

A Review of EEG, ERP, and Neuroimaging Studies of Creativity and Insight

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Creativity is a cornerstone of what makes us human, yet the neural mechanisms underlying creative thinking are poorly understood. A recent surge of interest into the neural underpinnings of creative behavior has produced a banquet of data that is tantalizing but, considered as a whole, deeply self-contradictory. We review the emerging literature and take stock of several long-standing theories and widely held beliefs about creativity. A total of 72 experiments, reported in 63 articles, make up the core of the review. They broadly fall into 3 categories: divergent thinking, artistic creativity, and insight. Electroencephalographic studies of divergent thinking yield highly variegated results. Neuroimaging studies of this paradigm also indicate no reliable changes above and beyond diffuse prefrontal activation. These findings call into question the usefulness of the divergent thinking construct in the search for the neural basis of creativity. A similarly inconclusive picture emerges for studies of artistic performance, except that this paradigm also often yields activation of motor and temporoparietal regions. Neuroelectric and imaging studies of insight are more consistent, reflecting changes in anterior cingulate cortex and prefrontal areas. Taken together, creative thinking does not appear to critically depend on any single mental process or brain region, and it is not especially associated with right brains, defocused attention, low arousal, or alpha synchronization, as sometimes hypothesized. To make creativity tractable in the brain, it must be further subdivided into different types that can be meaningfully associated with specific neurocognitive processes.

Keywords: art, divergent thinking, music, right brain, prefrontal cortex

Creativity is the fountainhead of human civilizations. All progress and innovation depend on our ability to change existing thinking patterns, break with the present, and build something new. Given the central importance of this most extraordinary capacity of the human mind, one would think that the underlying neurocognitive mechanisms of creative thinking are the subject of intense research efforts in the behavioral and brain sciences. To study creative ideas, and how and where they arise in the brain, is to approach a defining element of what makes us human. Furthermore, by identifying the basic principles of our ingenuity, researchers might be able to enhance this process in the future, with potentially enormous benefits for society.

There are several reasons why neuroscientists did not tackle creativity with the same kind of resolve as they did, say, with attention, memory, or intelligence. The most important of these is surely the problem of finding a way to study the creative process, especially its neural basis, in the laboratory—under tightly controlled conditions. Clearly, one cannot simply take a volunteer,

shove him/her into the nearest brain scanner, and tell him/her: Now, please be creative! The same, one might think, holds for insights. An insight is so capricious, such a slippery thing to catch *in flagrante*, that it appears almost deliberately designed to defy empirical inquiry. To most neuroscientists, the prospect of looking for creativity in the brain must seem like trying to nail jelly to the wall.

It is perhaps no surprise, then, that the experimental study of creativity did not develop over the past 50 years like other areas of the psychological sciences—that is, relentlessly forward and upward. To clarify, there has been, no doubt, considerable progress in many areas of creativity research. Through surveys, case studies, historical records, or personality inventories, psychologists have amassed a large database about the creative process, from the traits and habits of individual geniuses to general patterns common to the career trajectories of all creators (e.g., Gardner, 1993; Simonton, 2003). Laboratory-based research on creativity, however, the mainstay of nearly all other domains in psychology, did not proliferate in the same way.

Early experimental work by Gestalt psychologists on insight aside (e.g., Wertheimer, 1945), creativity research is commonly said to have begun with Joy Paul Guilford's farewell address as president of the American Psychological Association in 1950. In this article, Guilford (1950) called for the study of creativity and backed his call to arms with a proposal on how to go about doing so, via the concept of divergent thinking.

The idea of *divergent thinking*, defined as the ability to generate multiple solutions to an open-ended problem (Guilford, 1967), was quickly taken up because it represented a method to bring a hitherto intractable problem into the folds of empirical science.

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Several standardized psychometric instruments of creativity were subsequently developed. The most popular of these tools, to this very day, include Torrance's (1974) Torrance Test of Creative Thinking, which is based on divergent thinking, and Mednick's (1962) Remote Associates Test, which is based on the related construct of associative hierarchies. A prototypical example of a divergent thinking task is the Alternative Uses Test (Guilford, 1967), which asks participants to generate alternative uses for, say, a brick or an automobile tire. The dependent variables of divergent thinking tasks, such as the Alternative Uses Test, are ideational fluency (i.e., the number of ideas), flexibility (i.e., the number of different types or categories of ideas), and novelty (or uniqueness/originality) of the ideas. Whereas ideational fluency and flexibility are variables that can simply be counted, the third variable, novelty, is commonly assessed with the so-called consensual method (Amabile, 1983), in which naïve judges rate the originality of the answers.

By tentatively distinguishing creative from noncreative (convergent, in this case) information processing, the construct of divergent thinking was an attempt to get an initial grip on the problem. In many ways, it was the kick start creativity research needed to get underway. However, from this rather promising beginning, in a development that even Guilford did not intend, this idea morphed from a first crack at this hard-to-pin down phenomenon into *the* standard conception of creativity, dominating theoretical and empirical work ever since. Once established, tests of divergent thinking became, for the sake of convenience, tests of creativity; and findings using these scales were often discussed, without badly needed qualifying remarks, as if applicable to creativity in general.

This practice of accepting divergent thinking as proxy for creative thinking has been strongly criticized (Dietrich, 2007b; Ward, Smith, & Finke, 1999). The problem is two-fold. First, it is obvious at a moment's reflection—and certainly was to Guilford himself—that creativity can just as well be the result of a convergent process. What would we otherwise make of Edison's assembly line, nearly algorithmic approach to inventing; Bach's methodical way of composing hundreds of cantatas; the imaginative ways in which National Aeronautics and Space Administration engineers solved the problems of the otherwise doomed Apollo 11 mission; or the countless creative solutions generated by systematically eliminating alternative possibilities?

This critique raises the following, rather obvious question: What, exactly, is it about divergent thinking that is creative? That divergent thinking can also generate nonnovel outcomes—and convergent thinking novel ones—renders it incapable of identifying the fundamental processes, cognitive or neural, that make information processing creative. In addition, divergent thinking is a compound construct. Because it consists of various different, and separate, mental processes, it cannot isolate the cognitive elements that turn ordinary thinking into creative thinking. This composite nature makes the construct all but intractable with current neuro-imaging tools.

This critique extends, without modification, to proposals of component stages of creativity. Take, for instance, the introspective hunch, first expressed by Wallas (1926), that the creative process consists of four stages: preparation, incubation, illumination, and verification. It should be obvious that stages such as preparation or verification (a) are also at work during "normal," noncreative thinking and (b) are compound constructs that lack a coherent theoretical notion as to the individual cognitive processes

they require. Despite these drawbacks, and perhaps because of a lack of alternatives, tests of divergent thinking, such as the Torrance Test of Creative Thinking and Remote Associates Test, are the most widely used methods for assessing creativity. More than half of all experiments reviewed in the present study exploit this paradigm.

There are, however, other avenues. In their search for the neural correlates of creativity, investigators have also made use of entirely different kinds of tasks. These tasks do not share a common underlying rationale but can perhaps best be categorized as neuroscientific studies on musical and artistic performance. One of the most remarkable features about the experiments fitting this broad paradigm is the innovative way in which the subject of creativity is approached. This alternative approach has had important yet underappreciated consequences for our understanding of the neural basis of creativity, particularly in terms of slowing the ever-present danger of treating creativity as a monolithic entity (Dietrich, 2007b). This problem arises most prominently in the divergent thinking literature, in which it is not uncommon for investigators to effectively equate divergent thinking with creativity and, on the basis of this sleight of hand, draw conclusions about creativity *per se*. Investigations of musical and artistic processes, such as free jazz composition, imagining a painting, or drawing an abstract concept, reveal that several of the theoretical distinctions that have dominated the field to date—for example, divergent versus convergent thinking, right versus left brain processing, and focused versus defocused attention—are too simplistic.

A third domain has also been invoked to help uncover the mechanisms underlying creative thinking: insight. Insight events are rightfully a subfield of creativity because the first step toward a finished creative product is, more often than not, a creative insight. Insight tasks are more narrowly defined than those of the other two domains, and they help reveal the full measure of how complex, varied, and multistep the neural mechanisms of creativity must be.

The current study reviews, for the first time, the entire literature that relates creativity to brain activity. The main goal is to take stock of several long-standing theories and widely held beliefs about creativity by evaluating their claims against the extant evidence. To do this properly, we adopted an approach that is theoretically neutral—that is, we assessed each theory on its own merit rather than from a competing conceptual perspective. There are two advantages to this method. First, there exists no sound, theoretical framework on the neural basis of creative thinking that we could use to guide the present review. Absent such a unifying framework, it is probably best to adopt a bottom-up, data-driven approach to reviewing the literature. Second, a theory should be evaluated against its own claims. There are many competing theories in the field, each with its own assumptions and *a priori* notions about creativity. Examining one theory by using the standards of another is not likely to yield unbiased assessments.

By reviewing the field, we hope to show that creativity, in all its forms, simply cannot be captured with any of the relatively coarse theoretical proposals currently in circulation, such as alpha synchrony, prefrontal activation, or low arousal. Conjectures such as these have survived, we believe, because the field is heavily fragmented. This fragmentation sets up a situation that permits isolated theories to be maintained by selectively citing those studies that support them, whereas there exist just as many data against

them. Only through systematically reviewing the evidence for different conceptions of creativity, we hold, can the temptation to appraise creativity as a single, simple mental process or brain region be overcome.

The Search Strategy

We reviewed neuroimaging and neuroelectric studies designed to investigate creativity and insight. The search strategy, along with the inclusion and exclusion criteria, was as follows. We attained all articles published in English claiming to investigate creativity and insight in conjunction with direct measures of brain activity, including (a) neuroimaging techniques—functional magnetic resonance imaging (fMRI), positron emission tomography (PET), single photon emission computed tomography (SPECT), and near-infrared spectroscopy (NIRS)—and (b) neuroelectric techniques—electroencephalography (EEG) and event-related potentials (ERP). Specifically, we searched the Web of Science, PubMed, PsycINFO, and other databases with Boolean operators using the following keywords: *creative, creativity, insight, innovation, drawing, music, designing, divergent thinking, art, and problem solving* along with *EEG, ERP, fMRI, SPECT, MRI, PET, NIRS, and imaging*.

This search yielded a large set of 1,910 articles that was then pruned using a consensual process according to the following selection criteria: If authors did not, even in passing, associate their work with creativity or insightful problem solving in the title or abstract, or did not (in the case of musical perception) examine behavioral expression, the study was excluded. We readily excluded, on the basis of this rule, over 90% of the initial selection of articles on art, music, and cognitive performance. However, as would be expected, borderline cases immediately presented themselves. For instance, we identified a large number of brain studies reporting on domains that are manifestly relevant to creative thinking, such as metaphorical reasoning, mental imagery, perceptual restructuring, the perception of music, or various processes involved in cognitive flexibility—set-shifting, planning, inhibition of existing knowledge, counterfactual thinking, or perseverance, to name prominent examples. Again, unless there was specific mention in the title or abstract of the keywords *creativity, creative thinking, hypothesis generation, aha effect, Eureka experience, novel ideas, original ideas, innovation, insight problem-solving, or insight*, we excluded these references. Similarly, we eliminated all studies from the initial set of articles that did not actually utilize neuroimaging techniques but based conclusions about the neural mechanism of creativity on brain abnormalities (such as dementia, stroke, or schizophrenia), pharmacological intervention (such as the use of ephedrine or lorazepam), or psychological disorders (such as bipolar disorder or the savant syndrome of autism). The reference lists of the final set of articles were also cross-checked for any additional articles that were then subjected to the same selection procedure.

Placing primacy on self-classification can, of course, be criticized. One could argue, for instance, that some studies included in the core set may actually involve little or no creativity, whereas other excluded studies on, say, mental imagery demonstratively do. However, we felt that such subjective judgments on our part would open the door to an indefensible slippery slope.

Using the above criteria, we gathered what we believe is a comprehensive list of brain imaging studies on creativity. In total, 72 experiments reported in 63 articles published until February 2010 were included in the review. Conspicuously, all but five of

these 63 articles were published after 2000, a striking testament to the sudden popularity of this research topic and to the recent development of some of the brain imaging strategies under review. We sorted articles into the three broad categories: (a) studies using the paradigm of divergent thinking, (b) studies investigating the cognition of art and music, and (c) studies looking at insight events. Other psychological research traditions—developmental, social, historiometric or even cognitive—feature many other approaches to creativity, but they have not made direct contact with neuroscientific paradigms and, as such, are beyond the scope of this article. We refer the reader to other reviews for this body of work (i.e., Runco, 2004).

