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2

COGNITIVE NEUROSCIENCE

LEARNING OBJECTIVES

2.1 Connect clinical case studies to our understanding of cognitive neuroscience.

2.2 Describe the basic structures of the nervous system and how they function.

2.3 Compare the strengths and limitations of different electrical recording techniques.

2.4 Compare the strengths and limitations of different brain imaging techniques.

QUESTIONS TO CONSIDER

- How do cognitive researchers make use of information about brain structure and activity?
- How do case studies of individuals with cognitive deficits inform us about the connection between cognition and brain function?
- What techniques do researchers use to examine brain structure and function?
- What can be learned about cognition through measurements of neuron activity in the brain?

INTRODUCTION: KNOWLEDGE FROM COGNITIVE DEFICITS

Imagine that you are a neurologist focusing on cognitive deficits in your patients. You see several patients in a day. One is an older woman who is having some memory problems. Another patient is a man who can identify which words on a page represent animals but cannot distinguish between an elephant and a horse or identify that a tiger is an animal that has stripes. Another patient is a veteran who lost a leg in a bombing in Afghanistan but still feels pain where the leg should be. A fourth patient can understand and follow verbal instructions but cannot produce verbal speech.

As you further examine each one of these patients, you realize that they illustrate the connection between brain function and cognitive abilities. The first patient is tested with some cognitive tasks, including remembering words and numbers for a short time. She shows lower functioning on these tasks compared with typical scores of nonclinical individuals, and you conclude that she may be showing the first signs of Alzheimer's disease. The second patient is one you have seen in your office several times before. He has Pick's disease, a disorder where fine-grained conceptual knowledge is gradually lost due to deterioration of the neurons that help us retrieve general knowledge. The veteran is suffering from a condition known as phantom limb syndrome, where a patient has perceptions of feeling from a limb that has been removed. The last patient is suffering from Broca's aphasia, a language disorder where comprehension abilities are spared but production abilities show a deficit.

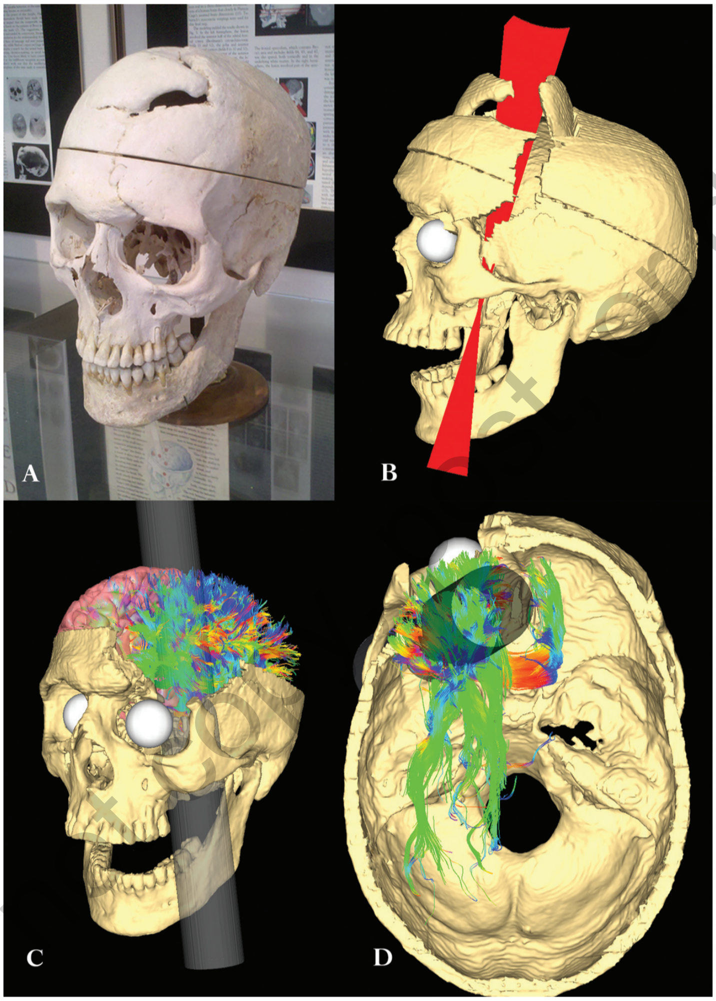
We can learn quite a lot about the connection between brain activity and cognitive abilities by examining patients with cognitive deficits. The first neuroscientists relied on such patients to learn about brain function and how it relates to different cognitive processes. When a patient showed a particular deficit, neuroscientists would identify the area of the brain that was damaged by learning about the patient's disease or accident and, in some cases, by examining their brain after the patient's death. These clinical case studies allowed neuroscientists to begin mapping out the cognitive functions of specific brain areas. However, in more recent years, new brain recording techniques allow researchers to examine brain activity in cases where there is no deficit and to more precisely pinpoint the affected areas in cases where a patient shows a deficit. In this chapter, we consider how cognitive neuroscientists study brain function and review some of the important case studies of clinical patients that helped us learn about the connection between brain function and cognitive processes. In upcoming chapters, we discuss current studies in cognitive neuroscience that contribute knowledge about brain functions that underlie attention, perception, memory, and language abilities.

CLINICAL CASE STUDIES IN COGNITIVE NEUROSCIENCE

As just described, early neuroscientists learned a lot about which brain areas contribute to different cognitive abilities through the examination of clinical patients. Although technological advances have increased the research techniques available, clinical case studies continue to contribute to our knowledge in this area. In this section, we review some well-known clinical case studies to show how these studies have contributed to the field of cognitive neuroscience and discuss the advantages and disadvantages of the case study methodology.

One of the first clinical cases to contribute knowledge about brain function was that of Phineas Gage (Damasio et al., 1994; Harlow, 1868/1993). Gage was a railroad foreman in the mid-1800s. While on the job, a blasting cap drove a metal rod through the left side of his face, up through the frontal lobe of his brain, and out the top of his skull (see Figure 2.1). Gage survived the accident and lived for several more years, but his personality and cognitive abilities were altered from the way he was before the accident. He was less able to control his emotions, and his decision-making abilities suffered. He was no longer able to serve as a foreman because he lacked the cognitive control needed for this role. From this clinical case, we learned that the frontal lobes are important in emotional regulation and decision making.

FIGURE 2.1 ■ Phineas Gage's Brain

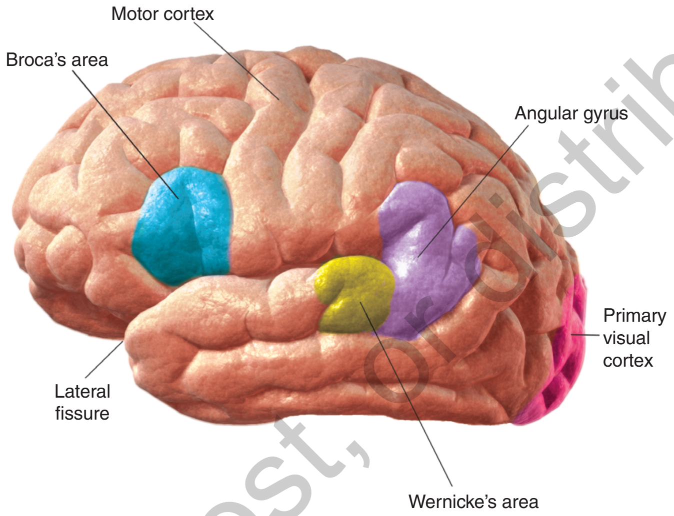


The area of damage to Phineas Gage's brain can be identified by examination of the path of the rod that went through his head.

