R. KEITH SAWYER

the SCIENCE of HUMAN INNOVATION

Explaining Creativity

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CHAPTER 10

COGNITIVE NEUROSCIENCE AND CREATIVITY[1]

When cognitive psychology emerged in the 1970s, there was no way to directly observe what was happening in the mind, so psychologists developed a series of experimental techniques that allowed them to infer what must be happening in the mind, based on how people act in highly controlled settings in the laboratory. This *experimental cognitive psychology* provided the research summarized in Chapters 5, 6, and 7.

Beginning in the 1990s, an exciting new technology became available to cognitive psychologists: *brain imaging.* Brain imaging allows psychologists to see what's happening in the brain while people are thinking. The technology uses powerful machines—originally developed for medical diagnoses—to develop three-dimensional images that show how brain activity changes while the mind is engaged in cognitive tasks. Brain imaging is at the core of the new field of *cognitive neuroscience.* In a cognitive neuroscience experiment, the researcher designs a simple task for the research participant. The participant engages in the task while his or her head is positioned inside the brain scanner. By examining brain activity while a person is engaged in a particular task, researchers can make inferences about which areas of the brain are associated with that task. Cognitive neuroscience has made great strides in a very short period of time, and funding agencies have been generous, so we can expect new developments to continue.

The fundamental assumption guiding all cognitive neuroscience is that all of our sensations, thoughts, and mental processing are based in the biological brain, and that when we have a subjective experience of a mental event, the neuronal activity of the brain that occurs at the same time is responsible for that experience. All scientists today accept this assumption and reject various 19th-century dualist theories that the mind is somehow different from the biological brain.

Cognitive neuroscience builds on two older methods. The first is *lesion studies*, studies of how cognitive abilities change after a debilitating brain injury that affects only one local part of the brain. Injuries that selectively damage the brain result from strokes; during World War II,

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many such injuries resulted from battle. The problem with lesion studies is that lesions indiscriminately affect a variety of brain regions, and it can be difficult to determine the exact location of the lesion. A second, older method is to insert electrodes through the skull and into the brain of an experimental animal; electrodes can detect exactly which neurons are active. The problem with this method is that it can't be used with humans. The brain imaging methods available today to cognitive neuroscientists are much more valuable than either lesion studies or electrodes because they allow us to examine normal, healthy brains, engaged in tasks designed by researchers.

I begin the chapter with a whirlwind introduction to three influential brain imaging technologies: EEG, PET, and fMRI. These technologies are rather complicated, and I can provide only a relatively short summary. But don't skip over the technical introduction; if you don't understand how these methods work, you won't be able to understand exactly what the specific studies mean. Science reporters love brain imaging studies, and just about every month you'll see a news story about "the location" of one or another human ability or personality trait, or you'll read that a certain region "lights up" or "turns on" when we're engaged in a particular task. These stories are almost always misleading. Not long ago, a friend who had read one of these news stories asked me, "Isn't creativity in the right anterior cingulate cortex?" The answer is no, and creativity isn't located in any other specific brain region, either. After reading this chapter, you'll realize why that's the case, and you'll be prepared to understand what these experiments really mean.

BRAIN ANATOMY

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*, each of which transfers 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 10 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's 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 brain.

If you've ever seen a picture of a brain, you'll remember that it's wrinkled (Fig. 10.1). Neuroscientists say that it's *folded*, and this is because the folds allow more of the outer cortical layer to fit into the skull. The tops of the folds—the part that's pressed right up to the skull—are