Divergent Thinking

EEG and Divergent Thinking

EEG is a noninvasive measure of electrical brain activity. It is a record of electric field potentials, represented as changes in potential difference between different points on the scalp, which arise primarily from excitatory and inhibitory postsynaptic potentials. Although the EEG signal has been used for decades to limn the neurophysiological changes that accompany mental processes, it was not used to study aspects of creativity until the late 1990s, save for three reports by Martindale and colleagues (Martindale & Hasenfus, 1978; Martindale & Hines, 1975; Martindale, Hines, Mitchell, & Covello, 1984).

Several EEG parameters are relevant to this review. EEG data are reported in frequency ranges. At the low end of the scale is delta activity, which is a regular, low-amplitude wave of 1–5 Hz. This frequency band reflects a low neuronal firing rate and is mostly associated with deep sleep. Theta activity is a medium-amplitude, medium-frequency rhythm of 5–8 Hz. A person exhibiting this rhythm reports feeling drowsy. Alpha activity is a fairly regular pattern between 8 and 12 Hz. The alpha band is prominent when a person is minimally aroused—awake but relaxed. Beta activity, which is an irregular pattern between 12 and 30 Hz, occurs mostly during alertness and active thinking. Finally, there is the gamma rhythm, which represents oscillations around the 40 Hz mark that are associated with the binding of perceptual information. Changes to the EEG records are reported in terms of power and synchrony. EEG power is obtained by doing spectral analysis; it reflects the frequency content in an electrode. EEG synchrony is a reflection of how the signals from different electrodes are related to each other. Power changes in time-locked events are known as event-related synchronization (ERS) and event-related desynchronization (ERD; Pfurtscheller & Lopes da Silva, 1999). Synchrony is used to indicate synchronous activity between pairs of electrodes that is independent of spectral power or amplitude.

ERP is EEG recorded in response to external stimuli. Stimulus-locked ERPs are usually much smaller in amplitude than EEG and are described in terms of their characteristic scalp distribution, polarity, and latency. The ERP record yields several components that provide information about different cognitive processes. The prominent P300, for instance, is a positive deflection occurring 300 ms after stimulus presentation; it is thought to reflect attentional resource allocation and cognitive processing speed. The N200, on the other hand, is a negative deflection 200 ms post stimulus onset and may reflect response inhibition. In creativity research, only insight studies have thus far made use of this technique.

The first part of Table 1 summarizes the findings from EEG creativity studies using the divergent thinking paradigm. To date, no ERP studies have been published in this domain of creativity research. An initial scan of this literature is sufficient to see the challenge of distilling the existing data into any sound conclusions. The findings from different studies are difficult to compare because (a) investigators have used a host of divergent thinking tests, including original measures that have not been replicated and for which standardization and validation data are lacking; (b) these divergent thinking tasks, as diverse as they already are, are then compared with a number of different control conditions; and (c) only a small fraction of the studies in this category use high-density EEG. These limitations should be kept in mind as conclusions are drawn from these data.

The data are summarized, for the sake of consistency, according to categories dominant in the EEG literature (see Table 1). This yields three main themes: (a) laterality, (b) changes to the alpha band, and (c) changes to all other frequencies.

The idea that creativity is a function, primarily or exclusively, of the right brain is surely the most popular theory on the neural basis of creativity in the wider public. However, duly sharpened versions of this idea have been seriously entertained in neuroscience as well (Bowden & Jung-Beeman, 2003; Jung-Beeman et al., 2004). EEG studies on divergent thinking do not confirm this contention. There are a few studies that can be recruited to support a special role for the right hemisphere in divergent thinking (Fink, Grabner, et al., 2009, Experiment 1; Fink & Neubauer 2006b; Grabner, Fink, & Neubauer, 2007; Jaušovec & Jaušovec, 2000a; Martindale & Hines, 1975; Martindale et al., 1984; Razumnikova, 2004). It should be noted, however, that the authors responsible for three of the seven articles cited above do not themselves interpret their data in this manner (Fink, Grabner, et al., 2009), and they do not believe the data should be used for this purpose (Fink, personal communication, March 10, 2008). Whereas only one study could possibly be drafted to claim the opposite, a left-brain theory of creativity as it were (Razumnikova, 2007), the majority of the investigations (14 in total), including those from authors cited above for possibly supporting right-brain dominance, lend no support to the right-brain theory (Bazanova & Aftanas, 2008; Danko, Shemyakina, Nagornova, & Starchenko, 2009; Fink, Grabner, Benedek, & Neubauer, 2006; Fink & Neubauer 2006a; Jaušovec, 2000; Jaušovec & Jaušovec, 2000b; Jin, Kwon, Jeong, Kwon, & Shin, 2006; Krug, Mölle, Dodt, Fehm, & Born, 2003; Martindale & Hasenfus, 1978; Mölle, Marshall, Wolf, Fehm, & Born, 1999; Razumnikova, 2004, 2005; Razumnikova, Volf, & Tarasova, 2009; Shemyakina & Danko, 2007). In sum, the EEG data on divergent thinking fail to substantiate the notion of lateralization in creativity for either cerebral hemisphere.

Another focus of interest in this literature is the alpha band because increases in power or synchrony at this frequency range have previously been taken to indicate low cortical arousal and defocused attention, two theoretical guideposts of empirical research (Martindale, 1999; Mendelsohn, 1976). This interpretation of alpha enhancement was primarily based on the understanding that alpha ERS reflects cortical deactivation (Pfurtscheller & Lopes da Silva, 1999), whereas ERD reflects cortical activation (Klimesch, 1999). Both interpretations have recently been revised, however (Klimesch, Sauseng, & Hanslmayr, 2007), which increases the challenge of understanding the functional meaning of EEG data. In addition, work on the alpha rhythm has also exposed the need to distinguish different subbands of this frequency because lower and upper alpha respond

differently, and at times in an opposing manner, to certain task parameters. Whereas low alpha appears to respond to various basic types of attentional demands, such as alertness and vigilance, higher alpha responds selectively to more specific task demands, primarily semantic memory processes (Klimesch et al., 2007).

Changes to alpha beyond that obtained in control tasks are indeed often observed when participants work on divergent thinking tests. The direction of this change, however, is not uniform. For frontal alpha, for instance, some investigators have reported increases in synchrony associated with divergent thinking (Fink et al., 2006; Fink, Grabner, et al., 2009; Grabner et al., 2007; Jaušovec, 2000; Razumnikova, 2004), although others have reported decreases (Jaušovec & Jaušovec, 2000b; Razumnikova, 2005, 2007; Razumnikova et al., 2009). This pattern also holds for power: Some investigations have shown increased alpha power at frontal sites (Bazanova & Aftanas, 2008; Fink & Neubauer, 2006a, 2006b; Jaušovec, 2000; Krug et al., 2003; Martindale & Hines, 1975; Martindale et al., 1984), others either have not reported significant increases (Martindale & Hasenfus, 1978) or have demonstrated the exact opposite—that is, divergent thinking is associated with higher theta, delta, and beta power but not alpha power (Danko et al., 2009; Mölle et al., 1999; Razumnikova, 2004, 2005, 2007; Shemyakina & Danko, 2007).

Examining the data in terms of subbands does not clarify the picture. Although several older studies have not reported lower alpha separate from higher, many have implicated both bands (e.g., Fink, Grabner, et al., 2009; Jaušovec, 2000; Razumnikova, 2005, 2007). Overall, however, slightly more studies have reported effects for lower alpha (Fink et al., 2006; Fink & Neubauer, 2006a; Grabner et al., 2007; Jaušovec & Jaušovec, 2000b; Razumnikova, 2007; Razumnikova et al., 2009) than upper alpha. What is most noticeable, however, is the lack of consistent creativity-related changes reported to frontal alpha in a majority of EEG divergent thinking studies. The lack of consistency across studies at this site, which holds in fact for all frequency bands, is surprising in light of the fact that neuroimaging studies of divergent thinking consistently implicate the prefrontal cortex.

The picture is similar for alpha at temporal or parietal sites. For synchrony, there are data showing increases (Fink & Neubauer 2006a), especially for the originality score (Fink, Grabner, et al., 2009), as well as decreases (Jaušovec & Jaušovec, 2000b; Razumnikova, 2007; Razumnikova et al., 2009; Shemyakina & Danko, 2007), with the vast majority of studies indicating no consistent change. Again, the lack of significant results in the majority of studies, along with the inconclusiveness of the data that does exist, is difficult to reconcile with the neuroimaging literature.

The data on all other frequency bands follow the same trend: They are spotty and contradictory. For the beta frequency, for instance, decreases in power have been described in all cortical areas (Krug et al., 2003; Shemyakina & Danko, 2007), but there are also studies that have described increases (Danko et al., 2009; Razumnikova, 2005, 2007). Some studies have found increases in beta ERS associated with divergent thinking at both frontal and parietal sites (Mölle et al., 1999; Razumnikova, 2004, 2005, 2007; Shemyakina & Danko, 2007). Overall, however, the single most common finding in this literature is the absence of significant changes to the beta frequency. Studies have also implicated other frequency bands, such as theta or delta, but such individual reports are infrequent and, at any rate, are rarely corroborated by a second study. Finally, there are no reports of consistent

Table 1
Summary of Creativity Studies Using the Divergent Thinking Paradigm

Study	N	Method	Type of creativity tests	Type of design	Main findings
Studies using EEG methods					
Martindale & Hines (1975)	32	EEG	DTT: RAT, AUT; CTT: IQ test	Within-task comparison and between-task comparison	High scorers on the AUT had higher basal alpha; high scorers on the RAT had the highest percentage of alpha during tests of creativity and lowest during IQ test. Creativity was associated with low cortical activation.
Martindale & Hasenfus (1978)	12 and 32	EEG	Creative inspiration and elaboration; Experiment 1: Creative story writing; Experiment 2: random vs. fantasy speech	Covariate (RAT, AUT), within-task comparison and between-task comparison	In two experiments, higher scorers had higher alpha indices during creative inspiration than during creative elaboration, which was not found for less creative participants. There was no correlation between creativity and basal EEG alpha.
Martindale et al. (1984), Experiment 1	24	EEG	Speech types: (a) random words, (b) sentences that are coherent but unrelated to next, (c) a meaningful story (fantasy speech)	Covariate (RAT, AUT), within-task comparison and between-task comparison	Higher scorers on the AUT and RAT had increased alpha indices (more time in alpha) over the right hemisphere. There was hemispheric asymmetry during creative activity.
Martindale et al. (1984), Experiment 2	38	EEG	Creating fantasy stories in response to Cards 1 and 11 of the TAT; inspirational stage (thinking of a plot) and an elaboration stage (writing the plot down)	Covariate (RAT, AUT), within-task comparison and between-task comparison	Higher scorers on the AUT and RAT showed higher left-hemispheric alpha amplitudes compared with the right hemisphere, whereas low scorers showed the opposite pattern. Creativity was related to hemispheric asymmetry.
Mölle et al. (1999)	30	EEG	DTT: (a) AUT, (b) unique consequences of a hypothetical situation, (c) think of funny similarities between two pictures, (d) unfinished pictures and what they could represent; CTT: four different tasks	Between-task comparison and task vs. rest	Higher theta, delta, and beta power on DTT compared with CTT or rest. DTT increased the dimensional complexity over frontal, central, and parietal areas compared with CTT and over central, parietal, and occipital areas compared with rest. Alpha power was highest during mental relaxation. Dimensional complexity was greater for DTT, which could be the result of the concurrent activation of a greater number of independently oscillating processing units.
Jaušovec (2000), Experiment 1	49	EEG	CTT: (a) changing the parking fee and frequency of bus departures and (b) the plan-a-day problem with different constraints	Covariate (IQ and TTCT) and task vs. rest	Highly intelligent participants had higher alpha power in frontal and central sites and more cooperation between brain areas. Highly creative S had higher cooperation between brain areas mainly in frontal areas. EEG was more influenced by IQ than by creativity.