Source: Van Horn, J. D., Irimia, A., Torgerson, C. M., Chambers, M. C., Kikinis, R., & Toga, A. W. (2012). Mapping connectivity damage in the case of Phineas Gage. *PLoS One, 7*(5), e37454. doi:10.1371/journal.pone.0037454.

Other clinical studies have helped researchers localize language functions in the frontal and temporal lobes of the brain (Rorden & Karnath, 2004). A patient named Tan was studied by Paul Broca in the late 1800s. Tan had been unable to speak for many years ("tan" was one of the only sounds he could produce). After Tan's death, Broca examined Tan's brain and found damage to the left frontal lobe, near the front of the temporal lobe (see Figure 2.2). This location was named Broca's area, and damage to this area causes *Broca's aphasia*, a disorder where a person has difficulty producing speech. Around this same time, another important brain area for language was identified by Karl Wernicke. This area is in the left temporal lobe close to the front of the occipital lobe and is known as Wernicke's area (see Figure 2.2). Damage to Wernicke's area causes a deficit in language comprehension and meaningful language production. A person with *Wernicke's aphasia* can speak, but his or her speech is meaningless. The person produces what is known as a "word salad," where the speech is fluent but incomprehensible. For Broca and Wernicke, clinical case studies were instrumental and contributed to our knowledge about the brain areas responsible for language abilities.

FIGURE 2.2 ■ Broca's and Wernicke's Areas



Broca's and Wernicke's areas can be seen in reference to motor and primary visual cortex areas.

A more recent case study illustrates the role of brain function in a more specific skill: object identification. Oliver Sacks (1990) described a patient who had difficulty in distinguishing between living and nonliving objects. For example, the patient mistook parking meters for children and furniture for people. However, the patient was an academic in the field of music and had little difficulty with other cognitive abilities. He could even identify objects by touch and describe them in detail. His deficit only occurred in visual recognition of the objects. This condition is known as *object agnosia*, the inability to correctly recognize objects. Patients with object agnosia typically have damage in the inferior (lower) temporal cortex, suggesting that the deficit is related to language abilities.

Knowledge about localization of memory function has also been gained from clinical case studies. As discussed in the previous chapter, one of the most well known of these cases is that of H. M., a man who we now know as Henry Molaison, since his death in 2008, who suffered from a form of amnesia where he could remember portions of his life before the damage occurred but could not remember episodes of his life that occurred after the damage (Hilts, 1996). H. M.'s brain lesion was caused by a surgical procedure he received early in his life to help diminish the severity of epileptic seizures from which he was suffering. During the surgery, a brain area known as the **hippocampus** and its surrounding tissue were damaged. After the surgery, H. M. seemed to have lost the ability to form new memories. He would meet new people but would not remember them a few minutes later when they came back into his room. He did not remember world events that occurred after the time of his surgery. It seemed as if the timeline of his life stopped at the point of his surgery. From H. M.'s case, researchers learned about the importance of the hippocampus in memory abilities, but they also learned that the hippocampus is not the only brain structure involved in forming and retrieving all types of memories.

H. M. showed the ability to improve on tasks requiring motor skills, indicating that he could still retain new information and retrieve implicitly (i.e., without intention). Thus, H. M.'s case taught us that the hippocampus is not necessary for all types of memory formation and retrieval but is important for intentional retrieval of memories.

Clinical case studies have revealed important connections between brain function and cognitive abilities. They provide clues to the brain areas most important for different types of cognitive tasks based on an examination of the damaged areas in these patients. However, this points to the major disadvantage of using case studies in neuroscience—the researchers do not control the brain damage. If, for example, the damage is spread across multiple brain areas, it may be difficult for researchers to pinpoint the specific brain areas connected to the cognitive deficits seen in the patients. In addition, researchers are limited to studying those damaged brain areas in patients that are available for them to study. Current neuroscience brain recording techniques provide a means to more precisely identify the brain areas most active during different tasks and to examine the brain areas researchers are most interested in studying. Thus, these recording techniques have helped us overcome the disadvantages present in clinical case studies to further add to the knowledge gained in these studies. In the next sections, we describe some of the techniques cognitive neuroscientists have employed in recent research, but first, we will review the general structure of the nervous system that the brain is a part of.

STOP AND THINK

2.1 Explain why controlled experiments cannot always be conducted to determine how different types of brain damage cause cognitive deficits.

2.2 Describe some of the limitations of using the clinical case study method in cognitive neuroscience.

STRUCTURE OF THE NERVOUS SYSTEM

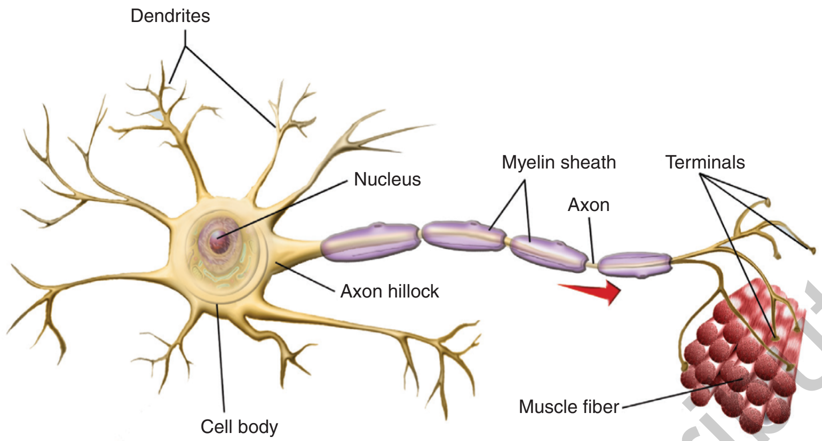
Clinical case studies are still used as a method of study in cognitive neuroscience research. However, advances in technology have also allowed researchers to record the brain activity present in clinical and nonclinical subjects to test hypotheses about what kind of activity is involved in different tasks and where in the brain that activity should be located under different task conditions. The specifics of how these recording techniques work rely on some understanding of the brain and the nervous system, so we will first review the relevant physiology in this section before we introduce the most common brain recording techniques used in cognitive neuroscience research.

The Neuron

The brain is composed of billions of microscopic **neuron** cells forming the basic structure seen in Figure 2.3. Neuron activity is both chemical and electrical. Chemicals called neurotransmitters are first brought into the cell by the **dendrites** at the top end of the neuron. These neurotransmitters provide signals to the cell that are either excitatory (i.e., more likely to fire) or inhibitory (i.e., less likely to fire). The cell body of the neuron takes in these chemical signals from the dendrites and determines if there is enough of an excitatory signal to allow the neuron to fire. If so, an action potential occurs that creates an electrical signal that travels down the neuron's **axon**. This electrical signal is detected in some of the brain recording techniques used by researchers. Once the electrical signal reaches the end of the axon, the terminal buttons release neurotransmitters into the **synapse** to be collected by other neurons nearby. Then the process begins again.

