The cognitive neuroscience of creativity: A critical review

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Abstract

Cognitive neuroscience studies of creativity have appeared with increasing frequently in recent years. Yet to date, no comprehensive and critical review of these studies has yet been published. The first part of this article presents a quick overview of the three primary methodologies used by cognitive neuroscientists: EEG, PET, and fMRI. The second part provides a comprehensive review of cognitive neuroscience studies of creativity-related cognitive processes. The third part critically examines these studies; the goal is to be extremely clear about exactly what interpretations can appropriately be made of these studies. The conclusion provides recommendations for future research collaborations between creativity researchers and cognitive neuroscientists.

Introduction

Cognitive neuroscience studies of creativity have appeared with increasing frequently in recent years. These studies have resulted in many intriguing findings, and a fair amount of media coverage (e.g., Carey, 2006; Hotz, 2009; Tierney, 2010). Yet to date, no comprehensive and critical review of these studies has yet been published (in spite of a few recent treatments: Kaufman et al., 2010; Skov & Vartanian, 2009). The purpose of this article is to provide a critical review of studies that have used the methodologies of cognitive neuroscience (CN) and that have implications for creativity researchers.

This article has three goals. The first goal is to provide creativity researchers with a working understanding of the three predominant CN methodologies: EEG, PET, and fMRI. To prepare the methodological summaries in part 1, three main textbooks (Gazzaniga, Ivry, & Mangun, 2002; Purves, Brannon, & Cabeza, 2008; Ward, 2006) as well as two more advanced texts on fMRI (Huettel, Song, & McCarthy, 2009; Logothesis, 2008) were consulted. Gaps were filled by consulting with expert cognitive neuroscientists (see the Acknowledgements).

The second goal is to review CN studies of creativity that had been published as of October 2010. Part 2 groups these studies into five categories: creative insight; mind wandering and incubation; differences between creative and noncreative people; musical improvisation; and differences with domain-specific training.

The third goal is to critically interpret these studies. Part 3 draws on the methodological understanding provided in part 1 to critically interpret the studies reviewed in part 2, and to summarize the implications of these studies for creativity researchers. The article concludes by providing suggestions for future creativity research that uses these methodologies.

Part 1: The methodologies of cognitive neuroscience

The brain is made up of between 100 and 150 billion neurons. Each neuron connects with between 1,000 and 10,000 other neurons, at connections called *synapses*. A neuron receives signals through short tentacles called *dendrites*; it sums up those signals to determine the strength of the signal it sends down its one single *axon*. Each axon has as many as a thousand or more *axon terminals* that each transfer signals to the dendrites of other neurons. Most axons connect to nearby neighbors, but a small percentage of neurons have extremely long axons that can send signals across the brain. All neurons are constantly *firing*, sending neurotransmitters from the axon across the synapses to the dendrites. The strength of the signal is how many times per second it fires. A relatively calm neuron fires less than ten times per second; a highly active neuron fires between 50 and 100 times per second.

Cognitive neuroscientists focus on the *neocortex*, the thin layer of "gray matter" on the outside of the brain, because it is responsible for all higher-level mental functions. The neocortex is about 5 mm thick (Huettel et al. 2009, p. 185). Inside the brain, below this outer layer, is the "white matter"; this large area is filled with the longer axons that connect distant parts of the brain. It appears to be white

because the axons are covered with *myelin*, a fatty substance that increases the efficiency and speed of the axon's electrical transmission. The neocortex appears to be gray in contrast, because it contains the neuronal cell bodies and the blood vessels that supply blood to the them.

The cortex is *folded*, to allow more of the outer cortical layer to fit into the skull (see Figure 1). The tops of the folds—the part that is pressed against the skull—are called the *gyri*; the crevices are called *sulci*. The total surface area of the cortex is about 2300 cm squared—about the size of a 12-inch pizza—but two-thirds of that is within the depths of the sulci.

> Insert Figure 1. Gross brain anatomy. (a) lateral view of the left hemisphere; (b) dorsal view of the cerebral cortex. The major features of the cortex include the four cortical lobes and various key gyri. Gyri (singular is "gyrus") are separated by sulci (singular is "sulcus") and result from the folding of the cortex. From p. 71 of Gazzaniga, M., Ivry, R. B., & Mangun, G. R. (2002). *Cognitive neuroscience: The biology of the mind* (2nd ed.). New York: Norton.

Cognitive neuroscience today uses three methodologies that allow psychologists to observe changes in brain activity while people are thinking: EEG, PET, and fMRI. Each has its own strengths and weaknesses; two of the methods are sometimes used in combination to take advantage of their complementary strengths. These methods use powerful machines—originally developed for medical diagnoses—to develop temporal and/or spatial representations that show how brain activity changes while the mind is engaged in cognitive tasks. In a CN experiment, the researcher designs a simple task for the research participant, one that can be done while the participant's head is being examined by the machine.

EEG

Neurons transmit signals down the axon and the dendrites via an electrical impulse. *Electroencephalography (EEG)* uses sensors placed on the scalp that measure electromagnetic fields generated by this neural activity. EEG detects the electrical activity at the dendrites—the receiving end of the synapse. If many neurons and their dendrites are lined up in parallel, and if a sufficiently large number of neurons are receiving signals at the same time, a tiny electromagnetic field is created. In the cerebral cortex, neurons and dendrites are indeed aligned in parallel, and a detectable change in the electromagnetic field is generated when neuronal activity increases or decreases. Neurons aren't necessarily aligned in the basal regions of the brain; and even when they are, the electrical signal is weaker because those neurons are more distant from the scalp. Thus EEG is most sensitive to cortical activity.

Any number of sensors, up to 256, can be placed on the head in standard locations. Most studies use between 32 and 128 sensors. The EEG is often most closely examined as a person responds to a stimulus event. The EEG that is recorded right after the stimulus event is presented, or during the response, is called an *event related potential (ERP)*.

Because all neurons are constantly firing, the brain always generates electric waves of amplitudes between 50-200 microvolts. The event related potentials (ERPs) that psychologists are interested in are much smaller amplitudes—usually just a few microvolts. As a result, in an EEG experiment, the participant is given the same activity at least twenty times, but usually many more, up to as many as 100 times; then, mathematical algorithms are used to average over all of the trials (see Figure 2). The normal brain waves of 50-200 microvolts cancel each other out, and what remains is the change in brain activity that is directly related to the cognitive event of interest—the ERP. EEG signals of interest to cognitive scientists occur in the frequency range of 1-50 Hz; ERP signals most often occur in the frequency range of .5 – 20 Hz.

> Insert Figure 2. In EEG experiments, participants are presented with the same stimulus or task up to 100 times, and the EEG waves are averaged across all of the tasks, to reduce the signal-to-noise ratio and reveal the event-related potential (ERP) associated with the task. These are waves of the EEG in response to presentation of an audio tone at time 0. The topmost wave represents a typical EEG from a single trial; the other waves represents averaging across 10, 50, and 100 trials. This is done for each electrode, and each will have a slightly different ERP profile. From Kolb and Whishaw, 2002, *Fundamentals of human neuropsychology, 5th edition*. Worth Publishers.

Different frequency bands of the brain's electromagnetic field indicate different sorts of brain activity:

- delta waves (.5 – 4 Hz)—during deep sleep
- theta waves (4-8 Hz)—greater in childhood; implicated in encoding and retrieval of information
- alpha waves (8-13 Hz)—occurs while awake, while relaxed with the eyes closed
- beta waves (13-30 Hz)—increased alertness and focused attention
- gamma waves (>30 Hz)—still not well understood, but have been implicated in creating the unity of conscious perception

Cognitive neuroscientists typically study alpha, beta, and gamma waves.