Table 1 (continued)

Study	N	Method	Type of creativity tests	Type of design	Main findings
Jaušovec (2000), Experiment 2	48	EEG	DTT: verbal—(a) name things making noise, (b) AUT, (c) ways in which radio and telephone are alike; figural—unfinished pictures and what they could be; a dialectic task: write a text describing reason of war between fictional states	Covariate (IQ and TTCT) and task vs. rest	Highly creative participants displayed higher alpha power in frontal areas for DTT. Creative participants also showed more coherence between brain areas in frontal and parietal sites, whereas gifted ones showed greater decoupling of brain areas when solving ill-defined problems, especially in LH. Creativity and intelligence were posited to be different abilities that also differed in neurological activity.
Jaušovec & Jaušovec (2000a)	115	EEG	DTT: verbal—(a) name things that make noise, (b) AU for an automobile tire, (c) all ways in which radio and telephone are alike; figural—unfinished pictures and what they could be; WAIS IQ test	Covariate (IQ and TTCT) and task vs. rest (open and closed eyes)	Only weak correlations emerged between resting EEG and creativity scores; correlations with IQ scores were even less pronounced. There were some correlations between coherence and both creativity and IQ with open eyes; these were mainly negative and distributed over RH. Creativity showed less cooperation between brain areas, whereas intelligence showed more.
Jaušovec & Jaušovec (2000b), Experiment 2	30	EEG	Same as Jaušovec (2000), Experiment 2	Between-task comparison and task vs. rest	Power differences were mainly related to the form of problem presentation (figural/verbal). Coherence was related to the level of creativity. Figural DTT showed highest ERD in lower alpha, especially between left temporal and frontal sites in LH and between frontal, temporal, and parietal sites in RH. Creativity required broader cooperation between brain areas.
Razumnikova (2000)	36	EEG	DTT: how to measure the length of hundreds of poisonous snakes in the zoo; CTT: mental arithmetic	Within-task comparison, and task vs. rest	CTT and DTT induced desynchronization in the alpha band. Theta power decreases and coherence increases in beta for DTT. Each mode of thinking, CTT and DTT, showed different EEG patterns.
Krug et al. (2003)	24	EEG	DTT: unique consequences of a hypothetical situation; CTT: logical thinking and mental arithmetic	Covariate (menopausal women: placebo estrogen and testosterone), between-task comparison, and task vs. rest	For placebo, CTT showed lower alpha activity, and DTT showed lower beta power at central and parietal leads. Estrogen impaired DTT, enhanced CTT, and was accompanied by less dimensional complexity over right posterior regions. Testosterone effects were opposite: They increased performance and dimensional complexity. Estrogen induced a shift from a divergent to a convergent mode of processing.

(table continues)

Table 1 (continued)

Study	<i>N</i>	Method	Type of creativity tests	Type of design	Main findings
Razumnikova (2004)	63	EEG	Same as Razumnikova (2000)	Covariate (gender), within-task comparison, and task vs. rest	RH coherence increased in good performers and decreased for bad performers. DTT was associated with more cortical activity in RH for both genders. Men were characterized by greater hemispheric specialization and more pronounced inhibition of LH on RH.
Razumnikova (2005)	39	EEG	DTT: LFT, SAT, RAT	Covariate (gender), within-task comparison, and task vs. rest	Compared with rest and SAT, the RAT showed increased coherence in Theta 1 and Beta 2 as well as increases for Beta 2 power. Originality was positively correlated with intrahemispheric coherence of the Beta 2 rhythm in LH; the time needed for RAT was negatively correlated with interhemispheric coherence in posterior cortex. Both LH and RH contributed to creativity.
Jin et al. (2006)	50	EEG	(a) Lee & Jeong's (2002) test of creative thinking and (b) the quail egg (hypothesis generation) task: find a tentative explanation for why 20 eggs from the same quail have surface differences	Covariate (nongifted vs. gifted students) and within-task comparison	Gifted children showed increased amount of transmitted information between different time series values between the left temporal and central, between the left temporal and parietal, and between the left central and parietal sites while generating scientific hypotheses. High-ability participants developed strategies that made relatively greater use of parietal regions; low-ability participants relied more on frontal regions.
Fink et al. (2006)	30	EEG	DTT: Unusual problems requiring creative solutions—(a) Insight task, (b) utopian situations, and (c) the AUT; CTT: WE Task	Covariate (2 weeks DTT training), between-task comparison, and task vs. rest	The training group had (a) higher originality scores for DTT and worse scores for the CTT, (b) higher alpha ERS, and (c) higher power increases in anterior cortices and in right temporal and parietal sites. Divergent thinking was linked to low alpha power, which could reflect hypofrontality needed to produce novel ideas.
Fink & Neubauer (2006a)	31	EEG	DTT: Unusual problems requiring creative solutions—(a) Insight task and (b) utopian situations	Covariate (verbal IQ and gender) and task vs. rest	Creativity was accompanied by increases in alpha power. Higher originality was associated with a stronger task-related alpha ERS in posterior (particularly centroparietal) cortices. This was moderated by verbal IQ and gender. More alpha power in anterior regions reflected hypofrontality; the frontal brain must be downregulated to produce creative ideas.

Table 1 (continued)

Study	N	Method	Type of creativity tests	Type of design	Main findings
Fink & Neubauer (2006b)	34	EEG	Same as Fink et al. (2006)	Covariate (extra/introversion), between-task comparison, and task vs. rest	Extraversion was not correlated with originality. Extraverts producing highly original ideas had the highest alpha power, whereas introverts with less original ideas had the lowest. EEG alpha activity was stronger in RH. Extraverts who were highly original had lowest level of cortical arousal, and vice versa.
Razumnikova (2007)	39	EEG	DTT: RAT, SAT	Within-task comparison and task vs. rest	The RAT showed higher power and coherence in beta, increased theta power at frontal sites, and increased alpha ERDs over posterior and prefrontal leads. Originality was positively correlated with more coherence focused in the fronto-parietal regions of both hemispheres in beta and in left parietotemporal loci for Alpha 1.
Shemyakina & Danko (2007)	30	EEG	DTT: possible definitions differing in meaning of (a) emotionally positive, (b) negative, and (c) neutral nouns	Within-task comparison and task vs. rest	The creative task without emotional induction led to a local decrease in beta power in the left frontotemporal area and a coherence decrease in most cortical zones. Emotional induction had a much stronger effect on the state of the cortex than the creative task did.
Grabner et al. (2007)	26	EEG	DTT: unusual situations that need an explanation taken from the TTCT	Within-task comparison and task vs. rest	More original ideas elicited a stronger alpha ERS and higher phase coupling in RH. Originality was indexed in lower alpha.
Bazanova & Aftanas (2008)	98	EEG	DDT: TTCT nonverbal	Within-task comparison and task vs. rest	The maximum alpha activity peak frequency was not significantly correlated with creativity score. Originality showed a trend with lowest values for individual alpha peak frequencies.
Fink, Grabner, et al. (2009), Experiment 1	25	EEG	DDT: (a) AUT, (b) invent names belonging to abbreviations; CTT: (c) Think of characteristics of normal objects, (d) WE Task	Between-task comparison and task vs. rest	For AUT, there was strong alpha ERS in frontal regions, and high originality was associated with alpha ERS in posterior brain regions, especially in RH. Low originality showed no hemispheric differences. Creative cognition was associated with frontal alpha synchronization.
Razumnikova et al. (2009)	53	EEG	DTT: to give original solution to one figural and to one verbal task; CTT: same tasks but S was to give any solution	Between-task comparison and task vs. rest	There was higher activation in RH, but that effect was independent of gender, test, and creative instruction. Desynchronization of Alpha 1, 2 and Beta 2 rhythms. Some changes to specific frequency were task dependent.

(table continues)

Table 1 (continued)

Study	<i>N</i>	Method	Type of creativity tests	Type of design	Main findings
Danko et al. (2009)	27	EEG	DTT: a creative task (overcoming a stereotype); CTT: a memory task	Between-task comparison and task vs. rest	The creative task produced a marked increase in EEG power in the Beta 2 and gamma bands. Induction had a much stronger effect on the cortex than the creative task.
Studies using neuroimaging methods					
Carlsson et al. (2000)	24	Right CBF 133-Xe	CFT: (a) automatic speech—count out loud, (b) verbal fluency task—say words beginning with a specific letter, and (c) AUT; also, the WAIS	Covariate (CFT), within-task comparison, and task vs. rest	Bilateral frontal increases (especially anterior frontal) were found for highly creative people, and right decreases were found for low creative ones; no consistent asymmetry was found; negative correlation between performance on (c) and blood flow in superior frontal regions; highly creative people did not perform better on (c).
Goel & Vartanian (2005)	13	fMRI	DDT: match problems—22 match configurations to be rearranged into other pattern by removing matches; start state was designed to obstruct lateral transformations towards end state; CTT: same task but end state is already known	Mixed design: prior assignment to DDT or CTT condition and between-task comparison	For DDT, there was activation in left DLPFC (BA 46) and right VLPFC (BA 47) in general; for correct solutions, activation occurred in left middle frontal gyrus (BA 9) and the left frontal pole (BA 10); DDT and CTT activated the right occipital gyrus. A bilateral frontal system was found to underwrite hypothesis generation involving set-shift transformations, especially in the right VLPFC (BA 47).
Howard-Jones et al. (2005)	8	fMRI	Semantic divergence and creative story generation; sets of three words, (a) half bore no relation to each other, (b) the other half did; instructions were to (c) “be creative” or (d) “be uncreative”	Between-task comparison and task vs. rest	For (c), there was increased prefrontal activity, including bilateral medial frontal gyrus and left ACC, and activation of visual cortices; for (a), there was increased activity in ventral areas of the ACC and in the frontal medial gyrus. Left PFC activity was linked to sentence completion and word association, and the right PFC was linked to divergent semantic processing.
Folley & Park (2005)	30	NIRS	DTT: A modified picture version of the RAT—participants had to make associations between a target object and 8 other pictures; CTT: a matching colors task	Covariate (schizophrenics, schizotypes, and healthy), between-task comparison	Schizotypes had higher DTT scores and showed greater reliance on right PFC activity; there was no difference between schizophrenics and controls, either in DTT performance or in prefrontal activation. Creativity recruited the PFC bilaterally; but enhanced performance, especially novelty, was related to right PFC activity.

Table 1 (continued)

Study	N	Method	Type of creativity tests	Type of design	Main findings
Chavez-Eakle et al. (2007)	12	SPECT (99m-Tc-ECD)	DDT: name all possible unusual uses for everyday objects	Covariate (TTCT Figural Form B, gender), within-task comparison, and task vs. rest	High scorers showed increased CBF in right precentral gyrus (BA 6), right cerebellum, left frontal gyrus (BA 6, 10, and 47), right frontal rectal gyrus (BA 11), left orbital frontal gyrus (BA 47), left temporal gyrus (BA 20 and 38), and bilateral inferior parietal lobule (BA 40). A bilateral distributed system was involved in highly creative performance.
Sieborger et al. (2007)	21	fMRI	Finding pragmatic links between (a) incoherent vs. (b) unrelated sentences; creativity was needed for incoherent sentences	Between-task comparison and task vs. rest	For (a), more activity occurred in frontoparietal regions; for (b), increased activation was found in the fusiform gyri. The time course of the signal change in frontomedial regions showed that all conditions engaged this brain region to an equal degree.
Blom et al. (2008)	13	PET (11C) raclopride (11C) FLB 457	DDT: subsample of the inventiveness battery of the Berliner Intelligenz Struktur Test	Within-task comparison and task vs. rest	There was a positive correlation between DTT and D2 binding potential in left sensorimotor striatum; there was an inverse correlation between DTT and D2 binding potential in right posterior thalamus. A limited level of dopaminergic hyperactivity was interpreted as promoting creativity.
Hori et al. (2008)	27	NIRS	DDT: LFT	Covariate (SPQ) and within-task comparison	The high SPQ group showed larger right PFC activation. A potential confound could be that the high SPQ group had a significantly higher mean age. Schizotypal traits were found to be related to right prefrontal laterality.
Hansen et al. (2008)	12	fMRI	Creative metaphors or analogies: (a) 30 fluid letter string items (if abc > abd, then pqrrr > ?); four answer choices differing in analogical depth and number of transformation; (b) control task: perfect-match letter string item	Covariate (IQ), between-task comparison and task vs. rest	For (a), there was bilateral activity of anterior frontal and posterior cortices, and the left middle superior frontal gyrus (BA 46/9) showed a linear relationship between IQ and BOLD change. High IQ and analogizing were correlated, especially when incorporating elements of creativity through adaptive reorganization and restructuring of novel information.
Jung, Gasparovic, et al. (2009)	37	MRI: DTI	DDT: five different tasks of creativity, all compiled into one creativity index	Tissue volume as a function of test scores	Tissue volume in occipital and frontal cortices as well as thalamus inversely predicted creative functioning. There was a possible role of frontal downregulation in creative capacity.
Jung, Segall, et al. (2009)	65	MRI: proton spectroscopy	DDT: (a) AUT, (b) free drawing, (c) four line drawing, all compiled into a single creativity index	Covariate (gender) and within-task comparison	Women had higher creativity scores and lower NAA in right anterior and posterior gray matter compared with men; for both genders, bilateral anterior NAA was inversely related to creativity.

(table continues)

Table 1 (continued)

Study	<i>N</i>	Method	Type of creativity tests	Type of design	Main findings
Fink, Grabner, et al. (2009), Experiment 2	21	fMRI	DDT: (a) AUT, (b) invent names belonging to abbreviations; CTT: (c) think of characteristics of normal objects, (d) WE Task	Between-task comparison and task vs. rest	All tasks elicited similar brain activation in all cortices as well as the cerebellum, except for bilateral occipital and cerebellar activation. Most brain areas showed mostly LH activation; strongest and most widespread activity in all tasks was in the left frontal lobe, including SMA and ACC; also activated were hippocampus—for (a) and (c)—and left thalamus—for (a) and (d). Frontal activity was associated with task performance.
Gibson et al. (2009), Experiment 2	20 and 15	NIRS	DDT: A modified AUT; participants decided which objects in the array could be used with a target stimulus; CTT: color categorization	Covariate (musicians vs. nonmusicians) and within-task comparison	No differences emerged between musicians and nonmusicians in or between the tasks. There was a prefrontal increase in musicians during the DTT compared with the CTT. Creative people were characterized by enhanced divergent thinking, via increased frontal cortical activity.
Moore et al. (2009)	21	MRI	DDT: TTCT	Tissue volume as a function of test scores	TTCT scores correlated negatively with the size of the corpus callosum volume. No hemispheric differences emerged.