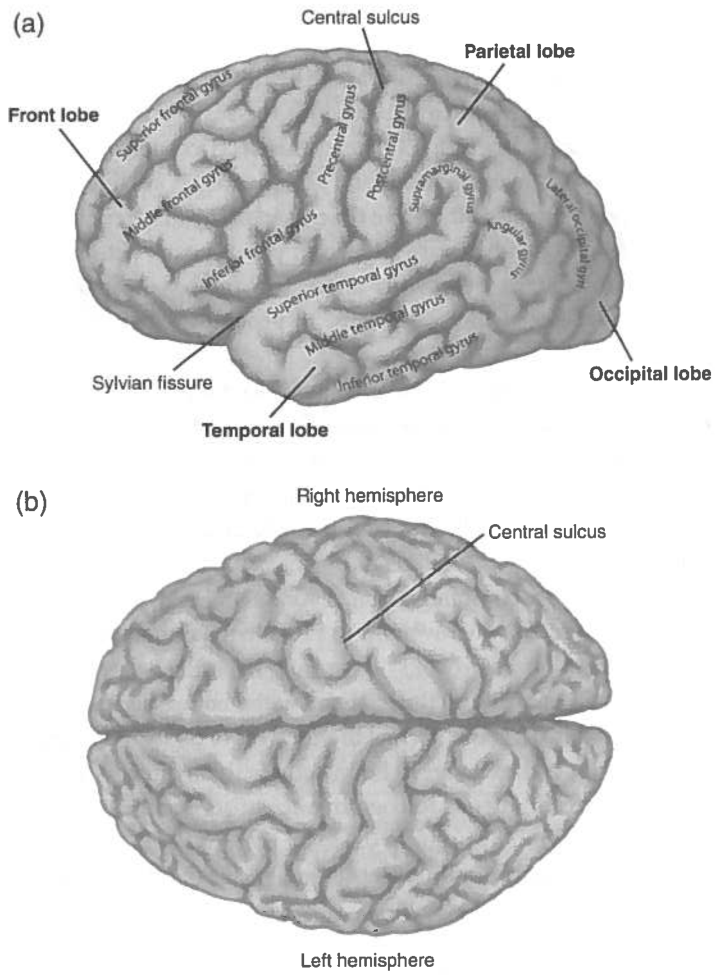

FIGURE 10.1: Gross brain anatomy. (a) Lateral view of the left hemisphere. (b) Dorsal view of the cerebral cortex. The major features of the cortex include the four cortical lobes and various key gyri. Gyri (singular is "gyrus") are separated by sulci (singular is "sulcus") and result from the folding 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. Copyright (c) 2002 by W. W. Norton & Company, Inc. Used by permission of W. W. Norton & Company, Inc.

called the *gyri*; the crevices are called *sulci*. The total surface area of the cortex is about 2,300 cm squared—about the size of a 12-inch pizza—but two thirds of that is within the depths of the sulci.

HOW IT'S DONE

Cognitive neuroscientists primarily use three different brain imaging methods: 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.

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 many of them are receiving signals at the same time, then a tiny magnetic field is created. In the cerebral cortex, neurons and dendrites are aligned in parallel, so a detectable electromagnetic field is generated. Neurons aren't necessarily aligned in the basal regions of the brain, and that electrical signal is weaker at the scalp; thus, in general only cortical activity is studied using EEG.

In the most common arrangement, 20 sensors are placed on the head in standard locations. (More specialized studies use as many as 256 electrodes.) In an EEG study, a person is presented with a stimulus. In many studies, the person is asked to evaluate the stimulus, and then told to press a button if a particular condition holds. The EEG that's recorded right after the stimulus is presented, or right at the time that the decision is made and the button pressed, is called an *event-related potential (ERP).*

The neurons in the brain are constantly firing, and the brain always generates electric waves of amplitudes between 50 and 200 microvolts. The ERPs that psychologists are interested in are much smaller—usually just a few microvolts. As a result, in an EEG experiment, the participant is given the same activity 50 or even 100 times; then, mathematical algorithms are used to average over all of the trials (Fig. 10.2). The normal brain waves of 50 to 200 microvolts cancel each other out, and what remains is the change in brain activity that's directly related to the stimulus event—the ERP. EEG signals of interest to cognitive scientists occur in the frequency range of 1 to 50 Hz, and ERP signals typically occur in 0.5 to 20 Hz.

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

- Delta waves (0.5–4 Hz)—during deep sleep
- Theta waves (4–8 Hz)—greater in childhood; implicated in encoding and retrieval of information
- Alpha waves (8–13 Hz)—occur 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 can't tell us much 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 20 electrodes positioned around the skull, an ERP at any particular electrode doesn't 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, we need technologies capable of a higher spatial resolution—PET and fMRI.

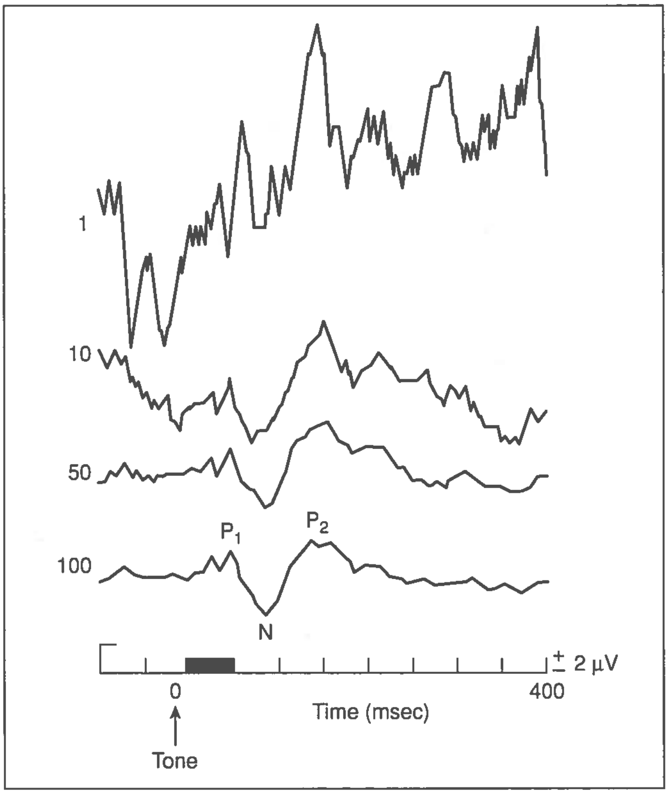

FIGURE 10.2: In EEG experiments, participants are presented with the same stimulus or task up to 100 times, and the EEG waves are averaged across all of the tasks to reduce the signal-to-noise ratio and reveal the ERP associated with the task. These are waves of the EEG in response to presentation of an audio tone at time 0. The topmost wave represents a typical EEG from a single trial; the other waves represent averaging across 10, 50, and 100 trials. This is done for each electrode, and each will have a slightly different ERP profile. (From *Fundamentals of Human Neuropsychology*, 5e by Bryan Kolb and Ian Q. Whishaw. © 2003 by Worth Publishers.)