The advantage of EEG is that it can detect the brain's response to the external stimulus event essentially immediately—to the microsecond. This is referred to as a *high temporal resolution*. The disadvantage is that EEG cannot support strong claims about where the neurons are that are causing the change in the electromagnetic field; this weakness is referred to as a *low spatial resolution*. Even

though there are as many as 256 electrodes positioned around the skull, an ERP at any particular electrode does not necessarily mean that the ERP was caused by neurons immediately underneath that electrode, because electromagnetic fields extend across the brain. To identify the brain regions associated with neuronal activity, technologies with a higher spatial resolution are used—PET and fMRI.

PET

When neurons in a particular region of the neocortex are firing more rapidly, that region is said to have *elevated neuronal activation*. As a result of elevated activity, the neurons require more oxygen, and blood flow is greater to that region. *Positron emission tomography (PET)* indirectly measures neuronal activity by detecting local changes in regional cerebral blood flow (rCBF). PET works by introducing a radioactive tracer into the bloodstream; where there is more blood flow, there is more radiation. A radioactive isotope of oxygen is often used that decays in less than one minute—a fast decay is important, to reduce the amount of radiation exposure.

During a PET experiment, a person is given a cognitive task that can be done within the time it takes for the oxygen isotope to decay, usually about 40 seconds. While they engage in this task, the associated brain regions increase in neuronal activation; regional cerebral blood flow increases to those regions; and the increased radioactivity is detected by the PET scanner—a large donut-shaped device with the head placed at the center. The result is a three-dimensional representation of the brain activity associated with the cognitive task.

PET has a fairly high spatial resolution; the technology is able to measure the neuronal activity associated with a neocortical region of about 5 millimeters cubed. This 5 mm^3 space is called a *voxel* for *volume element* (the word has an "x" in it because it's derived from "pixel," the term for the two-dimensional "picture element" that's used in televisions and computer screens). On average, neural density in the neocortex is 20,000 to 30,000 neurons per 1 mm cubed, and the number of synapses in a cortical space of 1 mm cubed is close to one billion. This means that in the typical CN study, each voxel effectively contains 5.5 million neurons and about 50 billion synapses (Logothetis 2008, p. 875).

Compared to EEG, PET has a very low temporal resolution; EEG detects the event-related potential (ERP) essentially immediately, but PET requires a full 40 seconds (the time associated with the isotope decay) to measure elevated brain activity.

fMRI

Functional magnetic resonance imaging (fMRI) emerged a few years after PET, but has rapidly become the most widely used brain imaging technique. It has been called "the most important imaging advance since the introduction of X-rays" in 1895 (Logothetis, 2008, p. 869). The fMRI machine uses a magnetic field to detect the ratio of oxygenated to deoxygenated blood; each affects the magnetic field differently. The ratio of oxygenated to deoxygenated blood is referred to as the *blood oxygen level dependent (BOLD)* signal. When neuronal activation increases in a region of the neocortex, blood flow increases faster than the neurons can use the oxygen, causing the BOLD signal to increase.

fMRI is used much more than PET for many reasons: the machines are more readily available; the spatial resolution is higher; unlike fMRI, PET does not actually provide a picture of the brain, so it has to be mapped onto brain space, giving fMRI better spatial identification; and with fMRI, there is no need to inject radioactive tracers with each trial, allowing hundreds of trials which can then be averaged. With a PET experiment, at most 12 to 16 trials can be done, because the radioactive isotope must be injected just before each trial. In addition, the temporal resolution of fMRI is significantly higher; with PET, the researcher must average the brain's activity over 40 seconds of engagement with a task, because even the fastest isotopes decay over 40 seconds, but an fMRI image can be captured every two seconds, allowing for an event-related fMRI (similar to the ERP provided by EEG). As with EEG, neuronal changes associated with any single trial are impossible to detect because of the complexity of brain response; researchers must average the responses to an identical cognitive task over approximately fifty identical trials. This allows the use of statistical algorithms that average out the unrelated brain activity fluctuations and reveal the signal related to the event being studied.

There are three challenges with fMRI that result from its dependence on BOLD signal changes. First, BOLD increases above the resting state only between 1 percent and 3 percent at maximum neuronal activation. When cognitive neuroscientists report increased neuronal activation in a particular brain region, they are reporting an increase that is never greater than three percent above the comparison baseline state of the normal neuronal firing rate within that region. Second, when neurons increase in activation, the BOLD signal does not increase immediately; the initial rise does not occur until several seconds after the increase in neuronal activity, the peak is 4 to 6 seconds later, and it does not decline back to baseline for 15 or 20 seconds (Fink et al., 2007; Huettel et al., 2009). This delay in *hemodynamic response* varies between individuals, so each experiment has to correct for that variation. The hemodynamic response delay varies across different brain regions even in the same person; there is no known way to normalize these variations, but they are not thought to be large. Third, the spatial location of BOLD does not always correspond exactly to the neurons that are increasing in activation, because BOLD detects the anatomical locations of the blood vessels that supply the neurons, not the location of the neurons themselves (Huettel et al., 2009). Furthermore, for accurate localization, fMRI has to detect blood flow in the tiniest capillaries, the ones immediately next to the neuronal cell bodies; but there are much larger blood vessels that feed those capillaries. fMRI technology is largely able to focus only on the smallest capillaries, but this ability varies subtly with different

cortical regions. Researchers who use fMRI have developed techniques to account for these problems, but it will always be an inexact methodology, because of one final challenge: When neurons become more active, blood flow increases not only right next to those neurons, but also over a bigger area that extends to a few millimeters distant, where there may be no increase in neuronal activity (Huettel et al., 2009, p. 179).

Combining methods

Because these technologies have complementary strengths, they can be used together to develop fairly elaborate understandings of how activity in the biological brain corresponds to human mental functioning. One of the most common approaches is to use EEG for its high temporal resolution; then to use fMRI with the same task for its high spatial resolution; then to combine the two findings for a more complete picture of the brain's activity.

Statistical averaging

With EEG, PET, and fMRI, it is not possible to study just one response to a single event, because there are large changes in the EEG, rCBF, and BOLD signals that are always occurring as part of the brain's normal activity. So each participant does the same task tens or even hundreds of times, and the brain activity is averaged across all of these trials. The normal background variation of the brain's activity is thus averaged out, and what remains is the activity of interest.

When research studies report that a specific voxel shows elevated neuronal activity in a particular task, the brain is not necessarily engaging these regions every time it engages in the task; what is being reported is an average over many repetitions of the task.

Standard brains

To account for the ordinary variability in human brains, cognitive neuroscientists do not study a single person. Instead, they perform the same experiment on many people; with PET and fMRI, they do statistical image averaging across all of the brains; and they use statistical algorithms to identify the average location of neuronal activation, across all of the subjects' brain images, averaged together to generate a single "average" brain image.

Even though the overall organization of all brains is quite similar, each human brain is slightly different. Heads come in different sizes and shapes: some more narrow, some shorter front to back. Thus, comparing two brains requires the researcher to mathematically adjust the size of all of the brains so that they are roughly the same. Most researchers adjust the brains to align with a *standard brain* as published in standard neuroscience atlases. Otherwise, normal anatomical variation would make averaging impossible.