The process of the action potential is what creates the electrical signal in the neuron when it fires. This activity occurs within the axon of the cell. Before the neuron fires, the inside of the axon contains a resting state negative charge due to the division of ions in the fluid inside and outside the cell (see Figure 2.4). The action potential redistributes these ions through channels in the axon's membrane that control the

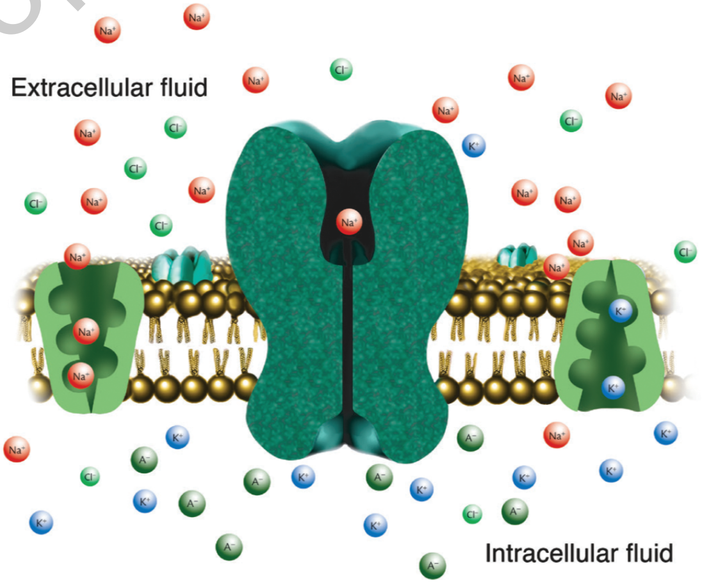
FIGURE 2.3 ■ A Neuron



The neuron is the primary cell that transmits information through electrical and chemical signals in the brain and nervous system. Information is received by the network of dendrites. When enough information is collected by the cell body to reach threshold, an electrochemical signal is triggered, which flows down the axon. At the ends of the axon at the terminal sites, the signal results in the release of neurotransmitters that carry the signal to the dendritic network of other neurons.

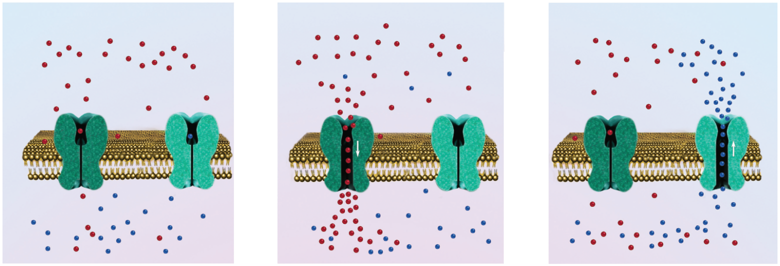
flow of potassium (K^+), sodium (Na^+), and chlorine (Cl^-) ions in and out of the cell (Figure 2.5). When the excitatory signal comes down the axon from the cell body, the axon opens specific channels in the axon membrane to allow sodium to flow into the axon, producing a positive charge inside the cell. The channels open quickly in sequence from the top of the axon (at the axon hillock) near the cell body down to the end near the terminals that contain the neurotransmitter (see Figure 2.6). This positive charge can be detected and recorded by electrodes that are placed either inside the cell or on top of the scalp, as described shortly in the discussion of brain recording techniques. Once the action potential is complete, other channels open in the axon membrane to allow potassium (K^+) to flow out of the cell and the sodium channels close. This redistributes the ions back to the resting negative state inside the axon. The excitatory message then reaches the terminals, and a neurotransmitter is released into the synapse.

FIGURE 2.4 ■ Distribution of Ions Inside and Outside the Resting Neuron

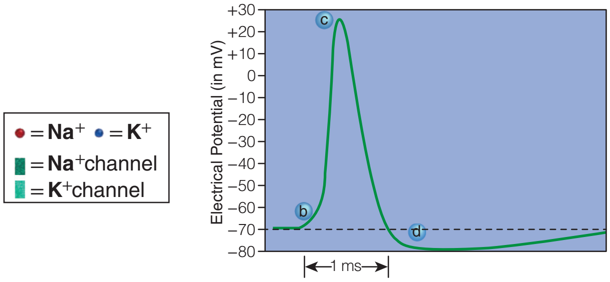


The electrochemical signal that travels down the axon is created by changing the electrical potential inside (intracellular) and outside (extracellular) of the neuron.

FIGURE 2.5 ■ Ions' Movement and Voltages During and After an Action Potential



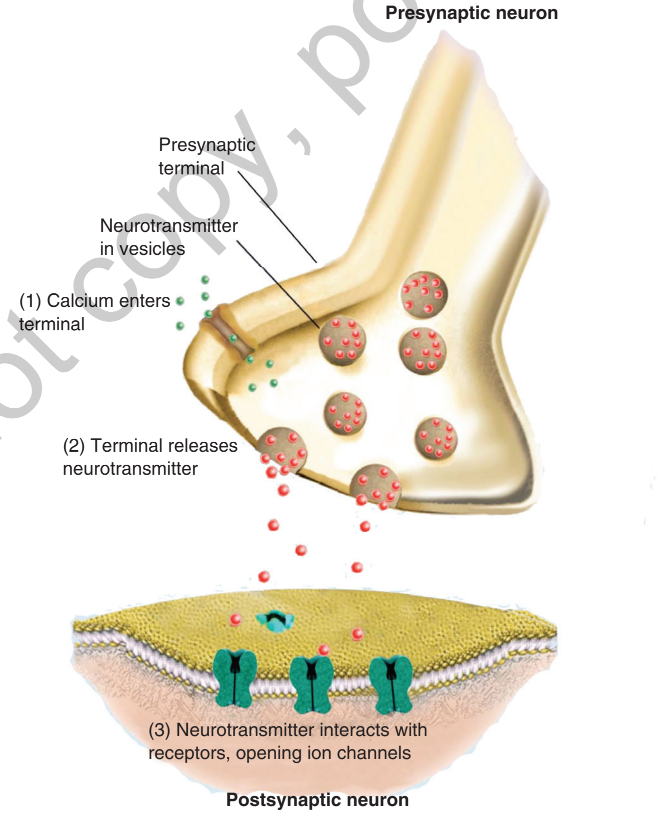
(b) Resting **(c) Depolarization** **(d) Recovery**



(a) Voltage Changes

The electrical potential (voltage—see the curve in the graph) inside and outside of the neuron is changed by the "opening" and "closing" (see panels b, c, and d) of ion channel proteins in the cell membrane.

FIGURE 2.6 ■ Release of Neurotransmitter by the Presynaptic Neuron Into the Synapse



When the signal reaches the end of the axon, it causes vesicles of neurotransmitters to be released into the space between the axon terminal and a dendrite of another neuron. Neurotransmitters flow across this space and attach to receptors on the postsynaptic membrane surface, resulting in the opening of ion channels.