Note. ACC = anterior cingulate cortex; AUT = Alternative Uses Task; BA = Brodmann's area; BOLD = blood oxygenation level dependent; CBF = cerebral blood flow; CFT = Creative Functioning Test; CTT = Convergent Thinking Task; D2 = Dopamine 2 receptor; DLPFC = dorsolateral prefrontal cortex; DTI = diffusion tensor imaging; DTT = Divergent Thinking Task; EEG = electroencephalography; ERD = event-related desynchronization; ERS = event-related synchronization; fMRI = functional magnetic resonance imaging; HC = high-creative group; LC = low-creative group; LFT = Letter Fluency Test; LH = left hemisphere; NAA = N-acetylaspartate; NIRS = near-infrared spectroscopy; PET = positron emission tomography; PFC = prefrontal cortex; RAT = Remote Associates Test; RH = right hemisphere; S = subjects; SAT = Simple Associates Task; SMA = supplementary motor area; SPECT = single photon emission computed tomography; SPQ = Schizotypal Personality Questionnaire; TAT = Thematic Apperception Test; TTCT = Torrance Test of Creative Thinking; VLPFC = ventrolateral prefrontal cortex; WAIS = Wechsler Adult Intelligence Scale; WE = Word End.

changes to the gamma range, which is also surprising because such reports do exist for the artistic creativity domain.

Given this overall hit-and-miss pattern of EEG results for the divergent thinking paradigm, delving deeply into the possible functional meaning of creativity-related EEG changes is challenging, to say the least. Anyone wishing to attempt this speculative exercise would have to, as a first measure, explain away most of the existing evidence, as there are as many, if not more, data against any position one cares to take. Alternatively, a more in-depth understanding of the cognitive processes underlying a particular divergent thinking task could go a long way in disentangling the contradictory data. The real hope for the future of this endeavor undoubtedly lies in such an approach.

Brain Imaging and Divergent Thinking

Unlike the EEG data, which are highly variegated, neuroimaging data using the divergent thinking paradigm reveal more consistency. There are 14 studies in the brain imaging category, which are also summarized in Table 1. These data are ordered

broadly into four themes, which center on possible neural loci for divergent thinking effects. In addition to (a) laterality, we examine the evidence for the involvement of (b) the prefrontal cortex, (c) temporoparietal regions, and (d) all other brain structures.

On the issue of hemispheric differences, the neuroimaging studies amplify the EEG data. With the possible exception of two studies implicating the right prefrontal cortex (Folley & Park, 2005; Howard-Jones, Blakemore, Samuel, Rummors, & Claxton, 2005), none of the other 12 studies in this group can be viewed as supporting a dominant role for the right hemisphere, in part or whole (Blom et al., 2008; Carlsson, Wendt, & Risberg, 2000; Chavez-Eakle, Graf-Guerrero, Garcia-Reyna, Vaugier, & Cruz-Fuentes, 2007; Fink, Grabner, et al., 2009, Experiment 2; Gibson, Folley, & Park, 2009; Goel & Vartanian, 2005; Hansen, Azzopardi, Matthews, & Geake, 2008; Hori et al., 2008; Jung, Gasparovic, et al., 2009; Jung, Segall, et al., 2009; Moore et al., 2009; Sieborger, Ferstl, & von Cramon, 2007). One study, in fact, even suggested that creativity, as measured by divergent thinking, may involve heightened activation in the left hemisphere. Fink, Grabner, et al. (2009) wrote the following:

The finding of lower right angular and supramarginal activity in the AU [alternative uses] task stands in contrast to studies emphasizing the role of right hemispheric cortices in creative information processing . . . to our knowledge there is no direct evidence that it is especially the right-hemispheric temporo-parietal regions that need to be strongly activated during creative idea generation . . . [R]ather the contrary seems to hold true. (p. 744)

In sum, the evidence from neuroimaging experiments demonstrates that divergent thinking is not associated with hemispheric specialization.

For those neuroimaging studies measuring functional aspects of brain activity—fMRI, PET, or NIRS—activation of prefrontal regions is consistently reported (Carlsson et al., 2000; Chavez-Eakle et al., 2007; Fink, Grabner, et al., 2009; Folley & Park, 2005; Gibson et al., 2009; Goel & Vartanian, 2005; Hansen et al., 2008; Hori et al., 2008; Howard-Jones et al., 2005; Sieborger et al., 2007). Such findings are expectable, as divergent thinking tests engage, presumably, working memory and executive attention. What is much less clear is which prefrontal cortices are involved. Although some studies have reported diffuse prefrontal activation patterns (Carlsson et al., 2000; Folley & Park, 2005; Gibson et al., 2009; Hori et al., 2008; Sieborger et al., 2007), others have pointed to specific regions. For instance, regarding the ventrolateral prefrontal cortex (BA 47), Goel and Vartanian (2005) reported right-sided activation, whereas Chavez-Eakle et al. (2007) reported left-sided activation. For the frontal gyrus (BA 9) and frontal pole (BA 10), four studies reported increases on the left side (Chavez-Eakle et al., 2007; Goel & Vartanian, 2005; Hansen et al., 2008; Howard-Jones et al., 2005). Chavez-Eakle et al. (2007) also found increased activation in the right premotor region (BA 6) and right ventromedial prefrontal cortex (BA 11). There are also reports of activation in the left anterior cingulate cortex (ACC; Fink, Grabner, et al., 2009; Howard-Jones et al., 2005), left dorsolateral prefrontal area (BA 46), and supplementary motor area (Fink, Grabner, et al., 2009).

Such a medley of cortical areas might be expected. First, divergent thinking is a composite, and tests based on this idea require a host of different, and quite separate, cognitive processes. This problem does not disappear by dividing creativity into component stages that are equally complex in terms of their constituent mental processes. Furthermore, each study uses a different rendering of the open-ended question concept, ranging from remote associations in a semantic network to alternative uses for an automobile tire; such findings are then compared with a variety of different control tasks that also consist of a multitude of different mental processes. The most sensible conclusion from these data is that divergent thinking is not neuroanatomically detectable as a stand-alone, independent entity. Rather, it appears to involve the same brain regions that also handle the normal, noncreative information traffic associated with a given task, a notion that has already been made on theoretical grounds (Dietrich, 2004a). Divergent thinking, then, is not a different or separate mode of thinking for which there is a specific set of processes or brain regions. Rather, it is broadly distributed (Dietrich, 2007a).

There are also several reports implicating parietal (Chavez-Eakle et al., 2007; Fink, Grabner, et al., 2009; Hansen et al., 2008; Jung, Gasparovic, et al., 2009; Sieborger et al., 2007) and temporal (Chavez-Eakle et al., 2007; Fink, Grabner, et al., 2009; Jung, Gasparovic, et al., 2009) regions of the cerebral cortex in divergent

thinking. Upon closer inspection, however, these findings do not coalesce into a coherent view either. Added to the fact that each represents a minority report, these studies show individualistic and diffuse activation patterns within this swath of tissue. Finally, a number of other brain structures, both cortical and subcortical, have been suggested to play a role in divergent thinking. There are reports for visual areas (Fink, Grabner, et al., 2009; Howard-Jones et al., 2005; Jung, Segall, et al., 2009), the thalamus (Blom et al., 2008; Fink, Grabner, et al., 2009; Jung, Segall, et al., 2009), the striatum (Blom et al., 2008), the hippocampus (Fink, Grabner, et al., 2009), the anterior cingulate gyrus (Fink, Grabner, et al., 2009; Howard-Jones et al., 2005), the cerebellum (Chavez-Eakle et al., 2007; Fink, Grabner, et al., 2009), and the corpus callosum (Jung, Gasparovic, et al., 2009; Moore et al., 2009). Yet, such findings are scattered and, for each brain structure, are not supported by the overwhelming majority of studies.

Interim Conclusion on Divergent Thinking

There is surprisingly little overlap between the EEG and the neuroimaging literature regarding implications for the neural basis of creativity. With the exception of a single article using a combined EEG and fMRI approach (Fink, Grabner, et al., 2009), theoretical discussions make little contact with one another. Notions such as laterality—the right brain, specifically—low arousal, defocused attention, or personality traits have strongly influenced the rationale and setup of EEG experiments and have led, in that domain, to several biases for which results are reported and for how they are interpreted with respect to creativity. This becomes vividly clear in light of the fact that these ideas, with the exception of hemispheric specialization, play only a minor role in the neuroimaging literature on creativity. For instance, the idea that low arousal is linked to creativity hardly ever gets a mention in neuroimaging research, presumably because relative deactivations, which would be needed to support such a claim, are rarely reported. Instead, results from neuroimaging experiments are commonly tied to the functional and anatomical characteristics of a given brain structure. Such discussion is not found in regard to EEG data because the poor spatial resolution of this tool makes such deduction speculative. Despite this fragmentation, we draw four broad conclusions from the existing data.

First, both EEG and neuroimaging experiments fail to support the notion that divergent thinking, and by extension creativity, is linked to the right brain—or to the left brain, for that matter. There is also no evidence to support the more cautious idea that specific substages of divergent thinking show a laterality effect. Divergent thinking, at any stage, entails cooperation among many different cerebral areas and involves both hemispheres.

Second, the data simply do not support a special role of any anatomical locus in divergent thinking (with the exception of the prefrontal cortices). For each brain structure, the single most visible fact is that the majority of studies do not find activation. In other words, in discussing the possible involvement of any brain region in creativity (e.g., the cerebellum; see Vandervert, Schimpf, & Liu, 2007), we must ask ourselves, first and foremost, why these individual results are, overwhelmingly, not replicated by other studies. One could possibly argue that this is due to the use of different divergent thinking tests. However, this raises another, much bigger problem. If, indeed, slightly varying implementations

of the divergent thinking paradigm, which all supposedly exploit the same concept—problems with no definitive, single solution—make such a huge difference in terms of brain activity, large enough to cause activation in brain structures as massive as the hippocampus (Fink, Grabner, et al., 2009), striatum (Blom et al., 2008), or cerebellum (Chavez-Eakle et al., 2007; Fink, Grabner, et al., 2009) on some test versions but not in others, how useful is the concept of divergent thinking, and the psychometric tests based on it, as a tool in the search for the neuroanatomical basis of creativity? It is likely that future research will identify specific brain areas for the creative processes, but this endeavor will require a more fine-grained division of creativity into different types or processes that are informed by cognitive neuroscience. Creativity, as a general construct, does not seem to be localizable.

Third, a similar conclusion emerges for theories based on specific mental processes, such as low arousal or defocused attention. The weight of the evidence simply does not bear them out. Added to this is the issue that the functional meaning of increased alpha synchronization on which the low-arousal hypothesis rests—that is, alpha ERS reflects cortical idling—is no longer current. This idling interpretation has been turned nearly on its head in the past decade by studies showing that it occurs in participants who withhold or control the execution of a response (Klimesch, 1999; Klimesch et al., 2007). ERS is functionally related to active information processing and may reflect top-down inhibitory processes. Desynchronization, on the other hand, occurs because different neural networks start to oscillate at different frequencies and with different phases. It is thus indicative of active cognitive processing. If ERS plays an active, inhibitory role, the occurrence of ERD may indicate a gradual release of that inhibition or, in short, the emergence of spreading activation (Klimesch et al., 2007). Applied to divergent thinking, ERS could be seen as the result of top-down inhibitory processes that keep out interfering activity from brain areas not directly involved in the performance of the task. This new interpretation, to be clear, is the opposite of the idea of defocused attention and low arousal because it supposes that ERS is a marker of enhanced concentration and alertness.

There could well be certain types of creative thinking that are facilitated by low cortical arousal—or a more global focus of attention—but not creativity as a whole. Overall, (a) most EEG studies do not show alpha enhancement; (b) the current understanding of the functional meaning of ERS does not allow for that interpretation even for those studies that do show these effects; (c) most neuroimaging studies show widespread cortical activation; and—moving to a different paradigm—(d) some pharmacological evidence shows that arousal has either no effect on creativity (Beversdorf, Hughes, Steinberg, Lewis, & Heilman, 1999) or, indeed, has the opposite effect (see Blom et al., 2008, who reported that dopaminergic hyperactivity promotes creativity).

