed the cognitive and perceptual processes that underlie creativity, including divergent thinking, improvisation and flow, domain-specific knowledge and perceptual skills, and the social reception of creativity. This was followed by a review of some interventions that attempt to foster creativity through brain training.

Taken together, the best available evidence suggests that creativity depends on both structural and functional connectivity between areas of the brain that are involved in domain-specific and domain-general processing, such as between primary sensory areas and top-down regions in the frontal lobe. This structural and functional connectivity is crucial for integrating specific systems of processing in the brain, thus giving rise to interactions between perceptual and cognitive abilities that are necessary for innovation within one's skilled domain.

Directions for future research

Three questions for the future

1. How do we foster creativity across multiple environments, while reconciling potentially conflicting results from contemporary research?
2. Which components of creativity are domain-general, and which are domain-specific?
3. How might an understanding of neural connectivity be useful in targeting interventions for creativity?

Although the importance of connectivity in creativity is clear, many issues remain to be resolved. Firstly, the degrees of overlap between different tests of creativity are as yet unclear: we know little, for instance, about whether (or how much) the Torrance Tests of Creative Thinking might overlap with the Welsh Figure Preferences Test. Secondly, much of the directionality between specific findings – such as alpha-level differences in EEG and default mode network differences in fMRI – remains unclear, with some research reporting increased alpha and/or increased default mode connectivity in creative individuals, and other studies indicating opposite patterns. Compounding these unresolved issues, it remains to be seen whether the general approach of cross-sectional studies in creativity (i.e. testing for individual differences in creativity, and their correlations in the brain) will yield convergent results with longitudinal studies (i.e. testing for effects of interventions on the brain). While longitudinal and cross-sectional studies seem to be complementary approaches, the added scientific value of controlled interventions (whether domain-general or domain-specific) lies in their ability to raise the tested assumptions from a correlational level to a causal level. In the realm of creativity research especially, future work on interventions will also carry the social importance of encouraging growth among individuals, in order to achieve greater generativity and agency in their lives. By studying the neural underpinnings of creative behaviors, thoughts, and personalities, we hope not only to gain a deeper understanding of everyday and extraordinary creativity, but also to contribute to an integrative effort to cultivate creativity and thus foster human flourishing.

References

Amabile, T. M. (1982). Social psychology of creativity: A consensual assessment technique. *Journal of Personality and Social Psychology, 43*(5), 997-1013.

Amabile, T. M. (1983). The social psychology of creativity: A componential conceptualization. *Journal of Personality and Social Psychology, 45*(2), 357-376.

Amabile, T. M. (1996). *Creativity in context: Update to "The Social Psychology of Creativity."*. Boulder, CO, US: Westview Press.

Andreasen, N. C. (1987). Creativity and mental illness: Prevalence rates in writers and their first-degree relatives. *The American Journal of Psychiatry, 144*(10), 1288-1292.

Annamma Joy, & John F. Sherry, Jr. (2003). Speaking of Art as Embodied Imagination: A Multisensory Approach to Understanding Aesthetic Experience. *Journal of Consumer Research, 30*(2), 259-282.

Antonenko, D., Lindenberg, R., Hetzer, S., Ulm, L., Avirame, K., Flaisch, T., . . . Meinzer, M. (2013). Transkranielle gleichstromstimulation verbessert kognitive leistung und moduliertfunktionelle hirnaktivität und konnektivität. [Transcranial direct current stimulation improves cognitive performance and modulates functional task-specific activation and connectivity.]. *Klinische Neurophysiologie, 44*(3), 204-208.

Arnheim, R. (1966). *Toward a psychology of art: Collected essays*: Univ of California Press.

Au, J., Sheehan, E., Tsai, N., Duncan, G. J., Buschkuehl, M., & Jaeggi, S. M. (2014). Improving fluid intelligence with training on working memory: A meta-analysis. *Psychonomic Bulletin & Review*, No Pagination Specified.

Aziz-Zadeh, L., Kaplan, J. T., & Iacoboni, M. (2009). "Aha!": The neural correlates of verbal insight solutions. *Hum Brain Mapp, 30*(3), 908-916.

Babbitt, M. (1958). Who cares if you listen? *High Fidelity, 8*(2), 38-40.

Baer, J. (2008). Commentary: Divergent thinking tests have problems, but this is not the solution. *Psychology of Aesthetics, Creativity, and the Arts, 2*(2), 89-92.

Baer, J., & Kaufman, J. C. (2005). Bridging Generality and Specificity: The Amusement Park Theoretical (APT) Model of Creativity. *Roeper Review: A Journal on Gifted Education, 27*(3), 158-163.