Even after doing this, brains differ in the size of the different gyri and the location of folds in the brain; the location of sulci can vary by as much as a centimeter. There is at present no method for manipulating each brain's detailed structure to conform to a standard. To accommodate this natural variation in brain structure, most studies use a mathematical technique known as *smoothing*—which spreads out the observed activation across nearby voxels, thus increasing the chance of overlap among different individuals when statistical image averaging is done.

Movement

Whenever people move their hands, or bend their knees, or turn their heads, large regions of the brain are active, including vast areas of the neocortex, where higher level thought takes place. Even blinking an eye, or twisting the head a tiny bit, or moving the eyes to the side even while the head is stationary, or twitching a leg muscle, causes neuronal activation that can interfere with the image. With the EEG, eye and eyelid movements create electric frequencies in the same range as the EEG signal. For these artifacts, many studies use a standard "correction" that subtracts out the artifact. When there are a lot of artifacts at an electrode, it is often possible to interpolate the signal from the neighboring electrodes. But sometimes the artifacts are severe and the trial has to be rejected completely.

As a result, it is important for participants to remain completely still during these experiments. Typically the head is physically restrained, and participants are asked not to move, but even so, muscles can tense or twitch enough to affect the results. With fMRI, many studies use algorithms that correct for head movement. And with fMRI, the participants cannot talk at the same time that the image is being taken; the vocal tract causes electromagnetic activity that can disrupt the BOLD signal. So for participants to communicate with the researcher, typically they are given a small handheld device with a single button, and they are instructed to push the button depending on what they perceive. This only requires one finger to move a short distance, reducing the associated neuronal activation to a minimum.

Paired image subtraction

There are three facts about the brain that make CN challenging.

- First, every neuron is always firing, at least a few times every second. So researchers always refer to relative activation levels, rather than neurons being "on" or "off."
- Second, it is not the case that when we stare off into space, all of our brain's neurons are firing only at a low activation level. Large parts of the brain are always fairly active. When the mind is engaged in a cognitively challenging task, the brain's energy consumption rarely increases by more than 5 percent (Raichle, 2009). One of the most solid and consistent findings of CN studies is that the brain's resting state is

quite similar to the problem solving state; to conceptual processing; and to memory retrieval (see citations in Smallwood & Schooler, 2006, p. 955).

- Third, there are parts of the cortex that always increase in neuronal activation whenever we engage in any cognitive task.

Cognitive neuroscientists are interested in all of these aspects of the brain; but most of the time, they try to identify specific cortical regions that increase in activation in one kind of task, but not in others. The methodology that allows researchers to identify specific brain regions associated with specific tasks, in spite of these three challenging facts, is called *paired image subtraction*. In every experiment, the first thing that is done is that a brain image is taken during a carefully selected *control state* or *baseline state*, while the participant lies still and does nothing, or stares at a target "X" on the presentation screen, or performs some simple comparison activity. This baseline is also sometimes called the *rest state*. Then, this baseline image is subtracted from the image that results during the task condition.

The key to designing an effective experiment is to design two tasks that are identical in every way, except for one small change that is the cognitive function of interest. The subtraction cancels out the normal activation levels of all of the neurons that do not undergo any change in activation level (facts 1 and 2) and it cancels out all of the neurons that change in activation level the same way in both conditions (fact 3). The image that results shows the differences in activity between a task condition, and the baseline of brain activity (see Figure 3). A specific brain region might be increasingly active in both the experimental and control conditions, but if the increase is greater in the experimental condition (above a threshold of statistical significance), the visual display will show heightened activation for the experimental condition.

Insert Figure 3. In the upper row of these PET scans, the control condition (resting while looking at a static fixation point) is subtracted from the experimental condition of looking at a flickering checkerboard 5.5 degrees from the fixation point. The subtraction produces a slightly different image for each of five subjects, as shown in the middle row. Statistical image averaging across these five subjects results in the image at the bottom. This procedure is always used in both PET and fMRI studies. From p. 65 of Posner, M. I., & Raichle, M. E. (1994). *Images of mind*. New York: Scientific American Library.

Paired image subtraction makes a key assumption: *pure insertion*, meaning that the additional cognitive process can be inserted into the baseline process without indirectly changing any of the activity associated with the baseline process. But this assumption is probably rarely the case, because the brain is complex and nonlinear (Logothetis 2008, p. 871). There is no way to detect these indirect changes, and the implications for interpreting CN studies remains unclear. In many cases, the violation of the insertion assumption is not relevant; and other designs can sometimes be used to ameliorate the problem.

Cognitive conjunction

Some studies make use of the technique of *cognitive conjunction*: participants engage in two slightly different tasks, such that each of the tasks shares one common cognitive component. Then, a paired image subtraction is done for each of the conditions against the resting state. Finally, the regions of heightened activation that are shared across the two tasks are identified; these regions are presumably associated with the common cognitive component.

Part 2: Findings

The following review groups CN studies relevant to creativity research into five categories:

- Creative insight: Remote association, hints and restructuring, hypothesis generation and set shift, story generation
- Mind wandering and incubation
- Creative brains vs. noncreative brains
- Musical improvisation
- Differences with training

Creative insight

Many psychologists have studied the moment of insight (e.g., Duncker, 1926; Metcalfe, 1986; Metcalfe & Wiebe, 1987; Perkins, 1981; Schooler, Ohlsson, & Brooks, 1993; Sternberg & Davidson, 1995; Weisberg & Alba, 1981). Many of these studies draw from a classic set of *insight problems* that are thought to require a moment of insight to be solved. The exact nature and role of insight in creativity is widely debated by creativity researchers, with some researchers emphasizing the critical role played by insight (Cunningham et al., 2009; Ohlsson, 1992), and others arguing that insight plays no role, and that creativity is essentially identical to everyday problem solving (Perkins, 1981; Weisberg, 1986, 1993). Brain imaging technologies are ideally suited to identifying the brain regions associated with creative insight, and to determining whether or not there are distinct cognitive processes that are involved when solving these problems.

The front of the brain is associated with the highest, most deeply human abilities—what are sometimes called "controlling" and "executive" functions of the brain (Srinivasan, 2007). Representational systems, such as symbols and verbal meanings, are processed in the frontal lobes. Dietrich (2004) hypothesized that conscious and deliberate creativity is driven by the front of the brain, but that

spontaneous insight emerges from three cortices behind and under the frontal cortex—the temporal, occipital, and parietal (TOP). The TOP areas are devoted primarily to perception and to long-term memory; they receive many neuronal axon signals from the lower, sensory brain systems. The frontal lobe does not receive direct sensory input; it integrates already highly-processed information from the TOP to enable even higher-level cognitive behaviors like abstract thinking, planning, willed action, working memory, attention.

Remote association

One problem with using insight problems in brain imaging studies is that many people say they solve them without actually having an experience of insight. Instead, they say that they worked systematically and incrementally toward the solution. For example, the three-word remote associates test (RAT) triplets (Bowden & Jung-Beeman, 2003b) are sometimes solved without an accompanying sensation of insight. Perhaps the sensation of insight is purely a subjective feeling of emotional intensity or excitement at having found the problem, but does not actually contribute to solving the problem. Several CN studies have examined whether or not insightful solutions result from different brain activity than solutions with no insight. Jung-Beeman et al. (2004) conducted a series of experiments to determine what happens in the brain when people are solving insight problems. Their studies were designed to address three questions:

1. Are there different cognitive and neural mechanisms involved in having an insight solution versus ordinary problem solving processes?