Fourth, the data do permit the conclusion that the prefrontal cortex plays a key role in divergent thinking. Beyond this rather general statement, however, it is not possible to be more specific. We cannot identify the areas of the prefrontal cortex that are involved, and we do not know the functional role each may play in the generation and evaluation of ideational combinations. We examine this issue again in the section on artistic creativity, as additional data from that domain seem to suggest one critical functional division for the prefrontal cortex with respect to creativity.

Finally, the validity and reliability of divergent thinking tasks must be focused on directly, especially in the context of neuroscientific studies. The possibility that divergent thinking tests simply represent an odd mental ability test requiring perhaps some extra mental effort and attention could explain the diffuse prefrontal activation. Yet, how relevant are these tasks to real-world creativity? Can we really expect to identify the Michelangelos and Curies of tomorrow by how many innovative uses they can come up with for a brick? As for reliability, the many different cognitive processes tapped by divergent thinking measures introduce a high degree of variability (see Dietrich, 2007b; Ward et al., 1999). It appears that such tests may be too crude a measuring device to make creativity tractable in the brain. Better psychometric instruments, along with a standardized set of control tasks, are mandatory.

Art and Music

EEG and Artistic Creativity

There are comparably fewer studies that examine creativity in the domain of music, dancing, and painting. For EEG, our search strategy identified seven experiments, all but two of them reported in three articles by Bhattacharya, Petsche, and their colleagues (Bhattacharya & Petsche, 2002, 2005; Petsche, Kaplan, von Stein, & Filz, 1997). Neuroimaging studies are similarly sparse, with five experiments using fMRI and one using PET. Still, these investigations contribute to our understanding of the neural basis of creativity by solidifying and clarifying some of the findings from divergent thinking studies. Table 2 summarizes these data.

One outstanding characteristic of all studies in this group is the innovative way in which the subject of creativity is approached, with emphasis on ecological validity. Theoretical discussion in these articles is wide-ranging, including themes of mental imagery, perceptual organization, designing, and response selection for musical composition or free improvisation. Perhaps not surprisingly, additional brain structures come into play that did not feature in divergent thinking studies, such as motor areas, somatosensory areas, and cortical regions concerned with spatial or auditory perception (see Table 2).

In a series of EEG experiments, Bhattacharya, Petsche, and their colleagues examined the contribution of a variety of cognitive processes manifestly involved in artistic creativity. To that end, they devised a number of novel tasks, such as mentally composing music, visualizing an abstract concept, looking at a painting, and imagining a previously shown drawing. Three experiments (Bhattacharya & Petsche, 2002, 2005; Petsche et al., 1997, Experiment 1) used a between-subjects design that separated artists from nonartists; one used experts only (Petsche et al., 1997, Experiment 2); and one used novices only (Petsche et al., 1997, Experiment 3). In addition to these studies, there is an older experiment by Martindale et al. (1984) that also used the novice-versus-expert approach. To summarize findings, we organize the data along similar lines to the divergent thinking research—that is, we first scrutinize the evidence with respect to laterality and then focus on the changes to the various EEG frequency bands for each of the different tasks.

Parallel to divergent thinking, the EEG data do not show a trend toward hemispheric specialization. Although there is some indica-

Table 2
Summary of Creativity Studies Using Tasks Related to Music or Painting

Study	N	Method	Type of creativity tests	Type of design	Main findings
Studies using EEG methods					
Martindale et al. (1984), Experiment 3	21	EEG	Drawing a cow's vertebra placed at an angle of 24 in. (60.96 cm) from the S; reading was used as a control task	Covariate (art vs. nonart majors), between-task comparison, and task vs. rest	Both controls and art majors exhibited greater right-hemispheric alpha amplitudes during reading, but this asymmetry was greater (in the opposite direction) for artists. There was a link between artistic creativity and hemispheric asymmetry.
Petsche et al. (1997), Experiment 1	38 women, half artists	EEG	Mentally composing a drawing: (a) contemplate a painting, (b) silent reading for distraction, (c) memorizing a painting, and (d) mentally creating your own painting	Covariate (nonartists vs. artists) and task vs. rest	There were decreases in alpha for all tasks; this effect was larger for artists. There were alpha coherence decreases for (a) and (c), which was larger for RH. For (d), alpha coherence increased, mostly in posterior brain regions. Artists and nonartists did not differ for (d). When perception was involved, a larger area of cortex was engaged, and there were more decreases in Alpha 2 than in Alpha 1.
Petsche et al. (1997), Experiment 2	7 male composers	EEG	Composing music: after (a) listening to music of different styles, participants (b) mentally composed their own during EEG and later wrote it down	Between-task comparison and task vs. rest	Compared with rest, coherence patterns differed for 6 out of 7 composers for (a) and (b), but all showed individualistic patterns. No EEG measure in the Alpha 2 band indexed common creative activities underlying the composing of music.
Petsche et al. (1997), Experiment 3	38	EEG	Abstract mentation: (a) visualize an abstract concept and sketch it later and (b) create a story with 10 words previously self-chosen and memorized	Covariate (gender) and task vs. rest	For (a), men had Alpha 1 coherence decreases and increases across the midline in Alpha 2; women had Alpha 1 coherence decreases across frontal regions and increases in Alpha 2 in left fronto-parietal regions. For (b), there were dramatic long-distance coherence increases in LH in women, especially in delta and theta. Creativity was associated with strong decreases in frontal regions and involved both hemispheres.
Bhattacharya & Petsche (2002)	20 women, half artists	EEG	(a) looking at paintings (perception) and (b) imagining the previously shown painting (mental imagery); for distraction, there were periods of rest and newspaper reading	Covariate (nonartist vs. artist), between-task comparison, and task vs. rest	For artists, there was enhanced phase synchrony in beta and gamma for (a) and enhanced delta for (b); there was strongly decreased alpha synchrony for (a) and (b); RH had higher synchrony in artists. Synchrony in beta and gamma reflected better binding ability and in delta reflected higher involvement of long-term visual memory.
Bhattacharya & Petsche (2005)	19 women, 9 artists	EEG	Mentally composing a drawing of their own choice while looking at a white wall; after EEG, they had to sketch it	Covariate (nonartists vs. artists) and task vs. rest	Compared with rest, artists had greater delta synchronization, and nonartists had greater beta and gamma synchronization, mostly in frontal sites. Compared with nonartists, artists had greater delta band synchronization and alpha desynchronization. RH had higher synchrony in artists. Higher delta synchrony reflected the involvement of extensive top-down processing.

(table continues)

Table 2 (continued)

Study	<i>N</i>	Method	Type of creativity tests	Type of design	Main findings
Fink, Graif, & Neubauer (2009)	32, 15 dancers	EEG	(a) mentally perform a creative dance, (b) mentally perform a waltz, and (c) the AUT	Covariate (nondancers vs. dancers), between-task comparison	Compared with novices, dancers had stronger LH alpha ERS in posterior brain regions for the AUT and stronger bilateral alpha ERS for the creative dance. No differences existed for imaging the waltz.
Studies using neuroimaging methods					
Solso (2001)	2, a portrait artist and a control	fMRI	Participants had to (a) copy six portraits of faces and (b) six geometric figures	Covariate (expert vs. novice), between-task comparison, and task vs. rest	For the artist, there were increases in right middle frontal areas. For both, there was activation in the right posterior parietal, especially fusiform gyrus, although this was less for the artist. The artist (<i>N</i> = 1) might have been more efficient in processing facial features, engaging in more abstract representation.
Brown et al. (2006)	10 amateur musicians	PET	(a) listen to incomplete novel melodies and generate, by vocally using "da," an appropriate phrase to complete it and (b) listen to novel sentence fragments and generate semantically and syntactically appropriate phrases to complete it	Between-task comparison and task vs. rest	For (a), bilateral activation in SMA (BA 6), pre-SMA, primary motor cortex (BA 4), lateral premotor cortex (BA6), frontal operculum (BA 44/45), anterior insula, auditory cortices (BA 41, 22), and superior temporal pole (BA 22/38), thalamus, basal ganglia, midbrain, pons, and posterior cerebellum. For (b), activation in pre-SMA, sensorimotor cortex (BA 3, 4), premotor cortex (BA 6), frontal operculum (BA 44/45), superior frontal gyrus (BA 8, 9), cingulate motor area (BA 24/32), ACC, anterior insula, parietal cortex (BA 39), auditory cortices (BA 41, 22), middle temporal gyrus (BA 21), hippocampus, ventral temporal pole (BA 38), thalamus, basal ganglia, posterior cerebellum, and midbrain. This was more left-lateralized in sensorimotor areas. Both tasks showed dramatic deactivation in parieto-occipital areas.
Bengtsson et al. (2007)	11 concert pianists	fMRI	Musical pieces had to be (a) improvised or (b) reproduced on the basis of prior presented sequences	Between-task comparison and task vs. rest	For (a), higher BOLD signal for right DLPFC, pre-SMA, dorsal premotor cortex, left posterior STG, fusiform gyrus, and middle occipital gyrus; no decreases reported. These areas reflected neural processes in the generation of new musical material during improvisation; DLPFC and pre-SMA were involved in the creative aspects or free selection of a response.

Table 2 (continued)

Study	N	Method	Type of creativity tests	Type of design	Main findings
Limb & Braun (2008)	6 jazz pianists	fMRI	Improvisation of novel melodic, harmonic, and rhythmic music; four types of pieces required: rehearsed vs. improvised across low vs. high complexity: (a) Scale-Control, (b) Scale-Improvisation, (c) Jazz-Control, (d) Jazz-Improvisation	Between-task comparison and task vs. rest	For improvisation, widespread deactivation in almost all areas of the PFC, except for selective activity in the frontal polar cortex (BA 10); broad increases in neocortical sensorimotor areas, including middle temporal gyrus (STG), inferior temporal cortex, fusiform gyrus, occipital and parietal regions, as well as premotor cortex, SMA, and primary motor cortex; activation also occurred in ACC and lateral cerebellar hemisphere; widespread attenuation of activity in limbic and paralimbic regions with selective deactivations in amygdala, entorhinal cortex, temporal pole, posterior cortex, parahippocampal gyri, hippocampus, and hypothalamus. Activations during improvisation were matched by deactivations during control tasks.
Berkowitz & Ansari (2008)	12 trained pianists	fMRI	Spontaneous musical performance: pianists were asked to improvise; four conditions varying in constraints on note choice (melodic freedom) and rhythm (rhythmic freedom)	Between-task comparison and task vs. rest	Increases for rhythmic (temporal) and melodic (ordinal) sequences in premotor cortex areas, rostral cingulate zone, posterior ACC, inferior frontal gyrus, left sensorimotor cortex, some parietal areas, and the cerebellum. Common activation suggested that invention and selection of novel motor sequences, whether melodic or rhythmic, engaged similar areas.
Kowatari et al. (2009)	40, half design majors	fMRI	Artistic creativity: (a) design a new pen while looking at samples during scanning and draw the designs afterwards and (b) counting (control task)	Covariate (expert vs. novice), between-task comparison, and task vs. rest	Activated regions for novices and experts: right inferior frontal gyrus, prefrontal cortex (parts of BA 8, 9, 44, and 45), occipital cortex (BA 37), right inferior parietal cortex (BA 19), inferior temporal cortex (BA 21, 22), and hippocampus; NS differences between the groups, except for ACC activation in novices. A trend for experts existed for right prefrontal and parietal increases and LH decreases, which was bilateral for novices. Professional training facilitated right PFC dominance for design creativity by decreasing left PFC activity via inhibitory control. Stronger suppression was associated with greater design originality.

Note. ACC = anterior cingulate cortex; AUT = Alternative Uses Task; BA = Brodmann's area; BOLD = blood oxygenation level dependent; DLPFC = dorsolateral prefrontal cortex; EEG = electroencephalography; ERS = event-related synchronization; fMRI = functional magnetic resonance imaging; LH = left hemisphere; PET = positron emission tomography; PFC = Prefrontal cortex; RH = right hemisphere; S = subjects; SMA = supplementary motor area; STG = superior temporal gyrus.

tion that artists exhibit comparatively greater alpha power (Fink, Graif, & Neubauer, 2009; Martindale et al., 1984), as well as beta and gamma synchrony in the right hemisphere on some tasks (Bhattacharya & Petsche, 2002, 2005; Petsche et al., 1997, Experiment 1), data also exist implicating both hemispheres in creativity (Fink, Graif, & Neubauer, 2009; Petsche et al., 1997, Experiments 2 and 3).