Baer, J., & McKool, S. S. (2009). Assessing Creativity Using the Consensual Assessment Technique. In C. S. Schreiner (Ed.), *Handbook of Research on Assessment Technologies, Methods, and Applications in Higher Education*. Guam: University of Guam.

Baird, B., Smallwood, J., Mrazek, M. D., Kam, J. W., Franklin, M. S., & Schooler, J. W. (2012). Inspired by Distraction: Mind Wandering Facilitates Creative Incubation. *Psychol Sci*.

Barron, F., & Welsh, G. S. (1952). Artistic perception as a possible factor in personality style: Its measurement by a figure preference test. *Journal of Psychology, 33*, 199.

Beaty, R. E., Benedek, M., Wilkins, R. W., Jauk, E., Fink, A., Silvia, P. J., . . . Neubauer, A. C. (2014). Creativity and the default network: A functional connectivity analysis of the creative brain at rest. *Neuropsychologia, 64C*, 92-98.

Bechtereva, N. P., Korotkov, A. D., Pakhomov, S. V., Roudas, M. S., Starchenko, M. G., & Medvedev, S. V. (2004). PET study of brain maintenance of verbal creative activity. *International Journal of Psychophysiology, 53*(1), 11-20.

Bengtsson, S. L., Csikszentmihalyi, M., & Ullen, F. (2007). Cortical Regions Involved in the Generation of Musical Structures during Improvisation in Pianists. *Journal of Cognitive Neuroscience, 19*(5), 830-842.

Berkowitz, A. L., & Ansari, D. (2008). Generation of novel motor sequences: the neural correlates of musical improvisation. *Neuroimage, 41*(2), 535-543.

Besançon, M., Lubart, T., & Barbot, B. (2013). Creative giftedness and educational opportunities. *Educational & Child Psychology, 30*(2), 79-88.

Boden, M. A. (1991). *The creative mind: Myths & mechanisms*. New York, NY, US: Basic Books.

Brown, S., & Pavlicevic, M. (1996). Clinical improvisation in creative music therapy: Musical aesthetic and interpersonal dimension. *The Arts in Psychotherapy, 23*(5), 397-405.

Calvo-Merino, B., Grèzes, J., Glaser, D. E., Passingham, R. E., & Haggard, P. (2006). Seeing or Doing? Influence of Visual and Motor Familiarity in Action Observation. *Current Biology, 16*(19), 1905-1910.

Campbell, D. T. (1960). Blind variation and selective retentions in creative thought as in other knowledge processes. *Psychological Review, 67*(6), 380-400.

Cappelletti, M., Gessaroli, E., Hithersay, R., Mitolo, M., Didino, D., Kanai, R., . . . Walsh, V. (2013). Transfer of cognitive training across magnitude dimensions achieved with

concurrent brain stimulation of the parietal lobe. *The Journal of Neuroscience, 33*(37), 14899-14907.
Carson, S. (2013). Creativity and Psychopathology: Shared Neurocognitive Vulnerabilities. *Neuroscience of Creativity*, 175-203.
Carson, S., Peterson, J. B., & Higgins, D. M. (2005). Reliability, Validity, and Factor Structure of the Creative Achievement Questionnaire. *Creativity Research Journal, 17*(1), 37-50.
Cerruti, C., & Schlaug, G. (2008). Anodal Transcranial Direct Current Stimulation of the Prefrontal Cortex Enhances Complex Verbal Associative Thought. *J Cogn Neurosci, 21*(10), 1980-1987.
Chan, A. S., Ho, Y.-C., & Cheung, M.-C. (1998). Music training improves verbal memory. *Nature, 396*(6707), 128.
Chen, Q., Yang, W., Li, W., Wei, D., Li, H., Lei, Q., . . . Qiu, J. (2014). Association of creative achievement with cognitive flexibility by a combined voxel-based morphometry and resting-state functional connectivity study. *Neuroimage, 102p2*, 474-483.
Christoff, K., Gordon, A. M., Smallwood, J., Smith, R., & Schooler, J. W. (2009). Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proc Natl Acad Sci U S A, 106*(21), 8719-8724.
Colom, R., Haier, R. J., Head, K., Álvarez-Linera, J., Quiroga, M. Á., Shih, P. C., & Jung, R. E. (2009). Gray matter correlates of fluid, crystallized, and spatial intelligence: Testing the P-FIT model. *Intelligence, 37*(2), 124-135.
Cropley, A. (2006). In Praise of Convergent Thinking. *Creativity Research Journal, 18*(3), 391-404.
Cropley, A. J. (2000). Defining and measuring creativity: Are creativity tests worth using? *Roeper Review: A Journal on Gifted Education, 23*(2), 72-79.
Cross, E. S., Kirsch, L., Ticini, L. F., & Schutz-Bosbach, S. (2011). The impact of aesthetic evaluation and physical ability on dance perception. *Front Hum Neurosci, 5*, 102.
Csikszentmihalyi, M. (1991). *Flow: The psychology of optimal experience* (Vol. 41): HarperPerennial New York.
Csikszentmihalyi, M. (1997). *Creativity: Flow and the psychology of discovery and invention*. New York, NY, US: HarperCollins Publishers.
Cytowic, R. E., & Eagleman, D. M. (2009). *Wednesday Is Indigo Blue: Discovering the Brain of Synesthesia*: MIT Press.
Dasgupta, S. (2011). Contesting (Simonton's) blind variation, selective retention theory of creativity. *Creativity Research Journal, 23*(2), 166-182.
Dietrich, A. (2004). The cognitive neuroscience of creativity. *Psychonomic Bulletin & Review, 11*(6), 1011-1026.
Dietrich, A., & Kanso, R. (2010). A review of EEG, ERP, and neuroimaging studies of creativity and insight. *Psychol Bull, 136*(5), 822-848.
Donnay, G. F., Rankin, S. K., Lopez-Gonzalez, M., Jiradejvong, P., & Limb, C. J. (2014). Neural Substrates of Interactive Musical Improvisation: An fMRI Study of 'Trading Fours' in Jazz. *PLoS ONE, 9*(2), e88665.
Ellamil, M., Dobson, C., Beeman, M., & Christoff, K. (2012). Evaluative and generative modes of thought during the creative process. *Neuroimage, 59*(2), 1783-1794.
Eysenck, H. J. (1993). Creativity and Personality: Suggestions for a Theory. *Psychological Inquiry, 4*(3), 147-178.