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's more blood flow, there's more radiation. A radioactive isotope of oxygen is often used that decays rapidly—a fast decay is important to reduce the amount of radiation exposure. O-15 is the most commonly used oxygen isotope; it has a half-life of 122 seconds.

During a PET experiment, a person is given a cognitive task that can be done in approximately the time it takes for the oxygen isotope to decay. After approximately 40 seconds, most of the O-15 isotope has decayed and the signal has peaked. While he or she is engaged in this task, the associated brain regions will increase in neuronal activation; rCBF will increase to those regions; and the increased radioactivity is detected by the PET scanner—a large doughnut-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 mm^3. 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. The size of the voxel is referred to as the *spatial resolution* of the image; smaller voxels equals higher spatial resolution. On average, neural density in the neocortex is 20,000 to 30,000 neurons per 1 mm^3, and the number of synapses in a cortical space of 1 mm^3 is close to 1 billion. This means that in the typical study we'll read about in this chapter, 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; whereas EEG detects the ERP essentially immediately, 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's been called "the most important imaging advance since the introduction of X-rays" in 1895 (Logothetis, 2008, p. 869). The fMRI machine detects the ratio of oxygenated to deoxygenated blood, because each affects the magnetic field differently. The ratio 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 because the machines are more readily available, the spatial resolution is higher, and you don't have to inject radioactive tracers with each trial, allowing hundreds of trials, which can then be averaged. (With a PET experiment you can do at most about 30 trials, because you have to inject the radioactive isotope just before each trial; 12 to 16 trials is more typical.) Also the temporal resolution is higher; with PET, you average over 40 seconds engaged in an activity (because even the fastest isotopes decay over 40 seconds), but you can get an fMRI image every two seconds, allowing for an event-related fMRI, similar to the ERP you get from EEG. As with EEG, changes to any single event are impossible to detect because of the complexity of brain response; when you average the responses to 50 trials, you average out the unrelated brain activity fluctuations and you see the signal related to the event being studied.

There are three challenging problems with fMRI that result from its dependence on BOLD signal changes. First, BOLD increases above the resting state only between 1% and 3% at maximum neuronal activation. When cognitive neuroscientists report increased activation in a particular brain region, they're reporting an increase that's never greater than 3% above the comparison baseline state of the normal neuronal firing rate. Second, when neurons increase in activation, the BOLD signal doesn't increase immediately; the initial rise doesn't occur for several seconds after the increase in neuronal activity, the peak is 4 to 6 seconds later, and it doesn't decline back to baseline for 15 or 20 seconds (Fink et al., 2007; Huettel et al., 2009). The delay varies between individuals, so experiments have to correct for that variation. And, the delay varies across different brain regions even in the same person; there's no known way to normalize these variations, but they're not large. Third, the spatial location of BOLD doesn't always correspond exactly to the neurons that are increasing in activation, because BOLD detects the anatomic locations of the blood vessels that supply the neurons, not the location of the neurons themselves (Huettel et al., 2009). For accurate localization, fMRI has to detect blood flow in the tiniest capillaries, the ones immediately next to the neuronal 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 used today 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 full picture of the brain's activity.

STATISTICAL IMAGE AVERAGING

With EEG and fMRI, it's not possible to study just one response to a single event, because there are large changes in the EEG signal or BOLD signal that are always occurring as part of the brain's normal activity. So in an EEG or fMRI experiment, each participant has to do the same task tens or even hundreds of times, and the ERP is averaged across all of these trials; the normal background variation of the brain's EEG wave or BOLD signal is then averaged out, and what remains is the ERP of interest. So when a specific voxel shows "elevated neuronal activation" in a particular task, the brain isn't necessarily engaging these regions every time it engages in the task; what we're seeing is an average over lots of repetitions of the task.

Standard Brains

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

Every one of us has slightly different fingerprints, even though they all look like fingerprints. And every one of us has a recognizable face, even though all faces have the same two eyes, one mouth, and one nose. In a similar way, each human brain is slightly different, even though the overall organization of all brains is quite similar. Heads come in different sizes and shapes: some more narrow, some shorter front to back. This means that to compare two brains, you have to mathematically adjust the size of all of the brains so that they're basically the same. Most researchers adjust the brains to align with a *standard brain* as published in standard neuroscience atlases. Otherwise, normal anatomic 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's 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, thus increasing the chance of overlap among different individuals when statistical image averaging is done.