For perceptual tasks, such as looking at paintings, compared with nonartists, artists show alpha ERD in frontal regions (Bhattacharya & Petsche, 2002, 2005; Petsche et al., 1997, Experiment 3) and posterior regions (Bhattacharya & Petsche, 2002; Petsche et al., 1997, Experiment 1). Again, these changes are generally reported for both alpha subbands. These findings of creativity-related alpha ERDs are contrary to those showing alpha ERS in

divergent thinking for frontal (Fink et al., 2006; Fink, Grabner, et al., 2009; Grabner et al., 2007; Jaušovec, 2000) and posterior (Fink, Grabner, et al., 2009; Fink & Neubauer 2006a; Martindale & Hines, 1975) sites. Artists also exhibit higher phase synchrony in the beta and gamma bands (Bhattacharya & Petsche, 2002), which the authors have suggested might indicate enhanced binding ability. Such increases in beta ERS have also been reported for divergent thinking by some studies (Mölle et al., 1999; Razumnikova, 2005, 2007; Shemyakina & Danko, 2007). Also, perceptual tasks tend to involve a larger swath of the cortex than mental imagery tasks, which are reviewed next.

During mental imagery, the EEG also reveals alpha desynchronization for frontal (Bhattacharya & Petsche, 2002; Petsche et al., 1997, Experiment 3) and posterior (Petsche et al., 1997, Experiment 1) regions. Contrary these findings, however, Fink, Graif, and Neubauer (2009) reported alpha ERS for creative dance imagery. Increases in synchrony were found in the delta band (Bhattacharya & Petsche, 2002). The results are similar for mentally composing a drawing, a task presumably heavily dependent on mental imagery. Here artists show the same pattern: ERD in alpha and ERS in delta (Bhattacharya & Petsche, 2005). The alpha desynchronization in these two tasks is in contrast to much of the divergent thinking paradigm and to the alpha ERS found by Fink, Graif, and Neubauer (2009). As for the increases in delta synchronization in both studies (Bhattacharya & Petsche, 2002, 2005), the authors have argued that this effect reflects the involvement of visual art memory and extensive top-down processing.

Two studies do not fit this trend. One is the above-mentioned report by Fink, Graif, and Neubauer (2009); the other is that of Petsche et al. (1997, Experiment 1). In the latter, participants were asked to mentally create their own painting, a task very similar to those generating alpha ERD. Findings indicated increases in alpha ERS for both artists and nonartists compared with rest. That experts and novices did not differ in this task, on any EEG index, is puzzling, as one would expect these two populations to approach the task of mentally creating a painting differently, given the likely outcome differences in quality if they were to execute it.

It may be instructive to directly compare the results of one task reported by Petsche et al. (1997, Experiment 3) with those in the divergent thinking literature, because in this task participants were asked to create a story using 10 self-chosen words, similar to some divergent thinking tasks (see Jaušovec, 2000, Experiment 2; Jaušovec & Jaušovec, 2000b; Martindale & Hasenfeld, 1978; Martindale et al., 1984). The main finding is that women have long-distance coherence increases in the left hemisphere in delta and theta, a set of results not reported by any divergent thinking study.

Brain Imaging and Artistic Creativity

The neuroimaging literature devoted to this topic is also sparse and, with the exception of one quasi case study (Solso, 2001), has all been published quite recently. The studies in this group are also difficult to integrate into a coherent picture on the neural mechanisms of creativity, in part because they, too, do not make extensive contact to the rest of creativity research. We group them in terms of findings regarding (a) laterality, (b) prefrontal cortex function, and (c) other brain areas.

For laterality, all six studies corroborate the conclusion that creativity requires multiregional, interhemispheric interactions and

should thus not be ascribed to one particular hemisphere. Given the data, artistic creativity is not a function of the right hemisphere.

The inspection of data on the prefrontal cortex yields a highly interesting observation that possibly harbors an important clue as to the role of the prefrontal cortex in creativity. Five studies reported activation in various areas of the prefrontal cortex, including premotor and supplementary motor areas (both parts of BA 6), motor cortex (BA 4), areas of the frontal gyrus (BA 8 and 9), frontal operculum (BA 44/45), dorsolateral prefrontal cortex (BA 46), and ACC (Bengtsson, Csikszentmihalyi, & Ullen, 2007; Berkowitz & Ansari, 2008; Brown, Martinez, & Parsons, 2006; Kowatari et al., 2009; Solso, 2001). None of these studies reported significant decreases. The main finding of the sixth study is quite dissimilar: Widespread prefrontal decreases in almost all areas of the prefrontal cortex were found, except for selective activity in the middle frontal polar cortex (BA 10; Limb & Braun, 2008). At first glance, nothing in this study appears to shed light on such diametrically opposed results. Like the other three music investigations (Bengtsson et al., 2007; Berkowitz & Ansari, 2008; Brown et al., 2006), Limb and Braun (2008) investigated improvisation of novel and melodic musical sequences and used trained musicians.

Significant changes to neural activity related to creative processes are also reported for other brain structures. Activation was found to occur in several temporoparietal areas (Bengtsson et al., 2007; Brown et al., 2006; Limb & Braun, 2008; Kowatari et al., 2009), the fusiform gyrus (Bengtsson et al., 2007; Limb & Braun, 2008), several visual cortices (Bengtsson et al., 2007; Limb & Braun, 2008; Kowatari et al., 2009), thalamus (Brown et al., 2006), basal ganglia (Brown et al., 2006), hippocampus (Brown et al., 2006; Kowatari et al., 2009), cerebellum (Brown et al., 2006; Limb & Braun, 2008), midbrain and pons (Brown et al., 2006), and ACC (Limb & Braun, 2008), especially for novices (Kowatari et al., 2009). Also, Limb and Braun (2008) reported deactivations over a wide limbic and paralimbic area, such as the hippocampus, amygdala, entorhinal cortex, hypothalamus, parahippocampal gyrus, and even parts of parietal and occipital cortex. This finding should open investigators to the possibility that creativity can also be linked to deactivations.

Interim Conclusion on Artistic Creativity

Findings from this group of studies underscore and broaden many conclusions from the divergent thinking literature. They highlight that no single brain area is necessary or sufficient for creativity or any of its component stages. This statement holds not only for lateralization but also for theories emphasizing the role of other brain regions, such as the temporoparietal region or the cerebellum. It might be stated that creativity is everywhere.

Studies in this section also suggest that the role of the prefrontal cortex in creative thinking is not of the yea-or-nay kind. On one side, there is a good deal of evidence supporting the idea that prefrontal *activation* facilitates creativity. On the flipside, there is a roughly equal amount of evidence supporting the exact opposite, that prefrontal *deactivation* facilitates creativity. This dichotomy appears to hold for both neuroimaging and EEG studies. It may be the case that there are different types of creativity, some that depend on prefrontal engagement and some that benefit from prefrontal disengagement. Whereas a mental ability as extraordinary as creativity would appear to be associated with activation of

the highest cognitive functions, creativity may also be associated with a state of hypofrontality (Dietrich, 2004a, 2004b). One suggestion along these lines is found in a careful reading of Limb and Braun (2008), who found deactivations in prefrontal regions of musicians in the context of a familiar environment conducive to a flow experience. To do this, they used a custom-built, real keyboard, on which well-learned melodic strings—“licks,” as they are known among jazz musicians—could be played implicitly without interference from less efficient explicit processes (Dienes & Perner, 1999). As a consequence, participants could perhaps afford more readily to downregulate any metacognitive, supervising processes, which, in turn, resulted in more intuitive and creative musical playing.

In contrast, the three other music studies reviewed above all required some sort of mental transformation of these licks; presumably, that participants could not afford downregulating higher order, executive processes. In Bengtsson et al.’s (2007) study, improvised strings had to be memorized and reproduced later; in Brown et al.’s (2006) experiment, incomplete melodies had to be finished vocally by using the syllable “da”; and in Berkowitz and Ansari’s (2008) study, musical notes were coded by letters (i.e., an ascending sequence would be CDEFG). All of these would require, at the very least, attentional resources and working memory processes that would be expected to engender prefrontal activations. In short, people can be creative in several ways. It may well be that sometime creativity results from trying really hard—think Thomas Edison—but at other times it may flourish under conditions of not “trying” at all (Dietrich, 2007a).

Insight

EEG, ERP, and Insight

To date, five EEG and six ERP experiments have been published on insight. There exist also nine neuroimaging studies, two using PET and seven using fMRI. Table 3 outlines all 20 studies.

This domain of creativity research has also utilized many novel tasks, which is not surprising given that the target here is what must be one of the most elusive of mental events, the so-called “aha” effect (also termed a Eureka experience). The drawback of this array of testing tools is, naturally, variability, which complicates the business of comparing brain activity across studies. Compared with other creativity domains, insight investigations emphasize different theoretical themes, such as conflict resolution and the role played by the ACC.

The field of insightful problem solving has spawned a neuro-anatomically upgraded variant of the right-brain theory. According to this theory, the right temporoparietal regions, and the superior temporal gyrus (STG) in particular, are hypothesized to mediate coarse semantic coding and in doing so facilitate the formation of remote associations (Bowden & Jung-Beeman, 2003; Jung-Beeman et al., 2004). However, the EEG and ERP data reviewed here do not support the notion of hemispheric differences. Although there are several studies that point to a special role of the right STG for insight events (Jung-Beeman et al., 2004; Kounios et al., 2008; Qiu, Luo, Wu, & Zhang, 2006; Sandkühler & Bhattacharya, 2008), there are more studies that do not support this contention (Danko, Starchenko, & Bechtereva, 2003; Kounios et al., 2006; Lang et al., 2006; Lavric, Forstmeier, & Rippon, 2000;

Mai, Luo, Wu, & Luo, 2004; Qiu et al., 2008a, 2008b). There is even one study that contradicts it by implicating the left hemisphere, albeit again the STG (Qiu et al., 2008a). This conclusion holds not only for the insight event itself but also for the substages of problem solving, as most studies fail to report selective right brain activity for these periods as well. Again, Qiu et al. (2008a) even reported left dominance for the early stages when coarse semantic coding purportedly occurs.

One consistent finding of insight EEG studies is a decrease in alpha power. This pattern is reported for frontal (Kounios et al., 2008, 2006; Sandkühler & Bhattacharya, 2008), parietal (Danko et al., 2003; Jung-Beeman et al., 2004), and temporal (Kounios et al., 2008, 2006) sites, especially during restructuring (Sandkühler & Bhattacharya, 2008). How these alpha power decreases fit with the prefrontal and temporoparietal activation detected in many insight-related neuroimaging studies is not clear at present. Given that combined EEG and fMRI studies have shown that increases in alpha power are related to decreases in cortical blood flow (Goldman, Stern, Engel, & Cohen, 2002; Sadato et al., 1998), these two sets of results would seem to run counter to each other.

The response of other frequency bands to insight reflects variegated results. For instance, there are general gamma and beta power increases associated with insight in some studies (Kounios et al., 2008; Sandkühler & Bhattacharya, 2008), yet there are also gamma power decreases, especially at left anterior temporal and inferior frontal leads (Kounios et al., 2008). In addition, Danko et al. (2003) reported widespread coherence decreases in all frequency bands, especially over the frontal cortex—a finding not corroborated by any other study.

Remote associates problems might constitute a particular type of insight task that engages the STG—a finding that would not be surprising given the role of this area in language processing. In addition to three EEG studies (Jung-Beeman et al., 2004; Kounios et al., 2008; Sandkühler & Bhattacharya, 2008), there are two ERP studies that implicate the STG, although one of them described a positive ERP deflection (Qiu et al., 2008a) and the other a negative one (Qiu et al., 2006) for this location. The cause for these opposing ERP results may lie in a slight variation of the test procedure. In Qiu et al. (2006), participants were given the correct solution for problems they did not solve and were then asked whether the answer provided by the investigators elicited an aha effect. On the other hand, Qiu et al. (2008a) required participants to find the solution on their own; this discovery of the solution counted as an aha event. The difference, in short, was that insight was a passive process in the former but an active one in the latter. In any event, the STG does not appear to be involved in insight events using other paradigms, such as implicit learning (Lang et al., 2006), Guilford’s match problems (Lavric et al., 2000), or solutions to Japanese riddles (Mai et al., 2004).

ERP studies also typically detect ACC activity during the occurrence of an insight. Several studies have reported a more negative deflection, which occurs at different latencies for different studies: N320 for Qiu et al. (2006), N380 for Mai et al. (2004), and N1500–N2000 for Qiu et al. (2008a). Conversely, a fourth study (Qiu et al., 2008b), which used the same Qiu et al. (2006) procedure, reported a positive deflection. The ACC is thought to be involved in breaking the impasse that marks the critical step of an insight problem.