2. Is there any unconscious processing that immediately precedes the sudden conscious awareness of the insight? Previous studies suggest this is the case (Bowers et al., 1990; Bowers, Farvolden, & Mermigis, 1995; Kotovsky & Fahey, in Kotovsky, 2003).

3. Does the sudden "Aha!" experience reflect a sudden change in the brain that contributes to the solution? Or is it simply an affective response that follows the solution?

From the overview in part 1, we know that all cognitive tasks result in elevated neuronal activity in many of the same frontal lobe regions. Likewise, solving problems with insight and without insight are likely to both involve many of the same cognitive processes and neural mechanisms. But insight solutions seem to require distant or remote associations; and a variety of CN studies have found that when the brain engages in associative tasks, there is elevated neuronal activation in the anterior superior temporal gyrus (aSTG) of the right hemisphere. For example, language comprehension studies show that sentences and complex discourse increase aSTG activation in both hemispheres, and that when distant semantic relations are used, the right hemisphere (RH) aSTG is more active. Solving an RAT triplet requires the simultaneous activation of distant associations, and there is evidence that the right hemisphere is more effective at semantic processing of distant associates (Howard-Jones et al., 2005; Bowden & Jung-Beeman, 2003a). And there is some evidence that the prefrontal part of the RH supports processing of distant associations (Seger et al., 2000).

Their first experiment used fMRI with 13 subjects, and presented each subject with 124 RAT triplets. Participants were given 30 seconds to identify each target word. As soon as they identified the word, they pressed a button in their hand. The researchers then asked them to say the word out loud, simply to confirm that they had the correct word (recall that fMRI cannot be used when subjects are talking). Then, they were asked to press the button again if they had experienced a feeling of insight accompanying the solution.

Fifty nine percent of the problems were solved, and people reported feeling insight for 56% of these solutions. The researchers examined the brain activity during the two seconds before the first button press and the four seconds after. The subjects who solved problems and reported having a sensation of insight showed elevated neuronal activation in the RH aSTG during this six seconds (both before and after the button press), compared to those who solved the problem without an insight sensation.

The temporal resolution of fMRI is low; in this experiment, one brain image was taken per second. Thus these findings might simply reflect a subjective experience of insight, and it is that subjective experience that corresponds to the elevated activity in the RH aSTG—but that activity might not contribute to the insight solution, it might simply be a response to the solution. A more important question is, was the problem actually solved differently when subjects felt they were having an insight? The researchers wanted confirming evidence with better timing information, so they did exactly the same experiment with a new group of subjects, but this time with EEG, and compared the time-frequency analyses of the EEGs of insight solutions and noninsight solutions.

When analyzing the EEG signal using the statistical averaging method described in part 1, they found an increase in gamma wave activity in the front RH (but not LH) associated with insight solutions, and this burst began about .3 seconds before the solution button-press. No increase was observed for noninsight solutions. The researchers used the converging evidence from the fMRI to suggest that this might correspond to the RH aSTG (the poor spatial resolution of EEG would never allow such a specific localization). The researchers hypothesized that the RH aSTG may have contributed to the solving of a triplet with insight, because the EEG increase preceded the button press and thus preceded the conscious realization of a solution.

However, the elevated EEG activity continued to increase for a full second after the button was pushed, suggesting an alternative explanation: it might reflect the excitement of getting the solution—an effect of the solution rather than a cause

(see Sheth, Sandkühler, & Battacharya, 2008). After all, brain activity that contributed to identifying a solution would most likely terminate once that solution were found. Providing evidence for their causal interpretation, in another study (Jung-Beeman, Bowden, & Haberman, 2002), when insight was reported, there was greater neuronal activity in the RH superior temporal succulus for the final 2 seconds before participants solve the problems, than when no insight was reported. Two seconds is long enough that it most likely precedes the subjective conscious awareness of knowing the solution.

In a third study (Kounios et al., 2006) different alpha wave patterns *preceded* the *presentation* of the problem when insight solutions were reported. There was no difference in the EEG between successfully getting the answer versus not getting the answer, suggesting that subjects were doing the same basic sort of mental work whether or not they got the answer. In Experiment 2, they did an fMRI to identify the pattern of brain activity *before* the problem was presented. Those people who solved a problem with insight displayed a greater activity of the anterior cingulate cortex (ACC) just before the problem was presented. They concluded that ACC activity is responsible for the alpha-wave mid-frontal activity detected with the EEG.

In sum, these experiments provide some evidence for a distinct pattern of neuronal activation immediately prior to an insight solution. The pattern of brain activation is consistent with other cognitive tasks that require distant semantic associations, including those that are not thought of as creative tasks per se. But because this pattern continues even after the solution, it is probably too simplistic to argue that the associated brain region is dedicated to solving distant associations like the RAT.

Hints and restructuring

The Gestaltist model of insight suggests that some sort of fixation leads to an impasse, and the impasse can only be overcome by a mental restructuring of the problem representation that would remove the fixation. Several creativity researchers have evaluated this model by using an experimental paradigm in which subjects who are stumped are then provided with *hints* designed to prompt a restructuring (Gick & Lockhart, 1995; Kaplan & Simon, 1990; Weisberg & Alba, 1981). A similar paradigm has been used in several CN studies.

Luo and Knoblich (2007) presented insight problems (Example: "the thing that can move heavy logs, but cannot move a small nail" answer: "river") followed by either hints that led to restructuring, or hints that reinforced the incorrect structuring. When they provided a restructuring hint, they observed elevated neuronal activation in the bilateral superior frontal gyrus, the medial frontal gyrus extending to the cingulate cortex, and bilateral posterior middle temporal gyrus. They also found elevated neuronal activation in the ACC with insight problems compared to noninsight problems. Interestingly, this ACC activation declined across

trials throughout the course of the experiment, suggesting that subjects were developing general strategies to deal with this sort of word problem.

Sheth et al. (2008), using EEG, found brain differences up to eight seconds before the solution, when the problem was solved with insight. They observed a reduction in beta power (15-25 Hz) over the parieto-occipital and centro-temporal regions, compared to a ten second preresponse baseline, with: (a) correct vs. incorrect solutions; (b) solutions without a hint, vs. with a hint; (c) success after the hint is provided vs. no success (they compared the ten seconds before hint and the ten seconds after); (d) self reported high insight vs. low insight. Gamma band (30-70 Hz) power was increased in the right fronto-central and frontal regions for (a) and (c). Lower alpha was increased for insight vs. non-insight solutions in the central-parieto region. The most intriguing result was that for those who were stumped and then were presented with a hint, the brain activation pattern was different *even before the hint was presented* for those who eventually got the answer vs. those who did not (cf. Kounios et al., discussed earlier). This suggests the existence of a brain state that better prepares a person to receive a hint and use it successfully.

Fink et al. (2009) found an increase in alpha synchronization in frontal brain regions, and a diffuse and widespread pattern over parietal cortical regions, in response to more free associative tasks (like the Alternative Uses test, and a Name Invention task). More original ideas were associated with stronger increases in alpha activity than conventional ideas. A corresponding fMRI study found strong activation of LH frontal regions in the same conditions, particularly the left inferior frontal gyrus (this finding was replicated by Jung-Beeman, 2005).