Movement

Whenever you move your hands, or bend your knee, or turn your head, 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 your head a tiny bit, or moving your eyes to the side even while your 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, there's a standard "correction" that subtracts out the artifact. When there are a lot of artifacts, it's 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's 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, heads often still move enough to affect the results. There are algorithms that are used to correct for head movement with the fMRI. And with fMRI, the vocal tract causes electromagnetic activity in the same range as the BOLD signal, making it difficult to design experiments during which participants talk. In most experiments, participants are given a small handheld device with a single button and are instructed to push the button depending on what they perceive. This requires only one finger to move a short distance.

PAIRED IMAGE SUBTRACTION

Three facts about the brain make cognitive neuroscience challenging:

- First, every neuron is always firing, so researchers always refer to relative activation levels, rather than neurons being "on" or "off."
- Second, it's 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.
- 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; however, 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, despite these three challenging facts, is called *paired image subtraction*. In every experiment, the first thing that's done is that a brain image is taken during a carefully selected "control state" or "baseline state." The participant lies still and does nothing, or performs some simple comparison activity. This baseline is 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's the cognitive function of interest. The subtraction cancels out the normal activation levels of all of the neurons that don't 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 (Fig. 10.3). 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, the visual display will show heightened activation for the experimental condition.

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

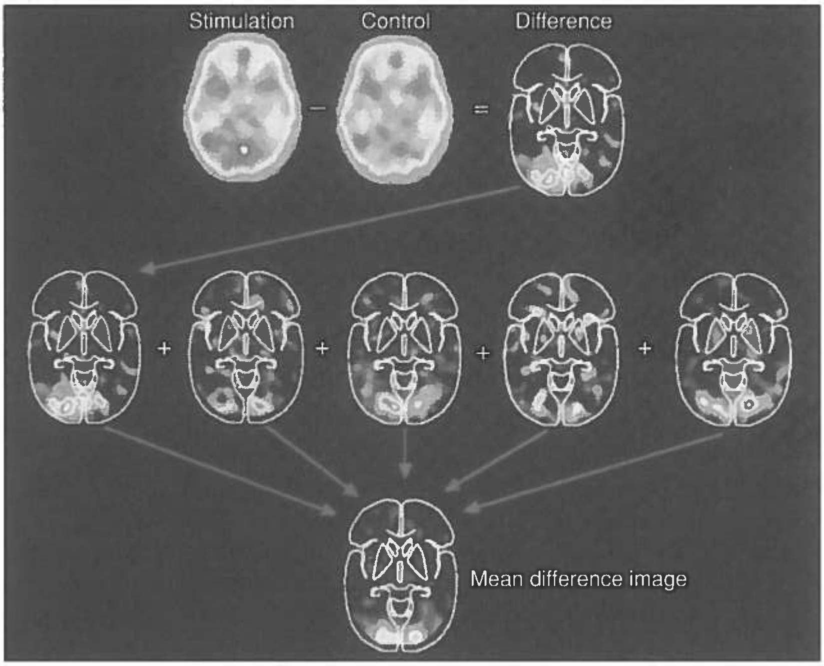

FIGURE 10.3: In the upper row of these PET scans, the control condition (resting while looking at a static fixation point) is subtracted from the experimental condition of looking at a flickering checkerboard 5.5 degrees from the fixation point. The subtraction produces a slightly different image for 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 to generate the images you see in research reports and in media coverage of these studies. Brain PET scan taken from the book *Images of Mind* by Michael I. Posner and Marcus E. Raichle. Copyright © 1994, 1997 by Scientific American Library. Reprinted by permission of Henry Holt and Company, LLC.

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's no way to detect these indirect changes.

COGNITIVE CONJUNCTION

Some studies make use of the technique of *cognitive conjunction*. They have people do two slightly different tasks, such that each of the tasks shares one common cognitive component. Then, they do a paired image subtraction for each of the conditions against the resting state. Finally, they identify which regions of heightened activation are shared across the two tasks; these regions are presumably associated with the common cognitive component.

MIND WANDERING AND INCUBATION

> *Watching older kids study, or try to study, I saw after a while that they were not sufficiently self-aware to know when their minds had wandered off the subject . . . Most of us have very imperfect control over our attention. Our minds slip away from duty before we realize that they are gone.*
>
> —Legendary teacher John Holt, in *How Children Fail*, (1964, pp. 7–8)

We learned in Chapter 5 that incubation often results in the sudden emergence of a good idea. And all of us have experienced the phenomenon of *mind wandering*, when our thoughts drift away from the task at hand to something completely unrelated. We shift away from a primary task to process some other, personal goals, but in a way that's not obviously goal-directed or intentional. There's some evidence that people prone to mind wandering score higher on tests of creativity (Hotz, 2009b; Tierney, 2010). What happens in the brain when the mind is wandering? Recent studies of the brain's idle states can potentially help us answer this question.

The brain is always active, even when the research participant is just lying in the scanner, staring at the ceiling, wondering what's for dinner that night, whether he got his parking ticket validated, or whatever. That's why the first step of any brain imaging study is to take a *baseline* or *resting* image of the brain, so that it can be subtracted from the brain while it's actively engaged in the task of interest. The most common resting state is to have the participant focus on a simple "X" target that's displayed in the same location where the stimuli will be presented. Some experiments simply average out a few brain images taken in the seconds before the experiment starts (while the participant is probably wondering when it's going to start).