Eysenck, H. J. (1997). Creativity and Personality. In M. A. Runco (Ed.), *The Creativity Research Handbook* (Vol. 1, pp. 41-66). Cresskill, NJ: Hampton Press, Inc.

Fauvel, B., Groussard, M., Chételat, G., Fouquet, M., Landeau, B., Eustache, F., . . . Platel, H. (2014). Morphological brain plasticity induced by musical expertise is accompanied by modulation of functional connectivity at rest. *NeuroImage, 90*, 179-188.

Fink, A., & Benedek, M. (2012). Eeg alpha power and creative ideation. *Neuroscience and Biobehavioral Reviews, 44*, 111-123.

Fink, A., Grabner, R. H., Benedek, M., & Neubauer, A. C. (2006). Divergent thinking training is related to frontal electroencephalogram alpha synchronization. *Eur J Neurosci, 23*(8), 2241-2246.

Fink, A., Grabner, R. H., Gebauer, D., Reishofer, G., Koschutnig, K., & Ebner, F. (2010). Enhancing creativity by means of cognitive stimulation: Evidence from an fMRI study. *NeuroImage, 52*(4), 1687-1695.

Flaherty, A. W. (2005). Frontotemporal and dopaminergic control of idea generation and creative drive. *J Comp Neurol, 493*(1), 147-153.

Fletcher, P. T., Whitaker, R. T., Tao, R., DuBray, M. B., Froehlich, A., Ravichandran, C., . . . Lainhart, J. E. (2010). Microstructural connectivity of the arcuate fasciculus in adolescents with high-functioning autism. *NeuroImage, 51*(3), 1117-1125.

Fox, M. D., Snyder, A. Z., Vincent, J. L., Corbetta, M., Van Essen, D. C., & Raichle, M. E. (2005). The human brain is intrinsically organized into dynamic, anticorrelated functional networks. *Proceedings of the National Academy of Sciences of the United States of America, 102*(27), 9673-9678.

Fugate, C. M., Zentall, S. S., & Gentry, M. (2013). Creativity and working memory in gifted students with and without characteristics of attention deficit hyperactive disorder: Lifting the mask. *Gifted Child Quarterly, 57*(4), 234-246.

Gabora, L. (2011). An analysis of the blind variation and selective retention theory of creativity. *Creativity Research Journal, 23*(2), 155-165.

Gillham, J. E., & Seligman, M. E. P. (1999). Footsteps on the road to a positive psychology. *Behaviour Research and Therapy, 37*, S163-S173.

Grossenbacher, P. G., & Lovelace, C. T. (2001). Mechanisms of synesthesia: cognitive and physiological constraints. *Trends Cogn Sci, 5*(1), 36-41.

Guilford, J. (1967). *The Nature of Human Intelligence*. New York: McGraw-Hill.