Using EEG, Sandkühler and Bhattacharya (2008) gave people RAT triplets; they could press a button if they were stumped, and right away they would be shown a hint: the first letter of the target word, or half of the letters of the target word. The first two seconds while they were reading the problem was used as a baseline. They found strong gamma band responses in parieto-occipital regions for insight vs. noninsight solutions (38-44 Hz). They also found increased upper alpha band response (8-12 Hz) in RH temporal regions. Alpha band activity is often associated with cognitive inhibition, suggesting that for initially unsuccessful trials that after a hint led to the correct solution, there was active suppression of weakly activated solution relevant information.

Hypothesis generation and set shift

Vartanian and Goel (2007) summarized several studies focused on *hypothesis generation* and *set shift*: a movement from one state in a problem space to a very different state, with no obvious incremental step-by-step transition (also see Goel & Vartanian, 2005). These included studies on Guilford's match problems (requiring re-arranging matches to generate a specified number of squares) which compared a divergent condition (generate all of the possible ways this problem could be solved) to a convergent condition (subjects were presented with a hypothetical

solution and asked to say whether it was correct). The hypothesis generation required by the divergent condition activated left dorsal lateral PFC and right ventral lateral PFC (vs. baseline). When subjects got a correct solution—which was evidence of a set shift—only the left dorsal lateral PFC was still increased in activation vs. baseline.

With anagram problems, right ventral lateral PFC was activated when problems were solved without any hint ("Can you make a word with CENFAR?") vs. given a specific semantic category as a hint ("Can you make a country with CENFAR?"). They concluded that hypothesis generation in open-ended settings activates a network that includes right ventral lateral PFC, for both spatial and linguistic stimuli. These are different areas than the ones implicated in the RAT insight studies—in those, it is the right temporal lobe. In another study, they found that activation in right dorsal lateral PFC covaried with the total number of solutions generated in response to match problems—which could be the result of working memory, cognitive monitoring, or conflict resolution.

Kounios et al. (2008) also studied anagram problems, and focused on the resting state, the period just before the anagram was shown. The researchers divided subjects into two groups based on how they reported having solved anagram problems: one group with people who were more likely to report solving a problem with insight (the "high insight" group, HI) and another group who were less likely to report using insight (the "low insight" group, LI). High insight people had different resting state EEGs compared to low insight people. LI people had more high alpha—which indicates less activity in the visual cortex—than the HI group. This suppression of activity was greater in the LH. The LI group had greater beta-1 EEG as well, suggesting more focused visual attention. The HI group had more RH activity, in low alpha, beta-2, beta-3, and gamma frequency ranges. Kounios et al. explained these findings by suggesting that a person's likelihood of using insight to solve a problem is influenced by the characteristics of the prior resting state; they could predict the likelihood that a person would later use insight to solve an anagram, by analyzing the EEG during the resting state just before the anagram was displayed. The tendency to use insight or not remained stable through the course of the experiment; people used the same amount of insight in the second half of the experiment as in the first half. This confirmed many other studies that have shown that resting state EEG is relatively stable over time.

In the above experiments, the brain regions that display elevated neuronal activity during creative tasks are also involved in a wide range of non-creative cognitive tasks. The RH aSTG is implicated in integration across sentences to extract themes; to form coherent memories for stories; generating the best ending for a sentence; and to repair grammatically incorrect sentences. The ACC is implicated in monitoring for competition among potential responses or processes; in voluntary selection; in conflict monitoring; in decision making; and in unrehearsed movements (see Berkowitz & Ansari, 2008, p. 541). Some studies suggest that ACC is involved in suppressing irrelevant thoughts. Neuronal activity in the ACC was elevated with insight solutions, suggesting that shifting the mind away from an answer that one realizes is incorrect involves cognitive control mechanisms similar to those involved in suppressing irrelevant thoughts.

Story generation

Howard-Jones et al. (2005) examined brain activity while participants generated fictional short stories, while engaged in a task designed to require verbal creativity: participants were presented with three words and then asked to create a story that contained all three words. The researchers varied this three-word short story task to create four conditions in a 2x2 design: (1) instructing subjects to "be creative" or "be uncreative"; (2) providing subjects with three unrelated words (flea, sing, sword), or three related words (magician, trick, rabbit). While in an fMRI scanner, the participants were given 22 seconds to generate each story. Using paired image subtraction to subtract the "be uncreative" image from the "be creative" image, an increase in prefrontal activity was observed, including bilateral medial frontal gyri and left anterior cingulate cortex (ACC). Using paired image subtraction to subtract the unrelated words image from the related words image, elevated neuronal activity was found in bilateral ACC and right medial frontal gyrus.

As with the insight studies, these brain areas are not unique to creative tasks; they are involved in a wide range of cognitive tasks. Left prefrontal activation is elevated in word association tasks and sentence completion tasks. Increased ACC activity has been linked to a wide range of tasks with increased information processing demands, including selecting items from episodic memory. Making divergent associations requires increased conflict monitoring; the ACC and the prefrontal cortex are associated with additional conflict monitoring and with insight solutions.

Mind wandering and incubation

One of the oldest observations in the psychology of creativity is that a creative idea is often preceded by a period of unconscious incubation (James, 1880; Poincaré, 1913/1982; Hadamard, 1945). Contemporary creativity researchers have often studied incubation and its role in creative insight (Beeftink, van Eerde, & Rutte, 2008; Ellwood et al., 2009; Kohn & Smith, 2009; Patrick, 1986; Sternberg & Davidson, 1995). The majority of studies has confirmed the existence of an *incubation effect*, although the exact nature of the associated unconscious processes remains uncertain. Hypotheses include mental relaxation, selective forgetting, random subconscious recombination, and spreading activation.

Cognitive neuroscientists have studied a closely related mental phenomenon: *mind wandering*, when our thoughts drift away from the task at hand to something completely unrelated. Mind wandering involves a shift away from a primary task to process some other, personal goal, but in a way that is not obviously

goal-directed or intentional. Some neuroscientists have hypothesized that people prone to mind wandering may score higher on tests of creativity (Hotz, 2009; Tierney, 2010). Recent studies of the brain's idle states can potentially help us identify what brain regions are associated with the mind wandering state, and potentially have implications for our understanding of the role of incubation in the creative process.

During waking hours, people's minds wander between 15 to 50 percent of the time, depending on the task. For example, people's minds are wandering 20 percent of the time they are reading, and half of those times people are not even aware that their minds are wandering (Smallwood & Schooler, 2006, p. 956). The content of mind wandering is dominated by typical life events and is rarely focused on fantasy (Andrews-Hanna et al., 2010; Singer & Antrobus, 1963). Mind wandering varies with fatigue, with alcohol, and with difficulty of the task. Kane et al. (2007) found that it averaged 30% in an experiential sampling of everyday life, and that it varied depending on working memory capacity (WMC). In people with high WMC, their minds wandered less when the task required focused concentration, but their minds wandered more when task demands were low.

Klinger (2009) found that on average, people have about 4,000 thoughts of all kinds during a typical day, each averaging 14 seconds in length, and that half of these qualify as "daydreaming" defined as undirected mind wandering or thought that is at least partially fanciful (p. 228). He hypothesized that even in cognitively demanding tasks, there would be a minimum rate of daydreaming of about ten percent of the time.