The brain accounts for about 2% of body weight but uses about 20% of all the energy the body consumes, even in a resting state with the eyes closed. When your mind starts thinking hard about a difficult problem, the brain's energy consumption rarely increases by more than 5% (Raichle, 2009). And I've already noted that from minimal to maximal neuronal activity, the blood demand almost never increases more than 3%. So it's not surprising that fMRI studies have shown 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).

During waking hours, people's minds wander between 15% and 50% of the time, depending on the task. For example, people's minds are wandering 20% of the time they're reading, and half of those times they're not even aware that their minds are wandering (Smallwood & Schooler, 2006, p. 956). Mind wandering, which is closely related to daydreaming, 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 the 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. In people with high working memory capacity, 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 10% of the time.

Raichle (2009) identified a *default network*—parts of the brain that are active in the resting state but that, intriguingly, become less active when engaged in various cognitive tasks. Brain imaging has found that the default network continues to be active in tasks that involve passive sensory processing, but it tends to reduce its activity with tasks with high central executive demand—which is exactly what you'd expect with 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. These same regions reduce in activity when you become unconscious (Andrews-Hanna et al., 2010). Christoff et al. (2009) found that the default network was most active when people's minds were wandering and they weren't aware of it. There's evidence that task performance is more severely disrupted by mind wandering when you're not aware it's happening.

Studies of mind wandering reveal that we spend more of our daily lives engaged in an incubation-like state than we probably realize. People typically are consciously aware of only half of their mind-wandering episodes. I propose an intriguing hypothesis: mind wandering serves to provide us with moments of "mini-incubation" that contribute to creative thought by temporarily taking our minds away from the problem at hand and providing a brief opportunity for insight to occur.

CREATIVE INSIGHT

The very front of the brain is associated with all of the highest, most deeply human abilities—what are sometimes called "controlling" and "executive" functions of the brain (Srinivasan, 2007). From brain lesion patients, we've long known that patients who have lesions in this area "lack initiative, foresight, activity and ability to handle new tasks . . . impaired in voluntary shifting and choice" (Goldstein, 1944, p. 192). 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 doesn't 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, and attention. Chapter 6 surveyed the research on the moment of insight, studies that typically use "insight problems" and make the assumption that the problem can be solved only with a moment of insight. Brain imaging technologies are ideally suited to identifying the brain regions associated with creative insight.

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 RAT puzzles summarized in Chapter 3 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 it doesn't actually contribute to solving the problem. Weisberg (1986) has argued that insight and non-insight problems are solved through exactly the same cognitive processes, and that insight is largely a myth.

The methodology of cognitive neuroscience is perfectly suited to determining whether insightful solutions result from different brain activity than solutions with no insight. Mark Jung-Beeman and colleagues at Northwestern and Drexel Universities (Jung-Beeman et al., 2004) conducted a series of experiments to determine what happens in the brain when people are solving insight problems. Their study was designed to address three questions:

1. Is there any unconscious processing that immediately precedes the sudden conscious awareness of the insight? Several studies in Chapter 6, using the "priming" experimental methodology, suggest an affirmative answer.
2. Are there different cognitive and neural mechanisms involved in having an insight solution versus ordinary problem-solving processes?
3. Does the sudden "Aha!" experience reflect a sudden change in the brain?

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; the brain area associated with associative relations is the anterior superior temporal gyrus (aSTG) of the right hemisphere. 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.

Their first experiment used fMRI with 13 subjects. They used 124 RAT triplets (see Bowden & Jung-Beeman, 2003b), and gave the participants 30 seconds to identify each target word. As soon as they identified the word, they pressed the button in their hand. The researchers asked them to say the word out loud, simply to confirm that they had the correct word. Then, they were asked to press the button again if they had a feeling of insight.

Fifty-nine percent of the problems were solved, and people reported feeling insight for 56% of these solutions. They examined six seconds of brain activity around the time of the first button press. The subjects who reported having a sensation of insight showed a heightened brain activation in the RH aSTG compared to those who didn't have the insight sensation.

The temporal resolution of fMRI isn't high; in this experiment, one brain image was taken per second. Thus, the findings from this experiment might reflect simply a subjective experience of insight, and it's that subjective experience that corresponds to the RH aSTG—but that region might not have anything to do with the insight itself, just with the sensation of insight. The real question is, was the problem actually solved differently when subjects felt they were having an insight? To answer that question we need a higher temporal resolution—so the researchers did exactly the same experiment and compared the time-frequency analyses of the EEGs of insight solutions and non-insight solutions.

They found that there was a burst of gamma-wave activity in the front RH (but not left hemisphere [LH]) associated with insight solutions about 0.3 seconds before the solution button-press, but not with non-insight solutions. In other words, when people reported a feeling of insight, they had a burst of frontal RH brain activity just before they pressed the button, but not when they solved without insight. The researchers interpret this as the sudden conscious availability of the solution word: the moment of insight.