Hanggi, J., Wotruba, D., & Jancke, L. (2011). Globally altered structural brain network topology in grapheme-color synesthesia. *The Journal of neuroscience : the official journal of the Society for Neuroscience, 31*(15), 5816-5828.

Hassler, M., Nieschlag, E., & de la Motte, D. (1990). Creative musical talent, cognitive functioning, and gender: Psychobiological aspects. *Music Perception, 8*(1), 35-48.

Holmes, J., Gathercole, S. E., Place, M., Dunning, D. L., Hilton, K. A., & Elliott, J. G. (2010). Working memory deficits can be overcome: Impacts of training and medication on working memory in children with ADHD. *Applied Cognitive Psychology, 24*(6), 827-836.

Horn, J. L., & Cattell, R. B. (1967). Age Differences in Fluid and Crystallized Intelligence. *Acta Psychologica, 26*(2), 107-129.

Howard-Jones, P. A., Blakemore, S. J., Samuel, E. A., Summers, I. R., & Claxton, G. (2005). Semantic divergence and creative story generation: an fMRI investigation. *Brain Res Cogn Brain Res, 25*(1), 240-250.

Hui, A., & Lau, S. (2006). Drama education: A touch of the creative mind and communicative-expressive ability of elementary school children in Hong Kong. *Thinking Skills and Creativity, 1*(1), 34-40.

Hunsaker, S. L., & Callahan, C. M. (1995). Creativity and giftedness: Published instrument uses and abuses. *Gifted Child Quarterly, 39*(2), 110-114.

Hyde, K. L., Lerch, J., Norton, A., Forgeard, M., Winner, E., Evans, A. C., & Schlaug, G. (2009). Musical training shapes structural brain development. *The Journal of Neuroscience, 29*(10), 3019-3025.

Jamison, K. R. (1996). *Touched with fire*: Simon and Schuster.

Janata, P., Tomic, S. T., & Haberman, J. M. (2012). Sensorimotor coupling in music and the psychology of the groove. *J Exp Psychol Gen, 141*(1), 54-75.

Jauk, E., Benedek, M., Dunst, B., & Neubauer, A. C. (2013). The relationship between intelligence and creativity: New support for the threshold hypothesis by means of empirical breakpoint detection. *Intelligence, 41*(4), 212-221.

Jones, D. K. (2008). Studying connections in the living human brain with diffusion MRI. *Cortex, 44*(8), 936-952.

Joy, A., & Sherry Jr, J. F. (2003). Speaking of art as embodied imagination: A multisensory approach to understanding aesthetic experience. *Journal of Consumer Research, 30*(2), 259-282.

Jung, R. E., Gasparovic, C., Chavez, R. S., Flores, R. A., Smith, S. M., Caprihan, A., & Yeo, R. A. (2009). Biochemical Support for the "Threshold" Theory of Creativity: A Magnetic Resonance Spectroscopy Study. *J. Neurosci., 29*(16), 5319-5325.

Jung, R. E., & Haier, R. J. (2007). The Parieto-Frontal Integration Theory (P-FIT) of intelligence: converging neuroimaging evidence. *Behav Brain Sci, 30*(2), 135-154; discussion 154-187.

Jung, R. E., & Haier, R. J. (2013). Creativity and intelligence: Brain networks that link and differentiate the expression of genius *Neuroscience of creativity.* (pp. 233-254): MIT Press, Cambridge, MA.

Jung, R. E., Mead, B. S., Carrasco, J., & Flores, R. A. (2013). The structure of creative cognition in the human brain. *Frontiers in Human Neuroscience, 7*.

Jung-Beeman, M., Bowden, E. M., Haberman, J., Frymiare, J. L., Arambel-Liu, S., Greenblatt, R., . . . Kounios, J. (2004). Neural activity when people solve verbal problems with insight. *PLoS Biol, 2*(4), E97.

Kadosh, R. C., Levy, N., O'Shea, J., Shea, N., & Savulescu, J. (2012). The neuroethics of non-invasive brain stimulation. *Current Biology, 22*(4), R108-R111.

Kaufman, J. C. (2005). The Door That Leads Into Madness: Eastern European Poets and Mental Illness. *Creativity Research Journal, 17*(1), 99-103.

Kaufman, J. C., & Beghetto, R. A. (2009). Beyond big and little: The four c model of creativity. *Review of General Psychology, 13*(1), 1-12.

Kaufman, J. C., & Sternberg, R. J. (2010). Preface. In J. C. Kaufman & R. J. Sternberg (Eds.), *Cambridge Handbook of Creativity* (pp. xiii-xv). New York: Cambridge University Press.