Table 3
Summary of Insight Studies

Study	<i>N</i>	Method	Type of insight problem	Type of design	Main findings
Studies using EEG or ERP methods					
Lavric et al. (2000)	20	EEG/ERP	IT: (a) the candle and (b) the two-strings problem; CT: Wason's selection task (analytical); both were done while doing a working memory task (count auditory stimuli)	Between-task comparison and task vs. rest	Counting disrupted CT but not IT. Peak and time-window average P300 more frontal for CT. Two factors in the P3 range (frontal and broad left-lateralized) distinguished CT from IT. Creative (insight) problem solving was less systematic, using less planning and requiring less working memory.
Danko et al. (2003)	30	EEG	IT: link a difficult sequence of 12 words from different semantic fields with other words; CT: choose 5 examples belonging to a given word category (easy sequences)	(a) covariate (nonactors vs. actors), (b) between-task comparison, and (c) task vs. rest	Compared with rest, IT and CT decreased alpha power in right parietal and left frontal areas; higher spectral power in delta and theta for temporal areas. Lower coherence for IT in all frequency bands in right prefrontal areas. Alpha ERS decreased in parietal and frontal areas, whereas it increased in temporal areas for insight tasks. Results were similar to patterns revealed in noninsight strategy creative tasks.
Jung-Beeman et al. (2004), Experiment 2	19	EEG	Problems triggering aha 50% of the time: on 3 words (e.g. back, clip, wall), generate a solution (paper) to form compound words with all (paperclip, paperback, wallpaper); aha was self-reported	Within-task comparison (aha, no aha, time-out) and task vs. rest	Burst of gamma activity associated with correct insight solutions at ca. 0.3 s before response at anterior right temporal sites; no difference between insight and noninsight in LH. Burst of alpha power associated with insight solutions over right posterior parietal cortex. The gamma insight effect reflected the sudden transition of solution-related processing from an unconscious to a conscious state.
Mai et al. (2004)	14	EEG/ERP	Consider riddles to which solution was presented after an interval; participants then indicated whether solution matched the one they thought of; if yes, it was classified as no-aha; if not, the presentation is said to elicit an aha; aha was self-reported	Within-task comparison (aha vs. no aha) and task vs. rest	Aha answers elicited a more negative ERP deflection from 250–500 ms after onset of the answer with a maximum amplitude over the central site and a peak latency of 380 ms (N380). Maps of the difference showed strong activity and current density in the frontocentral region, which was localized in the ACC. The N380 reflected an aha effect, and the ACC may be involved in the breaking of mental sets.
Qiu et al. (2006)	130	ERP	Chinese logogrphs: a character is transformed by changing strokes to alter its deep meaning; (a) easy riddles followed by a correct answer consistent with participant's thinking (no-aha) or (b) difficult riddles followed by a correct answer that broke a mental set (aha)	Within-task comparison (aha, no aha, not comprehended) and task vs. rest	For (b) and (c), a more negative ERP deflection was present. Maps of this difference showed strong activity at central posterior sites, especially right temporoparietal areas. The N320 for aha was near the ACC and the thalamus. Aha and uncomprehended answer elicited a more negative component. The N320 may embody the central locale of cognitive conflict that resolves familiar and new ways of thinking.

Table 3 (continued)

Study	N	Method	Type of insight problem	Type of design	Main findings
Lang et al. (2006)	26	EEG/ERP	Insight during implicit learning; NRT contains a hidden rule; participants who gain insight into that rule solve problems much faster via a short cut	Within-task comparison (solvers vs. nonsolvers)	Six of 26 participants gained insight. They had several larger ERP indexes from the outset: slow positive wave, frontocentral P3a, anterior N1 to digits triggering the critical repeating responses, and P3b to digit for the immediately repeating response. Participants who gain insight may be distinguished beforehand by their individual characteristics. Their explicit knowledge was based on processing that differed from implicit learning from the very beginning.
Kounios et al. (2006), Experiment 1	19	EEG	Same as Jung-Beeman et al. (2004)	Within-task comparison (aha, no aha, time-out) and task vs. rest	Compared with time out, insight was associated with less alpha power in midfrontal cortex and left anterior temporal cortex, and noninsight was associated with decreased alpha over the occipital cortex. Compared with noninsight, insight showed less alpha power in midfrontal, temporal, somatosensory, and right inferior frontal cortex, whereas noninsight showed less alpha power over posterior cortices.
Kounios et al. (2008)	26	EEG	A series of four- or five-letter anagrams, each of which had one solution only	Within-task comparison (aha, no aha, time-out) and task vs. rest	Insight strategy was associated with greater alpha, beta, and gamma power at right inferior frontal and anterior temporal sites and greater power for low insight at right dorsal frontal (alpha) and left occipital and parietal sites (Beta 2 and gamma). Creativity recruited RH association areas involved in semantic processing more than noncreative cognition.
Qiu et al. (2008a)	18	ERP	Same as Qiu et al. (2006), except that participant found solutions on their own	Within-task comparison (aha, no aha, not comprehended) and task vs. rest	Successful solutions elicited a more positive ERP deflection from 200 to 600 ms after stimulus onset. From 1,500 to 2,000 ms, successful solutions elicited a more negative deflection. P200–P600 was localized in the left superior temporal gyrus and posterior cortices. The N1500–N2000 occurred stronger over left frontal areas, which was localized in the ACC. The ACC was critical in breaking mental set and the forming of new associations.
Qiu et al. (2008b)	18	ERP	Same as Qiu et al. (2006)	Within-task comparison (aha, no aha, not comprehended) and task vs. rest	Successful logogriphs elicited a more positive ERP deflection. The source analysis implicated the ACC and the right parahippocampal gyrus. The ACC was linked to the initial stages of insight onset, an “early warning system” in the breaking of a mental set.
Sandkühler & Bhattacharya (2008)	21	EEG	Same as Jung-Beeman et al. (2004), except that participants indicated (a) finding the solution or (b) facing an impasse, which then prompted a hint; participants self-rated degree of (c) restructuring and (d) suddenness of solution	Within-task comparison	Increased upper alpha in right temporal regions for trials with high restructuring, decreased alpha power in right prefrontal area. Gamma power effect reflects selective attention and processes for emergence of spontaneous new solutions. Alpha effect was related to weak, unconscious processing of the solution in the right temporal area. With the hint, activity intensified and reached awareness.

(table continues)

Table 3 (continued)

Study	N	Method	Type of insight problem	Type of design	Main findings
Studies using neuroimaging methods					
Rose et al. (2002)	10	fMRI	A different version of the NRT (Lang et al., 2006); (a) first half in a trial was compared with performance on (b) the second half	Within-task comparison (Half 1 vs. Half 2) and task vs. rest	Decreases of RT across sessions, which were larger for Half 2. Improvements in applying explicit rule were accompanied by activation in the basal ganglia and cerebellum, which was also positively related to performance; for the hidden rule, there was activation in the MTL for Half 2 only. In bilateral superior parietal cortex, activation increased minimally for Half 2 and decreased for undetermined inputs in Half 1. Violating the hidden rule showed greater responses in right VLPFC. S became increasingly sensitive for the hidden structure, albeit implicitly. This engaged the basal ganglia and cerebellum and was outside awareness, but violation of hidden rule activated the VLPFC.
Luo & Niki (2002)	7	fMRI	Japanese riddles (e.g., the thing that can move heavy logs, but not move a small nail—river); if not solved, answers were given, and an aha effect was elicited	Within-task comparison (aha vs. no aha) and task vs. rest	Right hippocampus and large areas of the cortex were activated during an insight event. The hippocampus was involved in the neural network subserving the “insight” process of problem solving.
Starchenko et al. (2003)	9	PET	The same IT and CT tasks as Danko et al. (2003), plus a third CT: read out loud a sequence of words	Between-task comparison and task vs. rest	An insight strategy selectively activated the left supramarginal (BA 40) and the ACC (BA 32); task complexity is mostly reflected in activation of frontal areas (BA 8, 10, 47).
Bechtereva et al. (2004)	34	PET	IT: 12 nouns in a matrix—(a) fill the gaps between the words using logical associations, (b) list items aloud, (c) just reading; CT: 16 words arranged in a 4 × 4 matrix—create a story with words from (a) different semantic areas, (b) one semantic area, (c) changing word forms, or (d) memorizing the words	Covariate (type of self-reported strategy: insight vs. successive in pilot study) and between-task comparison	For IT, participants using an insight strategy showed most activation in superior occipital gyrus (BA 19), temporal gyrus (BA 21, 22, 38), angular gyrus (BA 39), precuneus (BA 7), many frontal areas (BA 8, 6, 11, 44, 45, 46, 47), parietal regions (BA 40), and the ACC. Strategies in creative thinking were related to activation in temporoparietal regions, especially BA 39 and 40.
Luo et al. (2004)	13	fMRI	Pairs of ambiguous/incomprehensible sentences followed by solution cues defined as (a) aha, (b) non-aha, (c) difficult cues, and (d) not understandable; aha occurred when the solution cue evoked a sudden understanding; aha was self-reported	Within-task comparison (aha, no aha, difficult, not understandable) and task vs. rest	Compared with non-aha, ACC and the left lateral PFC were activated during aha reactions and difficult solution. There was no difference in these ACCs between aha and difficulty. The highest activation was for difficult solution in the lateral PFC. Both areas contributed to conflict detection and breaking mental impasses.
Jung-Beeman et al. (2004), Experiment 1	12	fMRI	Same as Jung-Beeman et al. (2004), Experiment 2	Within-task comparison (aha, no aha, time-out) and task vs. rest	Insight solutions were associated with greater activity in the RH anterior STG. There was no significant frontal cortex insight effect. Solving verbal insight problems required an additional cortical component, the RH STG.

Table 3 (continued)

Study	N	Method	Type of insight problem	Type of design	Main findings
Rose et al. (2005)	18	fMRI	Similar to Rose et al (2005) but with blocks in which only the explicit rule applied	Within-task comparison (Half 1 vs. Half 2) and task vs. rest	Right VLPFC and left MTL structures (which showed a violation effect in Rose et al., 2002) did not reach significance in this study. Both brain areas, however, showed activation for rule violation. Implicit learning can result in unconscious expectancies, and the violation of these expectancies are thought to be detected by right VLPFC and left MTL areas.
Kounios et al. (2006), Experiment 2	25	fMRI	Same as Jung-Beeman et al. (2004)	Within-task comparison (aha, no aha, time-out) and task vs. rest	Insight solution was preceded by increased activity in anterior and posterior ACC as well as posterior STG activation. For noninsight preparation, there was a trend for activation in left middle and inferior occipital cortex. Insight involved medial frontal areas associated with cognitive control and temporal areas associated with semantic processing.
Aziz-Zadeh et al. (2009)	12	fMRI	Difficult anagrams from Novick & Sherman (2003) classified as (a) insight or (b) search; this classification is based on self-report and time (insight more and search less than 4 s)	Within-task comparison (insight vs. search) and task vs. rest	(a) vs. rest: activation in premotor cortex, SMA, occipital cortex, insula, and tegmentum; (b) vs. rest: activation in superior frontal sulcus and left insula; (a) vs. (b): Activation in right insula, Broca's area (left BA 45), angular gyrus, right PFC (BA 10, 46), ACC, pons, and right temporal pole. Solving anagrams activated distributed networks, including frontal language areas in RH and LH. For insight, right PFC, midbrain, and ACC were involved. The main difference to search was not a shift from left to right activation but of bilateral activity. Right ventral PFC played a role in evaluating insight problems rather than problem solving itself.

Note. ACC = anterior cingulate cortex; BA = Brodmann's area; CC = cingulate cortex; CT = Control Task; EEG = electroencephalography; ERP = event-related potential; ERS = event-related synchronization; fMRI = functional magnetic resonance imaging; IT = Insight Task; LH = left hemisphere; MTL = medial temporal lobe; NRT = Number Reduction Task; PET = positron emission tomography; PFC = prefrontal cortex; RH = right hemisphere; RT = reaction time; S = subjects; STG = superior temporal gyrus; VLPFC = ventrolateral prefrontal cortex.

In sum, EEG studies suggest that insight is associated with alpha power decreases. Also, ERP studies suggest that (a) the STG is important for some testing paradigms, but not others, and that (b) the ACC plays a critical role in the insight process. Further research needs to show whether, and for what type of insight problem, these trends hold.

Brain Imaging and Insight

Neuroimaging studies on insight are summarized on the basis of the trends identified in the neuroelectric data. After examining the literature for hemispheric differences, we explore the possible role of prefrontal regions, the ACC, and other brain regions, including the temporoparietal cortices.

A review of insight neuroimaging studies provides no support for right-brain dominance. One study concluded that aha effects correlate with activity in the right cortex—the right STG, more

precisely (Jung-Beeman et al., 2004)—whereas another can be interpreted to provide evidence to the contrary, namely activity in left prefrontal regions (Luo, Niki, & Philips, 2004). The majority of studies reveal bilateral activation patterns associated with insight events (Aziz-Zadeh, Kaplan, & Iacoboni, 2009; Bechtereva et al., 2004; Kounios et al., 2006; Luo & Niki, 2002; Rose, Haider, Weiller, & Büchel, 2002, 2005; Starchenko, Bechtereva, Pakhomov, & Medvedev, 2003). Most neuroimaging data, such as the EEG/ERP data, can also be examined for the early states of insight problem solving, as it is here that coarse semantic coding is thought to play a key role in the formation of remote associations. Again, the majority of studies do not bear this out. For instance, two PET studies (Bechtereva et al., 2004; Starchenko et al., 2003) reported bilateral activation patterns in a verbal task in which a search strategy can be contrasted with an insight one. Bilateral activation is also reported in another study using verbal stimuli: anagrams (Aziz-Zadeh et al., 2009).