Raichle (2009) identified a *default network*—parts of the brain that are active in the resting state, but that become less active when engaged in various cognitive tasks. Somewhat paradoxically, these same regions reduce in activity during unconscious states (Andrews-Hanna et al., 2010). Brain imaging has found that the default network continues to be active in tasks that involve passive sensory processing, but tends to reduce its activity with tasks with high central executive demand—a pattern similar to mind wandering, thus suggesting that the default network may be involved in mind wandering. Mason et al. (2007) found that when people were engaged in a task they had practiced on, allowing them to daydream, the default network was more active than when they were engaged in a novel task. Christoff et al. (2009) found that the default network was most active when people's minds were wandering and they were not aware of it. There is evidence that task performance is more severely disrupted by mind wandering when one is not aware that it is occurring.

The above studies of mind wandering suggest that people spend more of their daily lives engaged in an incubation-like state than they probably realize: People typically are only consciously aware of one-half of their mind wandering episodes. This suggests an interesting possibility that creativity researchers might study further: these brief episodes of mind wandering may provide the mind with

moments of "mini incubation" that contribute to creative thought, by temporarily taking conscious attention away from the problem at hand and providing a brief opportunity for insight to occur.

Creative brains versus noncreative brains

The methods of CN are not able to reliably analyze the activity within a single person's brain. But they can be used to identify differences between groups of people, so long as there are enough people in each group to do statistical image averaging. A few studies have examined differences in neuronal activity between people who get high scores on creativity tests, compared with people who get low scores. In one of the earliest studies, using EEG, Martindale and Hines (1975) found that creative people show higher levels of alpha wave activity when engaged in creative tasks like the Alternate Uses Test and the RAT, whereas medium- and low-creative groups had lower alpha wave activity.

Carlsson, Wendt, and Risberg (2000) used the Creative Functioning Test (CFT) to select a high creative and a low creative group (each with 12 male right-handed students). They then presented three tasks which were expected to activate the frontal lobes increasingly: the lowest expected activation was for an automatic speech task (count aloud, starting with 1), the next higher activation was a word fluency task (FAS: say all words you can think of that start with the letter "F" or "A" or "S"), and the final was a divergent thinking task (say as many uses as you can think of for a brick). They measured rCBF by using a special helmet with 254 sensors to detect radiation emitted by the isotype. They found that low creatives had more elevated LH during the word fluency task; high creatives had more elevated RH during the brick test. (Strangely, the automatic counting task resulted in higher blood flow than either of the other two tasks; the researchers could not think of a plausible explanation for this, so their analysis focused on the FAS-brick contrast.) The biggest differences, when comparing brain activity on FAS and on brick, were elevated anterior prefrontal activation in creatives (both hemispheres), and decreased fronto-temporal and anterior prefrontal activity for low creatives (particularly in the RH). They concluded that high creatives use bilateral prefrontal regions on the brick task, while low creatives used mostly LH. High creatives had more increased activity in these regions, compared to FAS, than low creatives—whose brains looked about the same in FAS and in brick.

Chávez-Eakle and her team (Chávez-Eakle, 2007) used PET to compare six individuals with TTCT (Torrance Test of Creative Thinking) scores in the 99th percentile with six individuals at the 50th percentile, by giving them the Unusual Uses test. The high scorers on verbal TTCT had greater rCBF (regional cerebral blood flow) in the right precentral gyrus; the high scorers on the figural TTCT had greater rCBF in right postcentral gyrus, left middle frontal gyrus, right rectal gyrus, right inferior parietal lobe, and right parahippocampal gyrus—indicating that "a

bilaterally distributed brain system is involved in creative performance" (p. 217) although most of the elevated activity is in the right hemisphere.

These studies provide some evidence that in less creative people, the right hemisphere is slightly less active. But it is misleading to say that creativity is "in" the right hemisphere (also see Feist, 2010, p. 118; Kaufman et al., 2010, p. 221); the above studies found that high creatives show patterns of bilateral hemispheric activation. And as always, one must keep in mind that these differences, resulting from paired image subtraction, are never greater than three percent in any single voxel.

Musical improvisation

A series of intriguing experiments have recently been conducted with trained musicians engaged in a variety of musical tasks. In the first such study, 11 professional pianists were imaged with fMRI as they improvised a simple melody, based on an eight-note melody that was displayed to them, and then were imaged as they reproduced the improvised melody (Bengtsson, Csikszentmihalyi, & Ullen, 2007). This resulted in "improvise minus reproduce" subtraction images. Then, the pianists freely improvised but without memorizing and reproducing the improvisation, and this resulting in "freeimp minus rest" subtraction images. Their keyboard had one octave of 12 keys (white and black), and the musicians could hear what they were playing through scanner-safe headphones.

When the averaged image of a brain reproducing an improvised melody was subtracted from the averaged image of the brain improvising that melody for the first time (the "improvise minus reproduce" condition), there were significant brain differences in 14 regions, including: right DLPFC, pre-SMA, bilaterally in the rostral portion of the dorsal premotor cortex (PMD); temporal lobe activations in the left posterior superior temporal gyrus (STG), and the fusiform gyrus; bilateral occipital activity in the middle occipital gyrus. Essentially, all of these areas were also activated in the conjunction between improv-minus-reproduce and freeimp-minus-rest. The right DLPFC is activated in many other free choice tasks, including word generation, number generation, word-stem completion, and sentence completion. A range of studies show that the DLPFC is centrally involved in planning and performing novel and complex behavioral sequences, including language and thought. Several of the other active areas are also activated in movement sequence production.

Berkowitz and Ansari (2008) studied twelve classically trained pianists engaged in four different tasks. The researchers designed a special five-note keyboard that the subjects could play with the fingers of one hand, only moving the fingers and not the hand. The keyboard had middle C through G, the white keys only. The subjects listened through scanner-safe headphones.

As with all CN studies, the goal was to identify the subtle differences between the tasks with paired image subtraction; each task required a slightly different degree of improvisation. Before the experiment, the subjects were taught seven different five-note patterns that were extremely simple: either five presses of the same key (CCCCC, DDDDD, EEEEE, FFFFF, GGGGG), an ascending scale (CDEFG), or a descending scale (GFEDC). In their first task, the pianists played any of the five-note patterns, in any order they chose. Thus they had to make a decision every five notes, resulting in a rather small degree of melodic improvisation. In the second melodic improvisation task, the pianists continuously invented five-note melodies—thus making a decision every note.

Both of these tasks were performed with or without a metronome that clicked two beats each second. With the metronome, subjects were told to play only one note per click. With no metronome, subjects were told to improvise rhythmically as well as melodically. This design allowed the researchers to isolate the brain regions associated with three different activities: rhythmic improvisation alone, melodic improvisation alone, and both types of improvisation combined.

Using the cognitive conjunction technique, the conjunction of the brain images during the two melodic improvisation tasks was associated with increased neural activity in the dorsal premotor cortex (dPMC), anterior cingulate cortex (ACC), and inferior frontal gyrus/ventral premotor cortex (IFG/vPMC), all in the left hemisphere (which was expected, since the task was performed with the right hand).

As with all studies above, these brain regions are the same ones that are used in a wide variety of everyday cognitive tasks. The dPMC is involved in a wide variety of motor tasks, including selection and performance of movements. The ACC, which is implicated in remote associations, is involved in many cognitive tasks, including unrehearsed movements, decision making, voluntary selection, and willed action. The third region includes part of Broca's area, typically associated with language production and understanding, or more generally with producing and processing sequential auditory information.