The synapse is the small gap between neurons. Each neuron is connected across synapses to other neurons in an organized network that allows the pattern of firing in the network to translate into specific thoughts or behaviors. This is how information is processed and stored in the brain: through the pattern of firing across multiple neurons within the network (i.e., specific neurons being active or not active or firing at different rates) and types of connections (excitatory or inhibitory) across the neurons connected in each network.

The Brain

The brain is composed of the neural networks described in the previous section, which are organized according to their cognitive functions. This is known as **localization** of function. Many of the clinical cases reviewed in the previous section provided the initial information we have about localization and **lateralization** (i.e., the two hemispheres of the brain contribute to different types of tasks) of brain function through the deficits present in different areas of brain damage. Looking at the kind of task deficits these patients exhibited helped researchers to identify brain areas (i.e., the damaged areas) that were important for completing those tasks. These early studies suggested that different areas of the brain specialized in different functions. Figure 2.7 shows the four lobes of the brain and functions that are localized in those brain areas. Recent research in cognitive neuroscience has used the knowledge gained in early case studies to focus on different areas of the brain as researchers examine the functioning in different cognitive tasks. The brain recording techniques described in the next sections have allowed researchers to go beyond the basic knowledge of localization and lateralization of function to map out more specific brain areas and to piece together full neural systems (i.e., a collection of brain areas organized in pathways) that are involved in different tasks. We explore some of the most recent research in cognitive neuroscience throughout the subsequent chapters that cover different cognitive processes in further detail.

FIGURE 2.7 ■ Diagram of the Four Lobes of the Brain and Functions Localized in These Areas

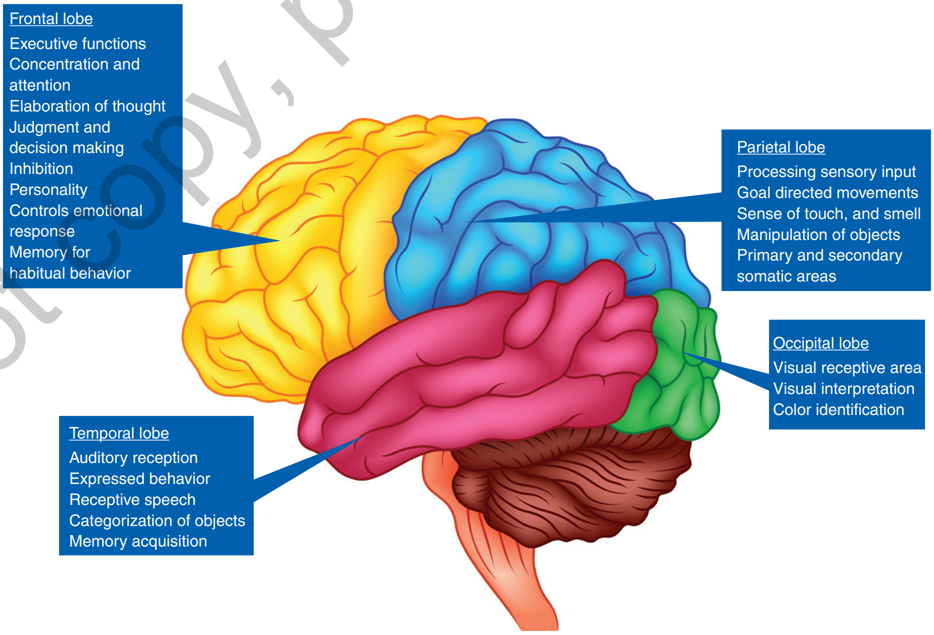


Image credit: iStock.com/Ciawitaly.

Although localization of function can be described as a general feature of the brain, many complex cognitive tasks (e.g., memory retrieval, object identification) have been shown to be a function of distributed processing in the brain. In other words, brain areas work together in systems to process different kinds of information. This idea is supported by research in different areas of study.

For example, a series of brain areas has been found to support explicit memory retrieval (i.e., intentionally retrieving a memory). This system seems to be separate from more automatic or unintentional uses of memory, such as those relied on when we perform a skill or task we know how to do (Squire, 2004). Pulvermüller (2010a) also describes neural circuits for lexical and semantic processes underlying language abilities as "distributed neural assemblies reaching into sensory and motor systems of the cortex" (p. 167). In other words, the processing of spelling, grammar, and meaning of words is distributed across several areas of the brain. Thus, there is localization of function for cognitive processes, but for most functions, multiple areas are organized into processing systems for different cognitive abilities.

MEASURES IN COGNITIVE NEUROSCIENCE: ELECTRICAL RECORDINGS

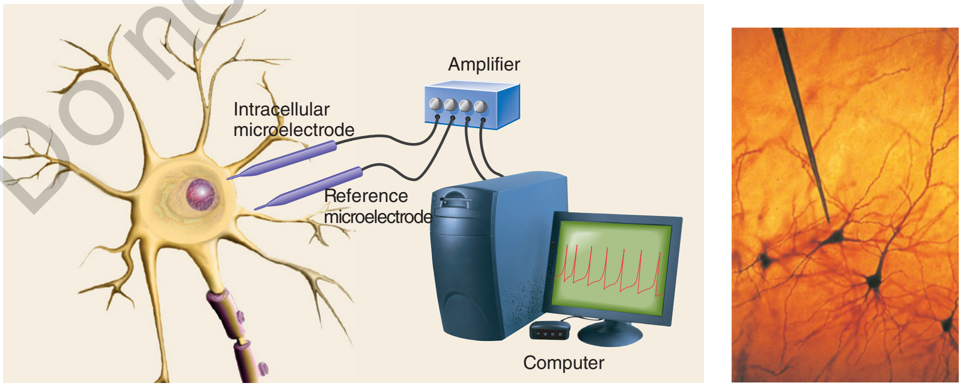
In Chapter 1, we described cognitive research that is conducted within the biological perspective. Using this approach, researchers attempt to connect brain activity with cognitive processes they observe along with some of the other behavioral measures they observed (e.g., accuracy, response time). For example, cognitive neuroscientists have investigated how brain activity differs for accurate and false memories (e.g., Düzel et al., 1997; Webb & Dennis, 2019), which areas of the brain are involved in language production and comprehension (e.g., Gernsbacher & Kaschak, 2003; Hamilton & Huth, 2020), and whether visual areas of the brain are involved in imagery (e.g., Kosslyn et al., 1993; Xie et al., 2020).

Advances in technology have allowed researchers to record different types of brain activity. Some techniques are considered too invasive and are typically only performed with laboratory animals (e.g., single-cell recordings), but many of the brain imaging techniques in use today can record brain activity in humans while they perform various cognitive tasks. However, all the techniques rely on activity of the neuronal cells in the brain. In this section, we review the primary techniques that rely on the recording of electrical charges from neurons in the brain.