Khan, S., Gramfort, A., Shetty, N. R., Kitzbichler, M. G., Ganesan, S., Moran, J. M., . . . Kenet, T. (2013). Local and long-range functional connectivity is reduced in concert in autism spectrum disorders. *PNAS Proceedings of the National Academy of Sciences of the United States of America, 110*(8), 3107-3112.

Klingberg, T. (2006). Development of a superior frontal-intraparietal network for visuo-spatial working memory. *Neuropsychologia, 44*(11), 2171-2177.

Klingberg, T. (2010). Training and plasticity of working memory. *Trends in Cognitive Sciences, 14*(7), 317-324.

Kounios, J., & Beeman, M. (2014). The cognitive neuroscience of insight. *Annual Review of Psychology, 65*, 71-93.

Kounios, J., Frymiare, J. L., Bowden, E. M., Fleck, J. I., Subramaniam, K., Parrish, T. B., & Jung-Beeman, M. (2006). The prepared mind: neural activity prior to problem presentation predicts subsequent solution by sudden insight. *Psychol Sci, 17*(10), 882-890.

Kundu, B., Sutterer, D. W., Emrich, S. M., & Postle, B. R. (2013). Strengthened effective connectivity underlies transfer of working memory training to tests of short-term memory and attention. *The Journal of Neuroscience, 33*(20), 8705-8715.

Kyaga, S., Landén, M., Boman, M., Hultman, C. M., Långström, N., & Lichtenstein, P. (2013). Mental illness, suicide and creativity: 40-year prospective total population study. *Journal of Psychiatric Research, 47*(1), 83-90.

Lavric, A., Forstmeier, S., & Rippon, G. (2000). Differences in working memory involvement in analytical and creative tasks: An ERP study. *NeuroReport: For Rapid Communication of Neuroscience Research, 11*(8), 1613-1618.

Lee, C. S., & Therriault, D. J. (2013). The cognitive underpinnings of creative thought: A latent variable analysis exploring the roles of intelligence and working memory in three creative thinking processes. *Intelligence, 41*(5), 306-320.

Lerdahl, F. (1992). Cognitive Constraints on Compositional Systems. *Contemporary Music Review, 6*(2), 97-121.

Ligon, G. S., Harris, D. J., & Hunter, S. T. (2012). Quantifying leader lives: What historiometric approaches can tell us. *The Leadership Quarterly, 23*(6), 1104-1133.

Limb, C. J., & Braun, A. R. (2008). Neural substrates of spontaneous musical performance: an FMRI study of jazz improvisation. *PLoS One, 3*(2), e1679.

Liu, S., Chow, H. M., Xu, Y., Erkkinen, M. G., Swett, K. E., Eagle, M. W., . . . Braun, A. R. (2012). Neural correlates of lyrical improvisation: an FMRI study of freestyle rap. *Sci Rep, 2*, 834.

Loui, P. (2014). Absolute Pitch. In S. Hallam, I. Cross & M. Thaut (Eds.), *Oxford Handbook of Music Psychology*: Oxford University Press.

Loui, P., Li, H. C., Hohmann, A., & Schlaug, G. (2011). Enhanced Connectivity in Absolute Pitch Musicians: A Model of Hyperconnectivity. *Journal of Cognitive Neuroscience 23*(4), 1015-1026.

Loui, P., Zamm, A., & Schlaug, G. (2012). Enhanced functional networks in absolute pitch. *Neuroimage, 63*(2), 632-640.

Luo, J., & Niki, K. (2003). Function of Hippocampus in "Insight" of Problem Solving. *Hippocampus, 13*(3), 316-323.

MacDonald, R., Byrne, C., & Carlton, L. (2006). Creativity and flow in musical composition: an empirical investigation. *Psychology of Music, 34*(3), 292-306.

Mason, M. F., Norton, M. I., Van Horn, J. D., Wegner, D. M., Grafton, S. T., & Macrae, C. N. (2007). Wandering minds: the default network and stimulus-independent thought. *Science, 315*(5810), 393-395.