However, the activity continued to increase for a full second after the button was pushed, suggesting an alternative explanation: they might reflect the excitement of getting the solution—an effect of the solution rather than a cause (see Sheth et al., 2008). But the burst of gamma activity in the EEG began before the button press, rather than after it. In another study (Jung-Beeman, Bowden, & Haberman, 2002), when insight was reported, there was greater neuronal activity in the RH superior temporal sulcus for the final two seconds before participants solved 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 another 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 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, the researchers obtained an fMRI to identify the brain regions before the problem was presented. Preparation preceding the presentation of problems that were then solved with insight involved greater activity of the anterior cingulate cortex (ACC). In other words, you could predict whether insight would be used even *before* the person saw the problem! They conclude that ACC activity is responsible for the alpha-wave mid-frontal activity detected with the EEG.

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 with: (a) correct versus incorrect solutions (compared ten second pre-response); (b) solutions without a hint versus with a hint (compared ten second pre-response); (c) success after the hint is provided versus no success (they examined ten seconds before the hint and ten seconds after); and (d) self-reported high insight versus 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 versus non-insight solutions in the central-parietal region. The most intriguing result was that for those who were stumped and then got a hint, the brain activation pattern was different, even before the hint was presented, for those who eventually got the answer versus those who didn't.

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 lead to restructuring, or hints that reinforced the incorrect structuring. When they provided a restructuring hint, they observed activation in the bilateral superior frontal gyrus, the medial frontal gyrus extending to the cingulate cortex, and the bilateral posterior middle temporal gyrus. They also found ACC activation with insight problems versus non-insight problems. Interestingly, ACC activation declined with time, suggesting that subjects were developing general strategies to deal with this sort of word problem.

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

Sandkuhler and Bhattacharya (2008) gave people RAT triplets; they could press a button if they were stumped, and right away they'd 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 sudden versus nonsudden solutions (38–44 Hz). They also found increased upper alpha-band response (8–12 Hz) in the right temporal regions, suggesting active suppression of weakly activated solution-relevant information, for initially unsuccessful trials that after a hint led to the correct solution.

One of the interesting benefits of cognitive neuroscience is that it can tell us the full range of tasks that a particular brain region is implicated in. From a large number of experiments, we know, for example, that the RH prefrontal cortex also experiences elevated activation with problems requiring a set-shift transformation, and on tasks involving sequential thinking when a belief–logic conflict causes a change in the reasoning process; and it helps make available a set of alternative and less probable word meanings in a lexical task.

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 rearranging 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). Hypothesis generation activated left dorsal lateral prefrontal cortex (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 versus baseline.

With anagram problems, right ventral lateral PFC was activated when problems were solved without any hint ("Can you make a word with CENFAR?") versus 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 insight studies—there, it's 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. They split everyone into two groups based on how they said they 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]). HI people had different resting-state EEGs (the resting state is the period just before the anagram was shown to them) compared to LI 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 you'd use insight to solve an anagram by analyzing your EEG during the resting state just before they showed you the anagram. 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, for example, and many other studies have shown that resting-state EEG is relatively stable over time.

In the above experiments, the brain regions that display elevated neuronal activity aren't some mysterious nether regions of the brain; other brain imaging studies show that they're involved in a wide range of cognitive tasks, many of which we don't associate with creativity *per se*. The RH aSTG is implicated in integration across sentences to extract themes; to form coherent memories for stories; to generate 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 the 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 you've discovered is incorrect involves cognitive control mechanisms similar to those involved in suppressing irrelevant thoughts.

STUDIES OF DIVERGENT THINKING

There's a variety of evidence that the RH is more effective at semantic processing of distant associates (Bowden & Jung-Beeman, 2003a; Howard-Jones et al., 2005). And there's some evidence that the prefrontal part of the RH supports processing of distant associations (Seger et al., 2000).

Howard-Jones et al. (2005) used the three-word short story task described in Chapter 3 (pp. 45–46). Recall that they created four conditions using two variables: (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 a story. After they left the scanner, they were asked to recall a random sample of 20 of the stories they had generated (five stories from each condition). Using paired image subtraction to subtract the "uncreative" condition image from the "creative" condition image, they observed an increase in prefrontal activity, including bilateral medial frontal gyri and left ACC. When participants were combining unrelated words as opposed to related words, additional activity was also found in bilateral ACC and right medial frontal gyrus.

As with the insight studies, these brain areas aren't unique to creative tasks; they're involved in a wide range of cognitive tasks. Left prefrontal activation occurs 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 PFC are associated with additional conflict monitoring (Howard-Jones et al., 2005, p. 248) and with insight solutions (see above).

CREATIVE BRAINS VERSUS NON-CREATIVE BRAINS

The methods of cognitive neuroscience aren't 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 in each group. A few studies have examined differences in neuronal activity between people who get high scores on creativity tests and 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 low alpha-wave activity.

Carlsson et al. (2000) used the Creative Functioning Test (CFT; see p. 46) to select a high-creativity and a low-creativity group (each with 12 male right-handed students). They then presented three tasks that 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 (say all the words you can think of that start with the letter "f" or "a" or "s"); and the final activation was a divergent thinking task (say as many uses as you can think of for a brick). Only the divergent thinking task was expected to activate RH areas associated with creativity. 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 don't know why.) The biggest differences, when comparing brain activity on the f-a-s task and on the brick task, were elevated anterior PFC in creatives (both hemispheres) and decreased fronto-temporal and anterior PFC 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 the f-a-s task, than low creatives—whose brains looked about the same in the f-a-s and the brick tasks.