Single-Cell Recording

A technique available to record the electrical signals from neurons is single-cell recording. In this technique, a tiny recording needle is inserted into a neuron or set of neurons in an area of the brain the researcher is interested in (see Figure 2.8). However, this technique requires surgical insertion of the needle and bonding to the head to keep the needle steady (see Figure 2.9). Thus, this technique is typically used only in research with laboratory animals. Such recordings have contributed important

FIGURE 2.8 ■ Recording Electrical Activity in a Neuron

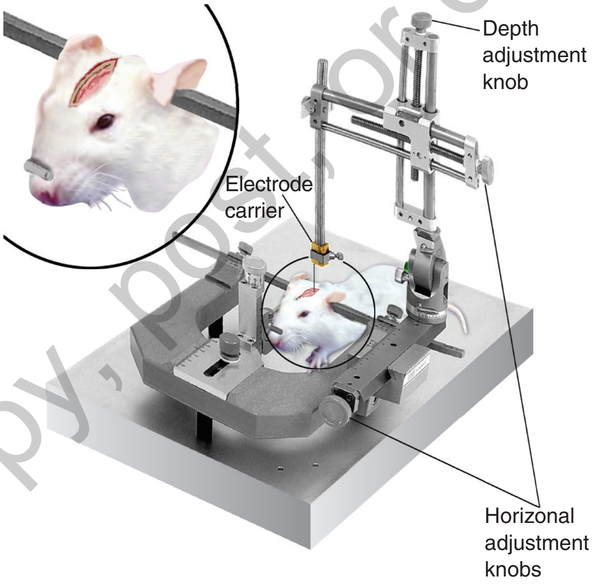


Microelectrodes are inserted into the brain, within the cell membrane. This allows the recording of electrical potential changes over time.

Source: Photo at right courtesy of Bob Jacobs.

information about cognition. For example, using **single-cell recordings** from monkeys, Rizzolatti et al. (1996) discovered an interesting activity in what they called a *mirror neuron*. This neuron fired both when the monkeys picked up an object and when the monkeys were watching the researchers or other monkeys perform that action. In other words, these neurons were active when motor actions were performed and when the monkeys were just watching a motor action they knew how to perform. Since this discovery, researchers have suggested that mirror neurons may play a role in many sorts of social cognition, including understanding others' actions, imitation of others' actions, and facilitation of language through gestures (Rizzolatti & Craighero, 2004). Other work using single-cell recordings has shown that neuronal cell responses can be extremely specific. For example, Quiroga et al. (2005) found neurons in the hippocampus (known to be involved in memory functioning) that were selectively responsive to photos of celebrities such as Jennifer Aniston and Halle Berry in recordings from epilepsy patients undergoing treatment. These results are consistent with the idea that neurons serve as feature detectors (see Chapter 3 for more discussion of feature detection); in this case, the features are specific faces. These neurons have been called "grandmother cells" (Gross, 2002), because they suggest that we might even have a neuron (or set of neurons) that selectively responds to the face of an individual person we know, such as our grandmother.

FIGURE 2.9 ■ Stereotaxic Instrument Used in Single-Cell Recordings



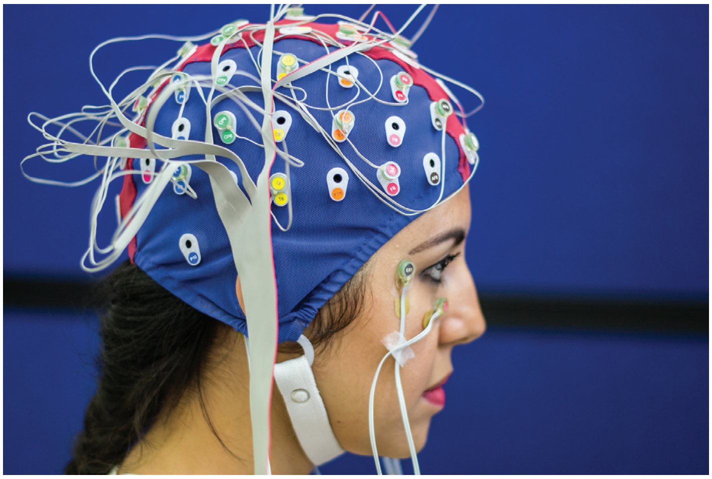


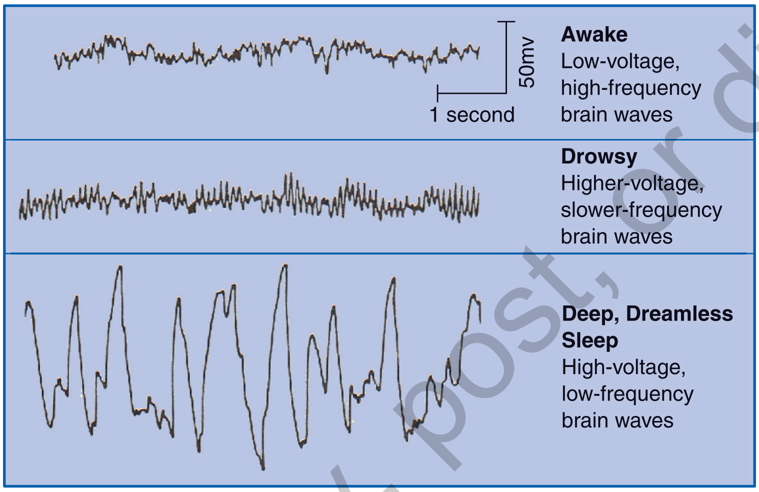
PHOTO 2.1 In recording an EEG, a scalp cap with electrodes in different locations on the head is worn by the participant.

iStock.com/latsalomao

Electroencephalography (EEG)

Another technique that records the electrical signals from neurons is **electroencephalography or EEG**. When recording an EEG, a set of electrodes is placed on the head to record the electrical signals from groups of neurons in different areas of the brain. Because the electrodes are recording from outside the skull, it is the activity of the neurons closest to the skull (primarily neurons in the outer cortex) that is being recorded. The activity is recorded over time to detect changes (positive or negative) in the electrical signals (see Figure 2.10). Researchers can use EEG recordings to examine an **event-related potential (ERP)**, which is a change in activity related to a specific event like the presentation of a stimulus. In that way, they can determine if there is an effect of the presentation of that stimulus on neuron activity and in what general area of the brain the effect occurs. Electrical activity patterns can be overlaid onto a map of the brain to show the general location on the cortex of the different levels of electrical activity.

FIGURE 2.10 ■ Sample EEG Recording



Source: Based on Hauri (1982).

An example of EEG/ERP research is provided by Gibbons et al. (2018), who recorded ERPs during a simple classification task ("Is this an animal or a plant?"). Prior to completing the task, each participant randomly selected two of the stimuli that they were instructed to intentionally mis-categorize (e.g., press the "plant" button when seeing the word "frog"). Voltage recordings were similar for items the participants truthfully classified. However, the electrical activity recorded in the ERP showed different patterns for the trials on which the participants intentionally responded incorrectly. For these trials, the recordings of the signals contained artifacts from areas associated with increased visual attention.