In sum, improvisation involves brain regions that are involved in the generation and comprehension of sequences, making decisions among competing alternatives, and the creation of a plan for the motor execution of that sequence. These are domain-general brain regions, suggesting a role for domain-general mental processes in creativity.

Limb and Braun (2008) used a more realistic improvisational musical task. They compared two conditions, using six trained jazz musicians: (1) subjects played a previously memorized jazz composition, while accompanied by a jazz quartet they could hear through headphones; (2) subjects improvised over the same chord sequence, while hearing the same accompaniment through their headphones. Their keyboard had 35 full-sized keys.

They observed activation in the same three brain regions as Berkowitz and Ansari (2008). But because the tasks were so much more complex, they found changes in activity in over forty brain regions. Many of these are likely to be not specific to music or to improvisation, but related to general cognitive activity such as

attention, working memory, and task complexity. One particularly interesting result was a decrease in activity in almost all of the lateral prefrontal cortices, particularly in the lateral orbital prefrontal cortex (LOFC) and the dorsolateral prefrontal cortex (DLPFC), suggesting inhibition of regions involved in monitoring and correction. They observed increased activation in superior and middle temporal gyri (STG and MTG) and ACC, as well as many other areas. They observed increased activity in the medial prefrontal cortex (MPFC), which has been associated with autobiographical narrative. The decreased activity is in the regions which are associated with consciously monitoring goal-directed behaviors.

As Berkowitz pointed out, "the brain imaging results from these two studies correlate quite well with artists' experiences of improvisation" (2010, p. 144). Musical improvisation involves brain regions associated with the skills that underlie everyday improvisational action: selection and performance of movement, decision making, language processing and sequential auditory information, and inhibition of monitoring. However, note that no brain areas are uniquely associated with improvisation; all of these brain areas are involved in a wide variety of cognitive tasks, many of them not considered to be creative.

Differences with training

Brain imaging studies have found that people with musical training process music differently, people with artistic training process art differently, and people with dance training process dance differently.

Music training

When listening to music and when generating music, the brains of trained musicians show different patterns of activation than nonmusicians. Berkowitz and Ansari (2010) compared trained musicians with nonmusicians in the simple five-note improvisational task described above. The key difference was that the musicians deactivated the right temporoparietal junction (rTPJ) while the nonmusicians did not. The authors cite evidence that this region is engaged in bottom-up stimulus driven processing (although it is involved in many other tasks as well); deactivation of this region seems to inhibit attentional shifts toward task-irrelevant stimuli during top-down, goal-driven behavior. Thus, musical training seems to result in a shift toward inhibition of stimulus-driven attention, allowing for a more goal-directed performance state. Schlaug (2006) demonstrated that trained musicians process a pitch memory task using different brain regions than non musicians.

Art training

Bhattacharya and Petsche (2005) used EEG to compare artists (MFA graduates from the Academy of Fine Arts in Vienna) and nonartists mentally composing a drawing (while staring at a white wall), and found significantly different patterns of functional cooperation between cortical regions. Comparing the tasks to rest, the artists showed stronger short- and long-range delta band synchronization, whereas the non-artists showed enhanced short-range beta and gamma band synchronization primarily in frontal regions; comparing the two groups during the task, the artists showed stronger delta band synchronization and alpha band desynchronization, and strong RH dominance in synchronization. These findings correspond to the more general finding that well-mastered tasks typically show greater coherence or synchronization across cortical regions. For example, expert chess players show stronger delta band coherence than novices when anticipating chess movements. The researchers interpreted these differences as due to more advance long-term visual memory, and extensive top-down processing.

Dance training

Fink et al. (2009) compared expert professional dancers with beginning dancers who had just completed a first class in basic dance. They asked them to wear EEG electrodes while they mentally performed either an improvised dance, or a classic waltz. They also did an Alternative Uses test (tin, brick, sock, ballpoint pen), and during these tests, the dancers showed stronger alpha synchronization in post-parietal brain regions. During improvisation imagery, dancers showed more RH alpha synchronization than the novices, while there were no differences with the waltz. The researchers interpreted the increased alpha synchronization as inhibition of processes not directly relevant, or of top-down control.

These studies that compare experts with nonexperts provide support for an intriguing hypothesis: Neuronal activation patterns may change in response to experience and learning (e.g., Posner & Raichle, 1994; Reiterer, Pereda, & Bhattacharya, 2009). However, causation has not yet been proven; it might be the case that people who become experts in a domain have different brains to start with. Longitudinal studies will be required to determine causation.

Part 3: Critical review

Although CN is still in its infancy, it has already contributed to our understanding of creativity.

- The entire brain is active when people are engaged in creative tasks. The studies reported above tend to obscure the diffuse nature of most brain activity, due to the paired image subtraction technique. At issue in all of these studies is not "which areas of the brain are active" (the answer is almost always "most of them") but rather a more specific technical question: which brain areas display statistically significant differential activation across two tasks?
- These studies generally do not reveal differential activation across the two hemispheres; left and right hemispheres are equally activated in

most creative tasks (although with some minor variations). Thus CN studies confirm what is already known from previous methodologies (see Runco, 2007, p. 74; Sawyer, 2006, pp. 78-83): there is no evidence for the popular belief that creativity is located in the right hemisphere of the brain. Many regions of the brain, in both hemispheres, are active during creative tasks.

- When people are engaged in creative tasks, the same brain areas are active that are active in many everyday tasks—even in ordinary tasks that we do not associate with creativity. Every normal, healthy human being engages in these brain processes; they are required for everyday functioning. These findings are consistent with research in the creative cognitive approach (Smith, Ward, & Finke, 1995) that has found that creativity involves a wide variety of everyday cognitive abilities.
- Mind wandering is likely to be the brain state that corresponds to incubation. But it seems to occur in very brief periods that could be thought of as *micro incubation*, and it occurs even when a person is unaware it is happening.
- The importance of association, and in particular, distant association, is confirmed by these studies.
- The role of unconscious progress toward insight is partially confirmed, consistent with the existence of an incubation effect, and with studies of intuition (e.g., Bowers, Farvolden, & Mermigis, 1995)
- The importance of domain specific expertise is confirmed. Extensive training in a domain is associated with different patterns of brain activation.

These findings suggest that CN has much promise as a methodology for creativity research. However, the methodology has several limitations:

1. For the most part, what CN has discovered are facts that are largely already known from the classic experimental methods of cognitive psychology (Carey, 2006, p. 4). For example, in the 1970s, these experiments had discovered that verbal and visual information were represented differently in the brain; so when brain imaging shows that these two types of information result in different patterns of neuronal activation, no one is surprised. To take another example, researchers also discovered that implicit memory and explicit memory were distinct, long before CN identified the associated brain regions.

2. Neuroscientists agree that all cognitive function involves many regions of the brain. The colorful images that are displayed in journal articles, with small colored dots showing "the locations" associated with a task, result from averaging and subtraction; what is not shown in that image are the many brain regions that are active in both conditions, before the subtraction (see Figure 3). An overly strong emphasis on localization has the potential to distract from the reality that what goes on in the brain is diffuse and distributed. These studies cannot be used to make claims that creativity is "in the right brain," for example; even if heightened activation had been observed in the RH—which it generally is not—the heightened activation is never more than 3 percent above the activation level of that region during the comparison task or the baseline state.

3. It is hard to use brain imaging studies to make claims about causation, because an area may be activated during a task but not play a critical role in performing the task; rather, it might be "listening" to other brain areas that provide the critical computations.