Chávez-Eakle and her team (Chávez-Eakle, 2007) compared six individuals with TTCT scores in the 99th percentile with six individuals at the 50th percentile by giving them the Unusual Uses test. The high scorers on the Verbal TTCT had greater cerebral blood flow in the right precentral gyrus; the high scorers on the Figural TTCT had greater cerebral blood flow in the 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 RH.

These studies provide some evidence that in less creative people, the RH is slightly less active. But ultimately, these studies found that high creatives show patterns of bilateral hemispheric activation, consistent with the studies described in Chapter 9. As we've seen from other studies in this chapter and in Chapter 9, it's misleading to say that creativity is "in" the RH (also see Feist, 2010, p. 118; Kaufman et al., 2010, p. 221); keep in mind that with all brain imaging studies, the differences in neuronal activation reported are never more than 3% above baseline state.

STUDIES OF 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 improvised while their heads were in the scanner, using a special keyboard with one octave of 12 keys (white and black). The musicians could hear what they were playing through scanner-safe headphones. They were instructed to improvise a simple melody based on an eight-note melody that was displayed to them, and then asked to 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.

When the image of a brain reproducing an improvised melody was subtracted from an image of the brain improvising that melody for the first time (the "improvise minus reproduce" condition), there were significant brain differences in many regions including the right dorsolateral prefrontal cortex (DLPFC) and right presupplementary motor area; bilaterally in the rostral portion of the dorsal premotor cortex; temporal lobe activations in the left posterior superior temporal gyrus (STG), and the fusiform gyrus; and bilateral occipital activity in the middle occipital gyrus. Essentially, all of these areas were also activated in the conjunction between improv-reproduce and freeimp-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 12 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, moving only 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 cognitive neuroscience studies, the most important thing was the subtle differences between the different tasks that would be revealed by 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, ACC, and inferior frontal gyrus/ventral premotor cortex, all in the LH (which was expected, since the task was performed with the right hand).

As with the insight and the divergent thinking tasks, these brain regions are the same ones that are used in a wide variety of everyday cognitive tasks. The dorsal premotor cortex is involved in a wide variety of motor tasks, including selection and performance of movements. ACC, which is implicated in insight and in divergent thinking, is involved in many cognitive tasks, including unrehearsed movements, decision making, voluntary selection, and willed action. The third region is 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 generating and comprehending sequences, making decisions among competing alternatives, and creating 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; and (2) subjects improvised over the same chord sequence, while hearing the same accompaniment through their headphones. Their keyboard had 35 full-sized keys.

The researchers also saw activation in the same three brain regions. But because the tasks were so much more complex, they found changes in activity in over 40 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 PFCs, particularly in the lateral orbital PFC and the 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 PFC, which has been associated with autobiographical narrative. The decreased activity was in the regions 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). Improvisation involves brain regions associated with the skills that underlie improvisational thought: selection and performance of movement, decision making, language processing and sequential auditory information, and inhibition of monitoring. And as with all of the studies we've reviewed so far, 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

We now know that the adult brain can generate new neurons, contrary to a previous belief that all neurons are present at birth. And neuroscientists have discovered that the brain is a lot more *plastic* than we previously realized—in other words, patterns of neuronal activation can change over time with experience. Of course, our brains must change any time we learn something—even the name of a person we met yesterday—but brain plasticity is much more extensive than simple fact learning; the structure of the brain itself can change. These changes can take years; for example, more fluent speakers of a second language process that language differently than less fluent speakers (Reiterer, Pereda, & Bhattacharya, 2009). But the brain is plastic enough to rewire itself in as little as a few weeks. One study showed that when the ACC is damaged, people can't talk for a few weeks, but then speech comes back to them as their brain is rewired to work around the damage (Posner & Raichle, 1994).

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

MUSIC TRAINING

When listening to music and when generating music, the brains of trained musicians show different patterns of activation. Berkowitz and Ansari (2010) compared trained musicians with non-musicians in a simple five-note improvisational task. The key difference was that the musicians deactivated the right temporoparietal junction while the non-musicians did not. This region is engaged in bottom-up stimulus-driven processing; deactivation of this region occurs 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 non-artists 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, artists showed stronger short- and long-range delta-band synchronization and non-artists showed enhanced short-range beta- and gamma-band synchronization, primarily in frontal regions; comparing the two groups during the task, artists showed stronger delta-band synchronization and alpha-band desynchronization, and strong

RH dominance in synchronization. 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. They interpret these differences as due to more advanced 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. They interpret increased alpha synchronization as inhibition (of processes not directly relevant), or top-down control.

These studies show that brain activation patterns are not genetic and are not prewired at birth. Neuronal activation can change fairly dramatically in response to environmental influences, experience, and learning.