An entirely different approach to insight problems is taken by Rose et al. (2002, 2005), who utilized an implicit learning paradigm. The interesting advantage of this paradigm is that it allows for a trial-by-trial analysis of the problem-solving process. Participants are presented with numerical problems that all contain the same underlying, hidden regularity, which, if detected, provides a short-cut to the solution. An insight into the hidden rule is revealed by a shift in strategy from implicit to explicit processing by the participant, which causes a sudden, large drop in the reaction time. This permits the researchers to pinpoint the exact moment an insight occurs in the mind, as well as to monitor preparatory stages, without relying on the participant's verbal report. Using this paradigm, fMRI did not reveal any laterality effects at any stage of the task. Taken together with the neuroelectric data, the idea that the right hemisphere, or any part of it, is more important at any stage of the insight process than the left has received no support.

Activation of various prefrontal regions often accompanies insightful problem solving (Aziz-Zadeh et al., 2009; Bechtereva et al., 2004; Luo & Niki, 2002; Rose et al., 2002, 2005). Still, a number of studies have not reported significant insight effects for frontal areas (Jung-Beeman et al., 2004; Kounios et al., 2006; Luo et al., 2004; Starchenko et al., 2003). The matter is made more complex by the fact that different studies locate the aha event in different prefrontal areas. Whereas Luo et al. (2004) honed in on left lateral regions, others have emphasized the role of right ventral regions (Aziz-Zadeh et al., 2009; Rose et al., 2002, 2005), and still others have emphasized that a diffuse bilateral activation is responsible (Bechtereva et al., 2004). In addition, it has been suggested that this prefrontal activation might simply be a function of task difficulty rather than the insight process itself (Luo et al., 2004; Starchenko et al., 2003). Compared with non-aha phenomena, Luo et al. (2004) reported that difficult solutions activate prefrontal areas just as much as aha events do. In other words, insight does not contribute to prefrontal activity above and beyond difficulty level. Because few studies controlled for the possibility that insight problems might simply be more difficult than those that do not, it remains to be seen whether there is indeed a selective prefrontal insight effect.

The anterior cingulate gyrus has been a major focus of interest in this field, and several studies show positive correlations with insight in this region (Aziz-Zadeh et al., 2009; Bechtereva et al., 2004; Kounios et al., 2006; Luo et al., 2004; Starchenko et al., 2003). There are exceptions, however (Jung-Beeman et al., 2004; Luo & Niki, 2002; Rose et al., 2002, 2005). Overall, on the basis of neuroelectric and neuroimaging data, there appears to be converging evidence that many insight events are accompanied by ACC activity.

Neural activity associated with insight is also reported for several other brain regions, chiefly among them are temporoparietal areas (Bechtereva et al., 2004; Kounios et al., 2006; Starchenko et al., 2003), especially the STG (Jung-Beeman et al., 2004). Authors of these studies often stress the importance of these cortical regions over frontal areas in insightful problem solving. Still, as in other areas under review, the evidence is not uniform. Other brain regions showing selective activity for insight events are, for instance, visual cortices (Bechtereva et al., 2004) and the hippocampus (Luo & Niki, 2002). Finally, there are also no reports of significant deactivations in this group of studies.

Interim Conclusion on Insight

Research on the neural basis of insight reflects greater consistency than research on either divergent thinking or artistic creativity. Although an integrated model of the neural generator of the aha experience has yet to be proposed, the data show several tendencies that could be the basis for such a model. First, Eureka experiences are not, in general, accompanied by right hemispheric dominance; this conclusion also holds for component states of insightful problem solving. Second, EEG data show that insight is associated with alpha power decreases. This finding, however, remains difficult to interpret, as such an effect should correlate with a decreased blood oxygenation level dependent signal. Functional MRI research, however, has not detected such decreases. Thus, simplistic explanations of complex mental events, as insight experiences are likely to be, are often defeated when data from different methods are integrated. Third, the STG appears to play some role in the successful solution of insight problems that require verbal associations, by perhaps making remote associations in a semantic network that might eventually trigger a solution path. Fourth, the ACC is activated by insight problems. This region appears to be important in detecting cognitive conflict and initiating processes that lead to the breaking of the mental mindset that keeps one stuck in the wrong solution space. Fifth, the role of prefrontal areas is not clear. With a somewhat even split between studies implicating prefrontal regions and those that do not, further research is needed to see whether, and to what extent, the prefrontal cortex mediates Eureka experiences. It is quite possible that both prefrontal activation and deactivation are again at work here, each associated with its own types of insight experience.

We contend that careful attention to a few methodological issues could account for some of the variability in the data and shed more light on the few trends that exist in the insight literature. For one thing, the field would greatly benefit if insight-related tasks are subjected to validation trials, preferably prior to their use with neuroimaging tools. Second, even if a task manifestly does require an insight strategy, what passes for an insight differs substantially from study to study. Self-report is used, but in two different ways: passive (participants cannot solve certain problems but then report an aha experience when investigators provide the correct solution) or active (the participant successfully solves a difficult problem). The importance of this distinction is indicated by the above-noted difference in the findings from Qiu et al. (2006) versus Qiu et al. (2008a). Yet, an entirely different method to determine the occurrence of insight does away with the necessity of a self-report altogether (Haider & Rose, 2007), via reaction-time data, which reveal the participant's discovery of a short-cut solution via discovery of hidden regularities in the problems presented. It is difficult to imagine that implicit learning paradigms using these different types of insight experiences would yield parallel patterns of brain activation.

General Discussion

The literature on the neural basis of creativity is, especially for its small size, surprisingly fragmented. This fragmentation is perhaps most readily seen in a citation count. Of the 63 articles we collated here, we could not find a single one that makes reference to even half of them. This observation even holds true for any of

the three individual domains of creativity: divergent thinking ($N = 34$ articles), artistic creativity ($N = 11$), and insight ($N = 21$). This observation also holds true for the two types of general recording methods: neuroelectric ($N = 37$) and brain imaging ($N = 29$).

The most forthright conclusion that can be taken away from the present review is that not a single currently circulating notion on the possible neural mechanisms underlying creative thinking survives close scrutiny. Indeed, the data are so highly variegated that even weak trends are difficult to make out. This conclusion holds equally for the literature as a whole as it does for each of its three subdomains. One effect of the fragmentation is that this fact has not been fully appreciated. For nearly every proposal on the neural underpinning of creativity one cares to press, there is as much evidence for as there is against it, yet one would not suspect this from a casual reading of the literature. The problem likely arises because empirical studies often refer to only those prior results from the same subdomain and recording methodology that tend to support the rationale of the reported experiments. This gives the impression that studies in this field are based on a solid background when, in fact, this is an artifact of selective reporting of the existing data.

The most adverse effect of this fragmentation is seen in the lack of progress in the theoretical discussion permeating the field. The fact that there is always enough evidence to maintain any theoretical position has led to the unusual situation that few theories as to the neural basis of creativity have been discarded. Advances in science depend on falsification, a process that eventually forces us to either abandon or revise our conceptions of how things work. There is little indication that this process has taken place here. Ideas first proposed in the 1960s and 1970s—laterality, divergent thinking, low arousal, remote associations, or defocused attention—are still those, and in essentially the same form, that drive current research efforts. It is ironic that no other area of psychology has seen so much perseverance.

Accordingly, the following conclusions can be drawn about creativity as a whole. First, creativity, or any alleged stage of it, is not particularly associated with the right brain or any part of the right brain. This is not a new deduction. It had been made even before the overwhelming majority of the experiments reviewed in this study had appeared. Katz (1997, p. 224), for instance, already lamented “the simplistic argument that the essential aspect of creativity resides in the right hemisphere” and recommended that “the claim that creativity is located ‘in’ the right hemisphere should be dispelled with at once.” The present review fully amplifies this conclusion.

Second, this conclusion can be broadened to include any phenomenological supposition on creativity. We can state, in short, that creativity is not particularly associated with any single brain region, the prefrontal cortex excluded. For the prefrontal cortex, the issue is a difficult one, as it is evidently not involved in creativity in a simplistic yes-or-no fashion. With EEG studies revealing in all frequency bands both increases and decreases for both power and synchrony, as well as brain imaging studies reporting both activations and deactivations, the main conclusion is quite general: Tasks purportedly involving creative cognition induce changes in prefrontal activity.

This is, however, already more than we can say about other brain structures. The evidence shows that for any brain region, there is always a majority of studies that does not report changes

in activity there. We must conclude, in other words, that creativity is not localized or, perhaps more accurately, given the current neuroimaging capabilities and the theoretical resolution with which the issue is seen, not localizable.

The same fate is met by proposals that posit a specific neurocognitive process for the whole of creativity, be it low arousal, defocused attention, or alpha synchronization. The weight of the evidence simply does not support them. Indeed, any such exercise in category formation of what is and what is not supposed to be linked to creativity is likely doomed to failure if it is applied to all of creativity. This may also be the case for the link between creativity and psychological disorders (such as bipolar disorder, schizophrenia, or autism), neurological diseases, or altered state of consciousness (such as sleep or meditation). Despite case reports and anecdotes, the evidentiary basis for such claims is lacking (see Dietrich, 2007b).

To avoid misunderstandings of our concluding argument, we do not suggest that any of the above proposals on the neural basis of creativity is wholly wrong. Some of the conclusions are based on collating the data into yes and no categories (i.e., does or does not activate a given brain area), which could carry a risk of missing subtle behavioral cues. Some types of creativity might indeed be associated with, say, low arousal or alpha synchronization. Overall, however, the evidence reviewed in this study illustrates that every one of these proposals fails when generalized to creativity as a whole. Although this is readily acknowledged in the field, results from individual studies continue to be framed in terms of creativity in general. This is partly a matter of language—using the word *creativity* without circumscribing it, for instance—but it is also partly a matter of conceptual confusion. Creativity, or any of its stages, is routinely treated as if it is a single entity, possessing at best several different aspects and therefore comprising a limited set of fundamental processes or brain structures underlying it. This is likely to be a fallacy. It is hard to believe that creative behavior, in all its manifestations, from carrying out exquisitely choreographed dance moves, to scientific discovery, constructing poems, and coming up with ingenious ideas of what to do with a brick, engages a common set of brain areas or depends on a limited set of mental processes.

The problem comes into focus when it is compared with an analogous situation in mainstream cognitive neuroscience. Researchers there also do not attempt to look for the neural mechanisms of thinking; they investigate attention, working memory, or perception. Creativity research must do the same and look at individual processes. Only when the amorphous concept of creativity is subdivided into different types or component processes broadly along the lines of known neurocognitive processes might it become tractable with neuroimaging tools.

Investigating when, and under which conditions, theoretical concepts such as defocused attention or divergent thinking are, and are not, associated with creativity, is likely to disentangle a great deal of the existing data that are, as it stands now, self-contradictory. To take a concrete example, Jin et al. (2006) investigated scientific creativity (hypothesis testing) and found that *less* gifted children used *more* of their prefrontal cortex, whereas more gifted children revealed less activation, presumably because they were able to use their cognitive resources better. The more-is-better versus less-is-better conceptions underlying brain activation

research continue to be a puzzle, on the basis of task parameters, sample definitions, and underlying conceptual models.

In another example, Lavric et al. (2000) used the candle problem, a traditional divergent thinking task, to study insight events and found that creativity is associated with a less frontal and less left-lateralized P300. The authors' interpretation was that "creative problem solving is less systematic, employs less planning, and needs less working memory" (Lavric et al., 2000, p. 1617). This explanation is at odds with 20 or so other insight and/or divergent thinking studies that found prefrontal enhancement correlated with creativity and, on the basis of this finding, argued the diametrically opposing position, that is, creativity critically depends on more systematic planning, working memory, response selection, and the suppression of stereotypical responses.

In EEG studies, increased synchrony is understood as an indicator of more cooperation between brain areas and, by extension, as a marker of more efficient information transfer or sensory binding. Yet, studies that report decreases in synchrony associated with creativity do not claim that creative information processing is inefficient, which would be, of course, the logical conclusion if this understanding is applied in a consequent manner. Instead, an entirely different explanation is often provided: conflict resolution or remote association formation, for instance. Clearly, accurate theorizing requires more compelling data.

The current theoretical discourse is self-contradictory only if the ideas that creativity is a monolithic entity and that there is only one way in which the brain generates creative outcomes are held onto. Once we fully commit to the idea that there are likely a multitude of processes and brain regions involved in the computation of ideational combinations, we can better constrain our theoretical notions. The present review demonstrates the need for current models on the neural basis of creativity to be developed further. As they are now, they do not yield predictions precise enough for falsification.

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