Magnetoencephalography (MEG)

A newer technique that records electrical signals from neurons in the brain is **magnetoencephalography (MEG)**. Instead of electrodes placed on the head as for an EEG, MEG involves placing the head in or near an electrical scanner that can detect electrical activity with better location accuracy than EEG. As with EEG recordings, MEG recordings can occur during a task such that changes in activity can be detected that correspond to the presentation of cognitive stimuli. However, as with EEG, MEG is limited to recordings on the outer cortex and cannot provide a good measure of activity occurring below the cortex (Gross, 2019).

Although MEG seems to be used less often than EEG due to equipment costs, it has been used in a number of studies for recording electrical activity. For example, Alexandrou et al. (2017) used MEG to examine the brain activity of participants who were processing naturalistic speech. In

PHOTO 2.2 A patient sits in a new brain scanner at the magnetoencephalography department of the Erasme hospital of Anderlecht in Brussels, Belgium.

Mark Renders/Stringer/Getty Images Entertainment/via Getty Images

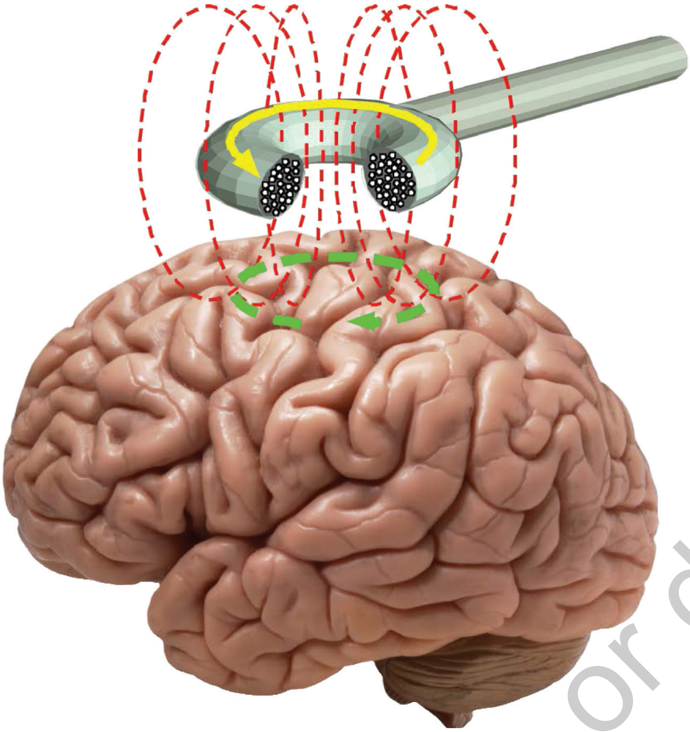
contrast to many results of studies that focus on isolated words and sentences, they demonstrated that processing naturalistic language engages cortical areas not only in the left hemisphere but also in the right hemisphere.

Electrical Stimulation/Inhibition of Neurons

Another technique that relies on the electrical activity in the brain involves **transcranial magnetic stimulation (TMS)**. With TMS, researchers use a magnetic field to excite or inhibit neuron activity to investigate functioning in specific areas or processing systems of the brain. Like EEG and MEG, this technique is noninvasive, as it involves tracing a magnetic coil over the area of the brain the researcher wishes to study (see Figure 2.11). The electrical activity (an increase or decrease) can then be recorded using one of the brain imaging techniques discussed in the next section (e.g., magnetic resonance imaging). Studies using TMS have shown that some cognitive tasks (e.g., making spatial judgments for visual stimuli) use a broader range of brain areas than what was previously thought using other brain recording techniques (e.g., Sach et al., 2007).

A similar technique is **transcranial direct current stimulation (tDCS)**. Like TMS, neuron activity can either be excited or inhibited using this technique. However, where TMS uses a magnetic field to create the electrical current, tDCS delivers a small electric current to the brain through electrodes attached to the scalp. Thus, it is also a noninvasive technique. The tDCS technique is cheaper and easier to use than TMS but produces a weaker effect on neuron activity than TMS.

FIGURE 2.11 ■ Transcranial Magnetic Stimulation (TMS)



In transcranial magnetic stimulation (TMS), a magnetic field generator placed near the target region of the brain produces a small electric field (the red dashed lines), which stimulates neuron activity (the green dashed line) in that area.

Source: Courtesy of Eric Wassermann, M.D., Behavioral Neurology Unit, National Institute of Neurological Disorders and Stroke.

PHOTO 2.3 A person undergoing transcranial magnetic stimulation.

Keith Bedford/The Boston Globe/via Getty Images

STOP AND THINK

2.3 What type of neuron activity is recorded in single-cell and EEG?

2.4 What is the primary disadvantage of single-cell recordings compared with the other electrical recording techniques?

MEASURES IN COGNITIVE NEUROSCIENCE: BRAIN IMAGING

Electrical recordings from the brain are useful, but in most cases are not very precise in the location of the brain that the measurements are coming from (with single-cell recordings as the main exception). Imaging techniques, however, can provide more precise localization of the activity being measured. In this section, we review the most common brain imaging techniques used in cognitive neuroscientific research.

Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging (MRI) is often used medically to gain clear images of interior structures of the body. Perhaps you or someone you know has gotten an MRI to examine an internal injury (e.g., a knee, hand, or foot). With the same technique, clear images of the brain can be gained. In an MRI scan, a magnetic field is generated to create an image using recordings of the signal coming from the positive hydrogen atoms within the cells of the body. An MRI of the brain can create a clear image of the different structures of the brain that allows comparison across individuals and identification of damage or the presence of tumors.

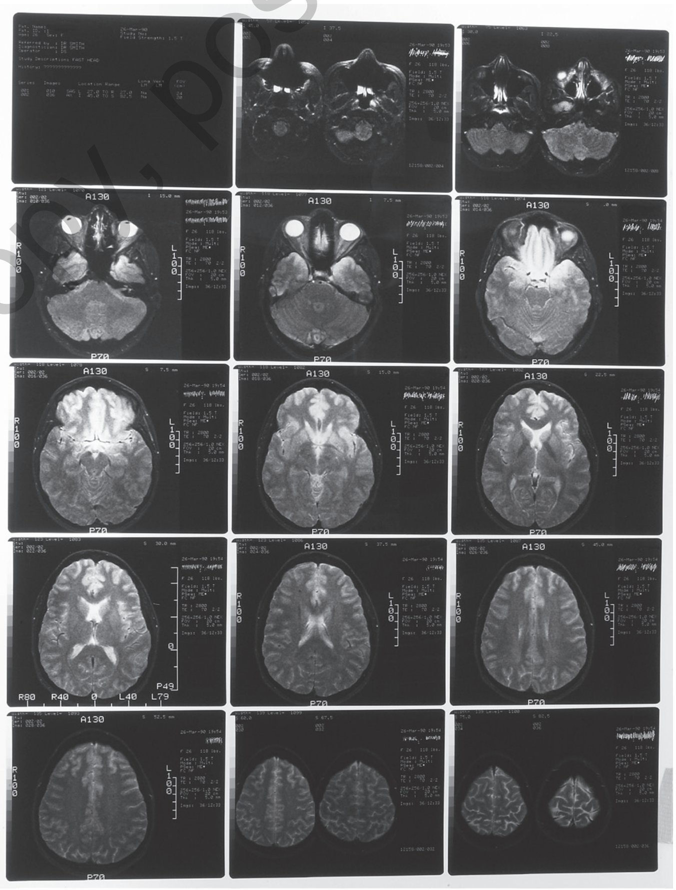


PHOTO 2.4 Images from an MRI of the brain.