CONCLUSION

> *[Creativity] cannot be reduced simply to the neural circuitry of an adult brain and even less to the genes behind our brains.*
>
> —Neuroscientist Antonio R. Damasio, (2001, p. 59)
>
> *If there was something truly distinctive in the brains of great men, great women, depraved hoodlums, or murderers, it would have been discovered by now. But nothing has turned up . . . all human brains look essentially alike.*
>
> —Burrell, (2004, p. 306)

Although this research methodology is still in its infancy, it has already contributed greatly to our understanding of creativity. We now know that many regions of the brain are active when people are engaged in creative tasks. And cognitive neuroscience has shown that 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 don't think of as requiring any creativity at all. In sum, these studies show:

- Creativity is based in ordinary, everyday brain processes, not in a distinct part of the brain. Every normal, healthy human being is capable of engaging in these brain processes; they're required for everyday functioning.
- There's no evidence for the popular belief that creativity is located in the RH of the brain. Many regions of the brain, in both hemispheres and pretty much equally, are active during creative tasks.

The bottom line is that creativity is not localized to a specific brain region. That's consistent with the cognitive research we examined in Chapters 5, 6, and 7, which showed that creativity involves a wide variety of cognitive abilities. Each of these cognitive abilities is itself a complex and emergent property of the biological brain; each involves many brain regions at a moment in time, and each requires many successive moments in time. Creativity can't be reduced to a single brain region at a single moment in time—the mythical flash of insight.

There are several issues to keep in mind when considering this sort of experiment:

1. Neuroscientists agree that pretty much all cognitive function involves many parts of the brain all at once; regions that show elevated neuronal activation are scattered all over the brain. The colorful images that we occasionally see in a magazine, with a small bright red dot showing "the location" for whatever, result from *averaging* and *subtraction*; what we're not seeing in that image are the many brain regions that are active in both conditions, before the subtraction. If we focus too much on localization, we lose sight of the reality that what goes on in the brain is diffuse and distributed.
2. It's hard to use brain imaging studies to make claims about causation; 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.
3. These findings result from averaging across many trials, typically about 50 per experimental condition. The brain area reported in the research paper isn't necessarily active in every single trial; it's just statistically more likely that it's active in one condition versus another. So it's incorrect to say that "creativity is located in the ACC" or even "the right hemisphere," although a quick read through the above studies might misleadingly give that impression. This is why I've put so much information about the methodology at the beginning of this chapter: to dispel simplistic notions that these methodologies are telling us "where" certain functions are located in the brain.
4. For the most part, what cognitive neuroscience has discovered are facts that are largely already known from the classic experimental methods of cognitive psychology (Carey, 2006, p. 4). In the 1970s, these experiments had discovered that verbal information 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. Researchers also had discovered that implicit memory and explicit memory were distinct long before cognitive neuroscience demonstrated that each corresponded to a different pattern of neuronal activation.
5. The scanners are large and expensive. People have to lie down and remain completely still while they listen to the 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's no hope of being able to study people engaged in normal activities in their everyday contexts.

Future technology can be expected to give us better and better images. However, there are limitations of these methods that cannot be overcome.

First, the temporal resolution of PET and fMRI can never be increased dramatically because the response of the blood system is so sluggish. After neuronal activation increases, blood flow doesn't become elevated in the associated region for about 4 seconds, and it takes 15 seconds for the blood system to settle back to its resting state, so we will never be able to do trials more often than every 20 seconds or so. Spatial resolution, however, will get much higher with increasing magnetic field strength; Logothetis (2008) predicts that slice thicknesses will decline to 0.5 mm, with voxel sizes two or three orders of magnitude smaller than at present (p. 871). But an increase in spatial resolution probably won't advance cognitive neuroscience 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.

Second, the spatial resolution of EEG will never get much higher due to the diffuse nature of the electric fields in the skull.

In addition to these technical issues, there's one final problem: 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 cognitive neuroscience works fine with some brain functions—for example, perceptual systems like vision, because vision is processed in a fairly regular way through a specific set of neurons. But with higher cognitive functions such as creativity, problem solving, language, decision making, memory, etc., our thoughts and behaviors are *emergent complex phenomena*: they involve many distinct neural groups, scattered throughout the brain. 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. Each of the eight stages of the creative process is likely to be realized in a distinct set of brain states. And in a creator's life, these mental moments occur over 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 (Chapter 7), and the role of social interaction requires study of the interactional dynamics of those groups (Chapter 12).

Cognitive neuroscience is an exciting and important component of the explanation of creativity. These studies all show us 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.

KEY CONCEPTS

- Lesion studies and electrode studies
- Neurons: synapses, axons, dendrites, axon terminals
- Brain anatomy: gray matter, white matter, sulci, gyri
- Electroencephalography (EEG)
- Event-related potential (ERP)
- Temporal and spatial resolution
- Positron emission tomography (PET)
- Voxel
- Functional magnetic resonance imaging (fMRI)
- Blood oxygen level-dependent (BOLD) signal
- Statistical image averaging

- Paired image subtraction (with baseline or rest state)
- Cognitive conjunction
- Mind wandering

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