McPherson, M., & Limb, C. J. (2013). Difficulties in the neuroscience of creativity: jazz improvisation and the scientific method. *Ann N Y Acad Sci, 1303*, 80-83.
Mehr, S. A., Schachner, A., Katz, R. C., & Spelke, E. S. (2013). Two randomized trials provide no consistent evidence for nonmusical cognitive benefits of brief preschool music enrichment. *PLoS One, 8*(12), e82007.
Moran, J. D. I., Milgram, R. M., Sawyers, J. K., & Fu, V. R. (1983). Original Thinking in Preschool Children. *Child Development, 54*(4), 921-926.
Moreno, S., Bialystok, E., Barac, R., Schellenberg, E. G., Cepeda, N. J., & Chau, T. (2011). Short-term music training enhances verbal intelligence and executive function. *Psychological Science, 22*(11), 1425-1433.
Mottron, L., Dawson, M., & Soulieres, I. (2009). Enhanced perception in savant syndrome: patterns, structure and creativity. *Philos Trans R Soc Lond B Biol Sci, 364*(1522), 1385-1391.
Mulvenna, C. M. (2007). Synaesthesia, the arts and creativity: a neurological connection. *Front Neurol Neurosci, 22*, 206-222.
Münte, T. F., Altenmuller, E., & Jäncke, L. (2002). The musicians brain as a model of neuroplasticity. *Nature Reviews Neuroscience, 3*, 473-478.
Novembre, G., & Keller, P. E. (2014). A Conceptual Review on Action-Perception Coupling in the Musicians' Brain: What Is It Good for? *Frontiers in Human Neuroscience, 8*.
Novick, L. R., & Sherman, S. J. (2003). On the nature of insight solutions: Evidence from skill differences in anagram solution. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 56A*(2), 351-382.
Nusbaum, E. C., & Silvia, P. J. (2011). Are intelligence and creativity really so different?: Fluid intelligence, executive processes, and strategy use in divergent thinking. *Intelligence, 39*(1), 36-45.
Oleson, P. J., Westerberg, H., & Klingberg, T. (2004). Increased prefrontal and parietal brain activity after training of working memory. *Nature Neuroscience, 7*(1), 75-79.
Pannells, T. C., & Claxton, A. F. (2008). Happiness, creative ideation, and locus of control. *Creativity Research Journal, 20*(1), 67-71.
Pariyadath, V., Plitt, M. H., Churchill, S. J., & Eagleman, D. M. (2012). Why overlearned sequences are special: distinct neural networks for ordinal sequences. *Front Hum Neurosci, 6*, 328.
Parkhurst, H. B. (1999). Confusion, lack of consensus and the definition of creativity as a construct. *The Journal of Creative Behavior, 33*(1), 1-21.
Pinho, A. L., de Manzano, O., Fransson, P., Eriksson, H., & Ullen, F. (2014). Connecting to Create: Expertise in Musical Improvisation Is Associated with Increased Functional Connectivity between Premotor and Prefrontal Areas. *J Neurosci, 34*(18), 6156-6163.
Plucker, J. A. (2004). Generalization of creativity across domains: Examination of the method effect hypothesis. *The Journal of Creative Behavior, 38*(1), 1-12.
Plucker, J. A., & Beghetto, R. A. (2004). Why Creativity Is Domain General, Why It Looks Domain Specific, and Why the Distinction Does Not Matter. In R. J. Sternberg, E. L. Grigorenko & J. L. Singer (Eds.), *Creativity: From potential to realization* (pp. 153-167). Washington, DC, US: American Psychological Association.
Polanía, R., Nitsche, M. A., & Paulus, W. (2011). Modulating functional connectivity patterns and topological functional organization of the human brain with transcranial direct current stimulation. *Human Brain Mapping, 32*(8), 1236-1249.

Pring, L., Ryder, N., Crane, L., & Hermelin, B. (2012). Creativity in savant artists with autism. *Autism, 16*(1), 45-57.

Rabinowitch, T.-C., Cross, I., & Burnard, P. (2013). Long-term musical group interaction has a positive influence on empathy in children. *Psychology of Music, 41*(4), 484-498.

Ramachandran, V. S., Hubbard, E. M., Butcher, P. A., Calvert, G. A., Spence, C., & Stein, B. E. (2004). Synesthesia, Cross-Activation, and the Foundations of Neuroepistemology *The handbook of multisensory processes.* (pp. 867-883). Cambridge, MA US: MIT Press.

Rothenberg, A. (1985). Review of Genius, Creativity and Leadership. Historiometric Inquiries by Keith Simonton. *Political Psychology, 6*(4), 733-736.

Rouw, R., & Scholte, H. S. (2007). Increased structural connectivity in grapheme-color synesthesia. *Nature Neuroscience, 10*(6), 792-797.

Runco, M. A. (1991). *Divergent thinking*. Westport, CT US: Ablex Publishing.

Runco, M. A., & Jaeger, G. J. (2012). The Standard Definition of Creativity. *Creativity Research Journal, 24*(1), 92-96.

Ryman, S. G., van den Heuvel, M. P., Yeo, R. A., Caprihan, A., Carrasco, J., Vakhtin, A. A., . . . Jung, R. E. (2014). Sex differences in the relationship between white matter connectivity and creativity. *Neuroimage, 101C*, 380-389.

Sawyers, J. K., & Canestaro, N. C. (1989). Creativity and achievement in design coursework. *Creativity Research Journal, 2*(1-2), 126-133.