Thomas Northcut/Photodisc/Thinkstock

Positron Emission Tomography (PET)

Using **positron emission tomography (PET)**, researchers can measure the blood flow to different areas of the brain. Blood flows in greater volume to more active areas of the brain; thus, the measure of the blood flow will indicate the areas of the brain most active during a cognitive task. Blood flow is detected through the ingestion of a small amount of a radioactive substance. The radioactive substance is then absorbed into the blood and flows to the brain as blood is needed in active areas. The radioactivity in the blood is then measured in a PET scan to determine which areas of the brain are more active than others during a task. The recording of the radioactivity is then overlaid onto a map of the brain to examine which areas are the most and least active. In a PET scan, color indicates the level of activity occurring in different areas. Photo 2.5 shows PET scans for two individuals: one who has taken cocaine and one who has not. The most active areas of the brain are colored in red (followed by yellow and then green, with the least amount of activity in blue). In this figure, it is clear there is less activity globally for individuals who have cocaine in their system than for individuals who do not (control).

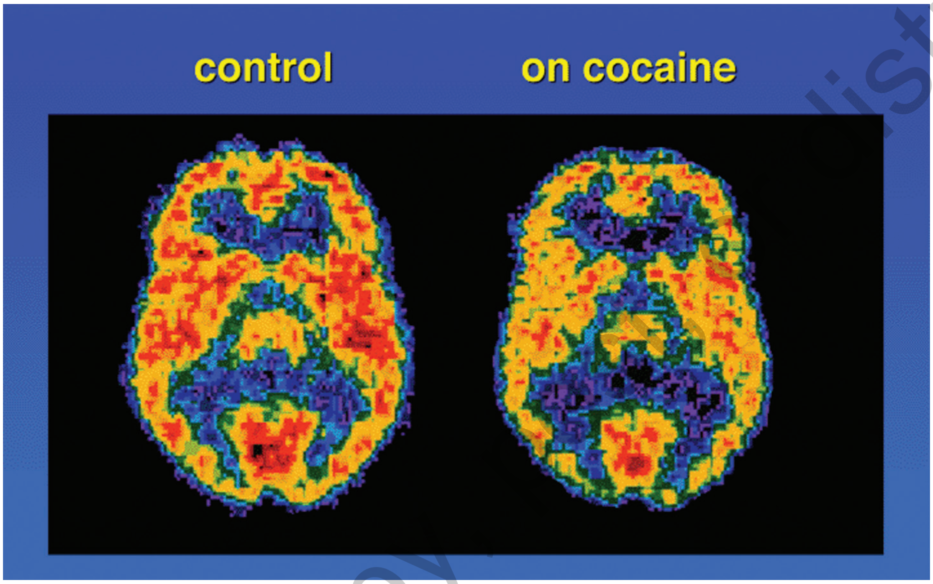


PHOTO 2.5 PET scans. The areas in red are the most active; those in blue are least active.

NIDA (2007, January 1), The Brain & the Actions of Cocaine, Opiates, and Marijuana, https://www.drugabuse.gov/brain-actions-cocaine-opiates-marijuana

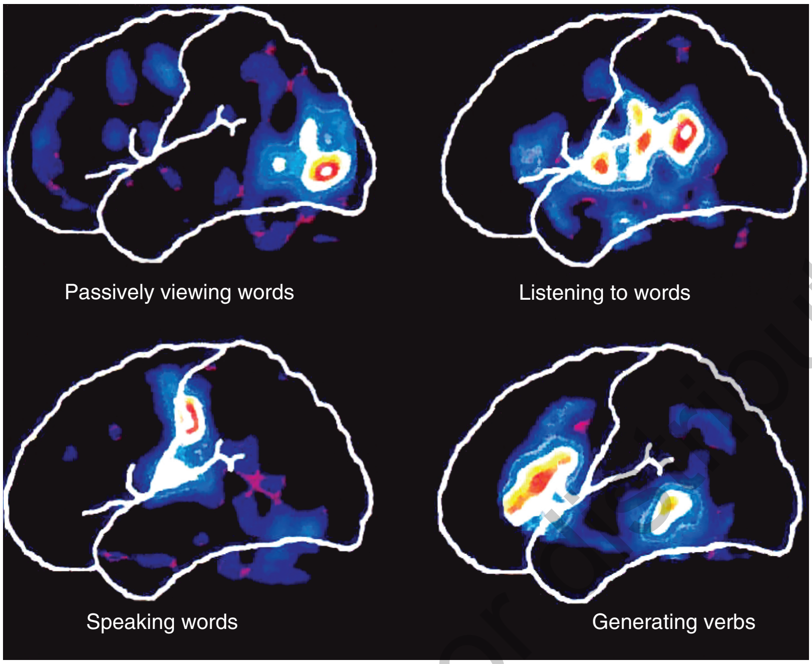
Functional Magnetic Resonance Imaging (fMRI)

Functional magnetic resonance imaging (fMRI) is a technique that records brain activity with a scan of the magnetic properties of the blood flowing through the brain. Similar to PET, fMRI shows blood flow activity to specific areas of the brain, with more active areas shown in brighter colors on the scan. The fMRI technique relies on a subtraction method, where activity recorded before the task (called the baseline recording, which is a control condition in this type of study) is subtracted from the activity recorded during the task. What is left is the activity present only during the tasks.

Like an MRI, an fMRI requires that the participant be placed in a magnetic scanner during the task. Typically, a mirror is positioned in the scanner for the participant to view the stimuli presented. fMRI is often preferred by researchers conducting brain scans because they are able to view brain activity during a task (unlike MRI) and there is no potentially harmful radioactive substance that needs to be ingested by the participant (unlike PET). Figure 2.12 shows images from fMRI scans for a participant performing different language tasks. As can be seen, different areas of the brain are most active during the various tasks.

The magnetic scanners used in MRI and fMRI are large, noisy, and require that those being scanned remain very still. These can be major limitations to using these scanning techniques. However, researchers have developed novel methods to circumvent these limitations, which have allowed them to, for example, scan awake infants who are looking at faces with fMRI (Deen et al., 2017).

FIGURE 2.12 ■ Images From PET Scans of the Brain Taken During the Different Language Tasks Identified in the Scan



Source: Adapted from Petersen, S. E., Fox, P. T., Posner, M. I., Mintun, M., & Raichle, M. E. (1988). Positron emission tomographic studies of the cortical anatomy of single-word processing. *Nature, 333*, 585–589.

Functional Near-Infrared Spectroscopy (fNIRS)

Like fMRI, functional near-infrared spectroscopy (fNIRS) measures neuronal activity from localized cerebral blood flow. However, the technique relies on the use of optical rather than magnetic scanning. Essentially, light is shined into the head (and within the head, the relatively transparent brain and vascular tissue), and the patterns of absorbed and reflected light are analyzed. This non-invasive technique has high temporal resolution but relatively low spatial resolution and is limited to cortical activity from within 2 cm of the surface. However, unlike an fMRI, these systems are relatively small, lightweight, quiet, portable, and in some cases wearable. Thus, fNIRS can be used in less constrained, more ecologically valid environments (Pinti et al., 2020).