4. These findings result from averaging across many trials, typically about 50 per experimental condition. The voxels that show statistically significant elevation after averaging and subtraction do not necessarily display elevated activation in every trial. So it is always incorrect to interpret these studies as showing that "creativity is located in the ACC" or even "the right hemisphere" although a quick read through a particular study might misleadingly give that impression. A more guarded conclusion is always in order for all CN studies, to wit: over large numbers of trials and over many subjects, on average, we observe a statistically significant difference (generally 3 percent or less) in brain activation across two tasks.

5. The scanners used for PET and fMRI are large and expensive. People have to lie down and remain completely still, while they listen to the extremely loud whirring of the scanner's motor. Bodily movements, even quite small ones, activate large regions of the brain and overwhelm the signal associated with the mental processing of interest. So there is no hope of being able to study people engaged in normal activities in their everyday contexts.

This makes the study of collaborative groups, and of people engaged in creative work with external representations—for example, the problem finding process used by many painters (Getzels & Csikszentmihalyi, 1976)—impossible to study.

6. The standard definition of creativity as "the general of something novel and useful" is not used in any of these studies. It is probably not possible to operationalize "usefulness" in CN terms; and "novelty" is not sufficient to define creativity, because the generation of novel behaviors and thoughts is a component of almost all cognitive activity (e.g., almost every sentence we speak during a day is one that we have never spoken before). So at present, there is a fairly large gap between creativity as operationalized in these experiments, and creativity as operationalized by most creativity researchers.

7. Finally, the approach is, by nature, reductionist; the mental processes studied are quite small, compared to the mental complexity and long-term cognitive processes that are associated with real-world creativity. The reductionist approach of CN is appropriate for many brain functions—for example, perceptual systems like

vision are processed in a fairly regular way through a specific set of neurons. But with higher cognitive functions such as problem solving, language, decision making, memory, and creativity, our thoughts and behaviors are *emergent complex phenomena*: they involve many distinct neural groups, scattered throughout the brain (Bechtel & Richardson, 1993). Any meaningful creative product is likely to have behind it tens or even hundreds of these brief mental events. Imagine a writer composing a poem; each selection of a single word is likely to result from multiple events of association and insight. And after a first draft is completed, the process of editing and revising will involve hundreds more such mental events. Thus in a creator's life, these mental moments occur over a long period of time, where the mind's processing is interspersed with solitary interactions with external representations, and social interactions with others working in the area. These two latter processes can't be localized in the brain—the role of external representations requires attention to externalization processes, and the role of social interaction requires study of the interactional dynamics of groups.

Cognitive neuroscience has the potential to contribute a valuable perspective to creativity researchers. These studies show that creativity is not localized in one brain region; rather, creativity emerges from a complex network of neurons firing throughout the brain. These findings paint a complex picture of the relationship between brain science and creativity. Future technology can be expected to give us better and better images; however, there are three limitations of these methods that cannot be overcome.

1. The spatial resolution of EEG will never get much higher due to the diffuse nature of the electric fields in the skull.
2. The temporal resolution of PET and fMRI can never be increased dramatically because the hemodynamic response is so sluggish. It takes 15 seconds for the brain's blood flow to return to its resting state, so it will never be possible to do trials more often than every 15 seconds.
3. The spatial resolution of fMRI will get much higher with increasing magnetic field strength. Logothetis (2008) predicted that slice thicknesses will decline to one-half of a millimeter, with voxel sizes two or three orders of magnitude smaller than at present (p. 871). But an increase in spatial resolution will not advance CN very much, due to the normal variations among brains that require averaging and smoothing, and also due to the fact that BOLD is itself not localized to one narrow location.

Recommendations for future study

The overall message emerging from these studies is that creativity is not dependent on any particular mental process or brain region. Over twenty different brain regions are implicated in the studies reviewed here. Partly, these findings reflect a lack of consistency in how "creativity" is operationalized. The studies use a wide range of tasks, and each of these tasks is likely to differentially activate the brain. Thus these studies suggest that what we think of as "creativity" involves a wide variety of cognitive processes, each of which results in distinct patterns of brain activation.

Some of the definitions of creativity used by creativity researchers—such as "novelty plus appropriateness"—are not suitable for CN methodologies. Another widely used concept—divergent thinking—does not seem to be localizable in the brain. Association (in the convergent thinking task of the RAT) is partially localizable, but not completely. For creativity research to effectively utilize CN methodologies, it is likely to be necessary to decompose the concept of "creativity" into more specific, more experimentally tractable constructs. Existing CN studies of cognition, memory, attention, etc. can potentially provide creativity researchers with new ways to think about how to subdivide the concept of creativity into a set of brain-based constructs. For example, it might be the case that there are many different neural pathways that result in behavior we characterize as "creative"—just as there are many different neural pathways for what we call "memory", depending on whether it is implicit or explicit, imagery or verbal, etc. As such, collaboration with cognitive neuroscientists could contribute to theory development in creativity research.

However, there is a risk that could limit the potential for links between CN and creativity research: once creative behavior is decomposed into experimentally tractable cognitive functions, these component functions may turn out to be the same functions involved in behavior that is generally thought to be non-creative, routine, or everyday. It may be the case that the construct of creativity simply cannot be defined in terms of cognitive events that occur in one minute or less.

The above review suggests several promising lines of future study:

1. More studies should use EEG to identify the temporal process of creative thought. EEG should more frequently be used in conjunction with fMRI, as done with the RAT triplet studies of (Bowden et al., 2005).
2. Studies that focus on spatial location can provide intriguing insight into the brain's cognitive structure; but these studies should not be interpreted as identifying "the location" for a particular cognitive activity. Rather, the promise of high spatial resolution technologies such as fMRI is that we can identify similar patterns of elevated neuronal activity in a variety of tasks, and potentially identify cognitive processes and mechanisms not formerly thought to be associated with creativity. Identifying such links will require working with experienced cognitive

neuroscientists who are aware of the full range of studies, not just studies focused on creative thought.

3. Mind wandering studies could be applied more specifically to incubation and creativity.

4. Most studies to date have focused on the neocortical regions associated with higher level cognitive processing. Future studies might extend the focus to brain regions associated with emotion, motivation, and the subjective experience of flow, because other methodologies have shown that these are associated with creativity.

5. There is much potential in studies of creativity in specific domains, both with experts and non-experts. Creativity research has concluded that creative performance is due to both domain general and domain specific components, with the majority due to domain specific components (Kaufman & Baer, 2005). If so, the majority of CN studies should likewise focus on creativity in the domains. This has not been the case to date.

6. A broad range of creativity research shows the important role of domain-specific knowledge, acquired over time and represented in long term memory (LTM), thought to be primarily in the temporal, occipital, and parietal lobes. Thus, future studies should explore the role of LTM in creative thought, and the complementary relationships between LTM and working memory (cf. Dietrich, 2004).

7. Domain-specific expertise also involves automatized routines, developed as a result of training and expertise. Future studies should examine the role of automatized routines in creativity; these are thought to be represented in the cerebellum (see Vandervert, Schimpf, & Liu, 2007).

Cognitive neuroscience has made great strides in a short period of time, and it has potential to enhance our understanding of creative cognition. These experiments demonstrate the benefits of collaboration between creativity researchers and cognitive neuroscientists. Continued interdisciplinary collaboration has the potential to further advance our understanding of the mental processes and structures associated with creative thought and behavior.

Acknowledgements

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