Schellenberg, E. G. (2004). Music Lessons Enhance IQ. *Psychological Science, 15*(8), 511-514.

Schellenberg, E. G., & Moreno, S. (2010). Music lessons, pitch processing, and g. *Psychology of Music, 38*(2), 209-221.

Schlaug, G., Forgeard, M., Zhu, L., Norton, A., Norton, A., & Winner, E. (2009). Training-induced Neuroplasticity in Young Children. *Annals of the New York Academy of Sciences, 1169*(1), 205-208.

Schlaug, G., Norton, A., Overy, K., & Winner, E. (2005). Effects of Music Training on the Child's Brain and Cognitive Development. In G. Avanzini, L. Lopez, S. Koelsch & M. Manjno (Eds.), *The neurosciences and music II: From perception to performance* (pp. 219-230). New York, NY, US: New York Academy of Sciences.

Schlesinger, J. (2009). Creative mythconceptions: A closer look at the evidence for the "mad genius" hypothesis. *Psychology of Aesthetics, Creativity, and the Arts, 3*(2), 62-72.

Scott, G., Leritz, L. E., & Mumford, M. D. (2004). Types of creativity training: Approaches and their effectiveness. *The Journal of Creative Behavior, 38*(3), 149-179.

Seligman, M. E., & Csikszentmihalyi, M. (2000). *Positive psychology: An introduction* (Vol. 55): American Psychological Association.

Seligman, M. E. P. (2011). *Flourish: A visionary new understanding of happiness and well-being*. New York, NY, US: Free Press.

Silvia, P. J., Beaty, R. E., & Nusbaum, E. C. (2013). Verbal fluency and creativity: General and specific contributions of broad retrieval ability (Gr) factors to divergent thinking. *Intelligence, 41*(5), 328-340.

Silvia, P. J., & Kaufman, J. C. (2010). Creativity and mental illness. In J. C. Kaufman & R. J. Sternberg (Ed.), *The Cambridge handbook of creativity* (pp. 381-394). New York, NY, US: Cambridge University Press.

Silvia, P. J., Wigert, B., Reiter-Palmon, R., & Kaufman, J. C. (2012). Assessing creativity with self-report scales: A review and empirical evaluation. *Psychology of Aesthetics, Creativity, and the Arts, 6*(1), 19-34.

Simonton, D. K. (1990). *Psychology, science, and history: An introduction to historiometry*. New Haven, CT, US: Yale University Press.

Simonton, D. K. (1999). Creativity as blind variation and selective retention: Is the creative process Darwinian? *Psychological Inquiry, 10*(4), 309-328.

Simonton, D. K. (2002). Creativity. In C. R. Snyder & S. J. Lopez (Ed.), *Handbook of positive psychology* (pp. 189-201). New York, NY, US: Oxford University Press.

Simonton, D. K. (2003). Expertise, competence, and creative ability: The perplexing complexities. In R. J. Sternberg & E. L. Grigorenko (Ed.), *The psychology of abilities, competencies, and expertise* (pp. 213-238). New York, NY, US: Cambridge University Press.

Simonton, D. K. (2011). Creativity and discovery as blind variation: Campbell's (1960) BVSR model after the half-century mark. *Review of General Psychology, 15*(2), 158.

Simonton, D. K. (2013a). Creative thought as blind variation and selective retention: Why creativity is inversely related to sightedness. *Journal of Theoretical and Philosophical Psychology, 33*(4), 253-266.

Simonton, D. K. (2013b). What is a creative idea? Little-c versus Big-C creativity. In K. Thomas & J. Chan (Eds.), *Handbook of Research on Creativity* (pp. 69-83). Cheltenham, UK: Edward Elgar.

Simonton, D. K. (2014a). The mad-genius paradox: Can creative people be more mentally healthy but highly creative people more mentally ill? *Perspectives on Psychological Science, 9*(5), 470-480.

Simonton, D. K. (2014b). More method in the mad-genius controversy: A historiometric study of 204 historic creators. *Psychology of Aesthetics, Creativity, and the Arts, 8*(1), 53-61.

Smith, G. J., & Amner, G. (1997). Creativity and perception. In M. A. Runco (Ed.), *Creativity research handbook* (Vol. 1, pp. 67-82). Cambridge, England: Cambridge University Press.

Smith, G. J. W., Carlsson, I., & Andersson, G. (1989). Creativity and the subliminal manipulation of projected self-images. *Creativity Research Journal, 2*(1-2), 1-16.

Starchenko, M. G., Bekhtereva, N. P., Pakhomov, S. V., & Medvedev, S. V. (2003). Study of the Brain Organization of Creative Thinking. *Human Physiology, 29*(5), 652-653.

Stein, M. I. (1953). Creativity and culture. *The Journal of Psychology: Interdisciplinary and Applied, 36*, 311-322.

Sternberg, R. J. (1999). Darwinian creativity as a conventional religious faith. *Psychological Inquiry, 10*(4), 357-359.

Sternberg, R. J., & Lubart, T. I. (1999). The concept of creativity: Prospects and paradigms *Handbook of creativity* (pp. 3-15). New York, NY, US: Cambridge University Press.

Sternberg, R. J., Lubart, T. I., Kaufman, J. C., & Pretz, J. E. (2005). Creativity. In K. J. Holyoak & R. G. Morrison (Eds.), *The Cambridge handbook of thinking and reasoning* (Vol. 137, pp. 351-369): Cambridge University Press Cambridge.

Stupacher, J., Hove, M. J., Novembre, G., Schutz-Bosbach, S., & Keller, P. E. (2013). Musical groove modulates motor cortex excitability: A TMS investigation. *Brain Cogn, 82*(2), 127-136.

Takeuchi, H., Taki, Y., Hashizume, H., Sassa, Y., Nagase, T., Nouchi, R., & Kawashima, R. (2012). The association between resting functional connectivity and creativity. *Cereb Cortex, 22*(12), 2921-2929.

Tamannaeifar, M. R., & Motaghedifard, M. (2014). Subjective well-being and its sub-scales among students: The study of role of creativity and self-efficacy. *Thinking Skills and Creativity, 12*, 37-42.
Torrance, E. P. (1968). Examples and Rationales of Test Tasks for Assessing Creative Abilities. *The Journal of Creative Behavior, 2*(3), 165-178.
Ukkola-Vuoti, L., Kanduri, C., Oikkonen, J., Buck, G., Blancher, C., Raijas, P., . . . Jarvela, I. (2013). Genome-wide copy number variation analysis in extended families and unrelated individuals characterized for musical aptitude and creativity in music. *PLoS ONE, 8*(2), e56356.
Vartanian, O. (2013). Fostering creativity: Insights from neuroscience. In O. Vartanian, A. S. Bristol & J. C. Kaufman (Eds.), *Neuroscience of creativity* (pp. 257-271). Cambridge, MA, US: MIT Press.
Vessey, W. B., Barrett, J. D., Mumford, M. D., Johnson, G., & Litwiller, B. (2014). Leadership of highly creative people in highly creative fields: A historiometric study of scientific leaders. *The Leadership Quarterly, 25*(4), 672-691.
Vines, B. W., Norton, A. C., & Schlaug, G. (2011). Non-invasive brain stimulation enhances the effects of melodic intonation therapy. *Front Psychol, 2*, 230.
Waddell, C. (1998). Creativity and mental illness: Is there a link? *The Canadian Journal of Psychiatry / La Revue canadienne de psychiatrie, 43*(2), 166-172.
Wallach, M. A., & Kogan, N. (1965). *Modes of thinking in young children*: Holt, Rinehart and Winston: New York.
Ward, J., Thompson-Lake, D., Ely, R., & Kaminski, F. (2008). Synaesthesia, creativity and art: what is the link? *Br J Psychol, 99*(Pt 1), 127-141.
Ward, W. D. (1999). Absolute pitch. In D. Deutsch (Ed.), *The Psychology of Music* (pp. 265-298): Academic Press.
Wei, D., Yang, J., Li, W., Wang, K., Zhang, Q., & Qiu, J. (2014). Increased resting functional connectivity of the medial prefrontal cortex in creativity by means of cognitive stimulation. *Cortex, 51*, 92-102.
Winner, E. (1996). *Gifted children: Myths and realities*. New York, NY, US: Basic Books.
Winner, E., Goldstein, T. R., & Vincent-Lancrin, S. (2013). *Art for art's sake?: The impact of arts education*. Paris Cedex 16, France: OECD Publishing.
Yammarino, F. J., Mumford, M. D., Serban, A., & Shirreffs, K. (2013). Assassination and leadership: Traditional approaches and historiometric methods. *The Leadership Quarterly, 24*(6), 822-841.
Zamm, A., Schlaug, G., Eagleman, D. M., & Loui, P. (2013). Pathways to Seeing Music: Enhanced Structural Connectivity in Colored-Music Synesthesia. *NeuroImage, 74*, 359-366.
Zhou, I. Y., Liang, Y.-X., Chan, R. W., Gao, P. P., Cheng, J. S., Hu, Y., . . . Wu, E. X. (2014). Brain resting-state functional MRI connectivity: Morphological foundation and plasticity. *NeuroImage, 84*, 1-10.