The use of fNIRS can also be paired with other techniques to find converging evidence that can overcome the limitations of using a single imaging technique. For example, Brockington et al. (2018) report a case study in which a participant viewed a brief 15-minute lecture about astronomy. While the participant was watching the lecture, the researchers simultaneously used fNIRS, eye-tracking, and pupil contractions/dilations to measure cognitive processing while the participant was learning in a realistic environment.

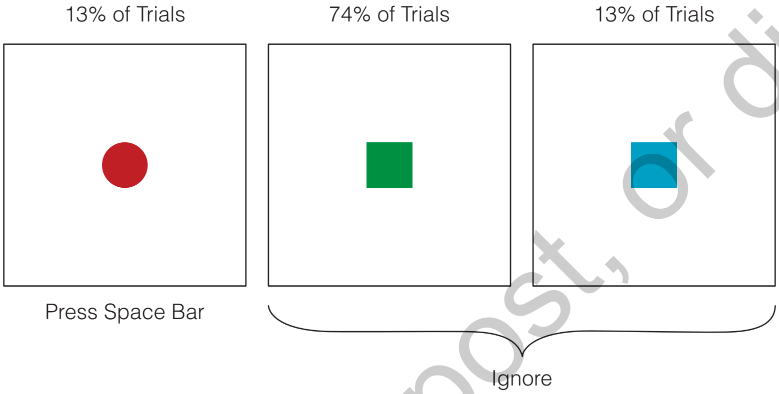
Recording Activity in the Living Brain

In upcoming chapters, we discuss studies that used the various techniques described in this chapter to illustrate the connection between brain function and the cognitive processes covered in those chapters. Here we highlight two such studies to demonstrate the use of these techniques in cognitive neuroscience. In later chapters, we discuss additional cognitive neuroscience studies in perception, attention, memory, language, and problem solving.

Two categories of brain recording techniques were described earlier in this chapter: recordings of electrical activity of neurons (single neurons or larger groups of neurons) and brain imaging techniques. Each technique has contributed important knowledge about the connections between cognition and brain function. For example, many EEG studies have shown the areas of the cortex most active during specific tasks. When EEG recordings are connected to specific stimulus presentations, as in ERP, this activity can be examined across stimulus conditions to make comparisons as tests of theoretical hypotheses.

In an example of this type of study, Barron and colleagues (2011) used ERP recordings to examine the factors that contribute to *mind wandering* (i.e., thinking about things other than the current task you are working on). Do you ever start thinking about something going on in your life (e.g., an argument with your boyfriend, girlfriend, or spouse or an assignment that is due at the end of the week) while you are reading this text? If so, then you have experienced the type of mind wandering that Barron et al. studied. These researchers recorded EEGs during a task where participants were asked to respond to a rare target event (a red circle appearing) that occurred in a series of presented stimuli (green and blue squares). However, the nontarget stimuli were presented in different proportions. Green squares were presented often and blue squares were presented as infrequently as the red circles. This type of stimulus presentation was used to determine if the blue squares would capture the participants' attention, even if they were not asked to respond to them (see Figure 2.13).

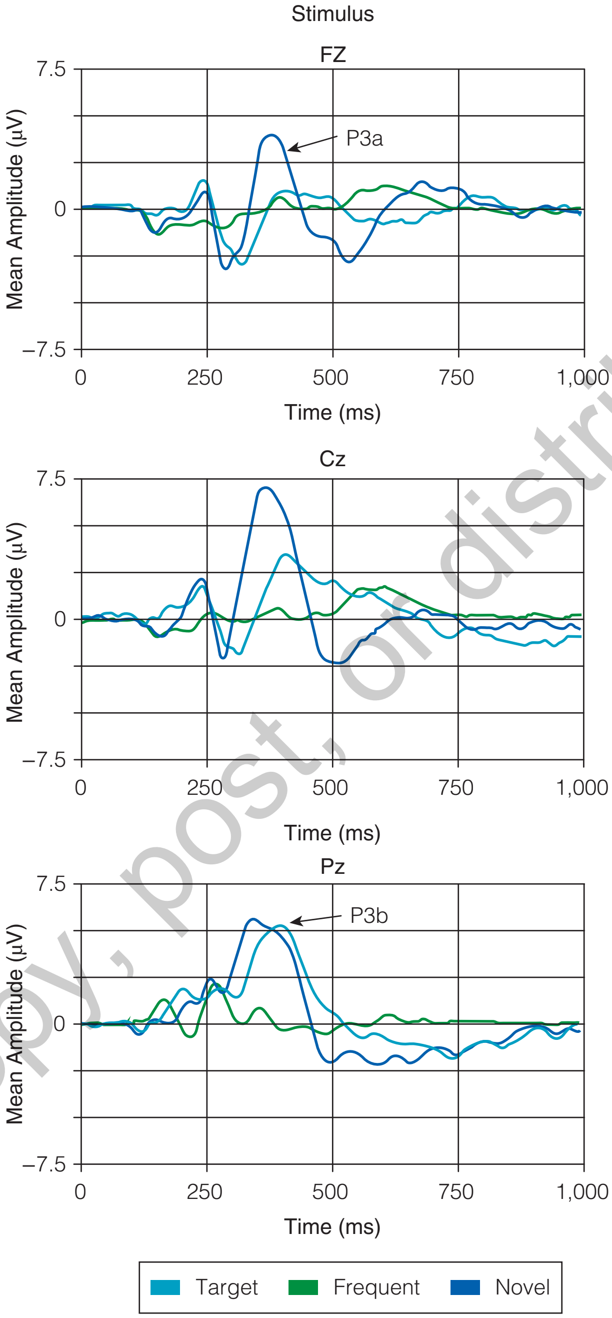
FIGURE 2.13 ■ Stimuli Used in the Barron et al. (2011) Study



Past studies using this task have shown an increase in neuron activity in the parietal cortex about 300–500 milliseconds (ms) after the red circle is presented, which is believed to be related to the maintenance of the stimulus in memory. Further, a similar increase in activity is shown in the frontal lobe if the blue square (that requires no response) is presented. The activity in the frontal lobe that occurs with this distracting rare event is believed to be due to attention being paid to this stimulus because it occurs infrequently in the trials (see Figure 2.14).

In the Barron et al. (2011) study, subjects also completed a survey at the end of the trials to gauge the amount of mind wandering that occurred during the task. Subjects were separated into groups: high, medium, and low mind wandering. The study was designed to investigate different theories about how mind wandering occurs for those who reported off-task thoughts during the task (i.e., the high mind wandering group). For example, mind wandering might happen because something distracts the person from their main task. If so, participants in the high group should show greater brain activity in the frontal cortex area when the distracting blue squares are presented. Alternatively, mind wandering might be due to participants completely disengaging from the task and focusing attention on other thoughts. If so, participants in the high group should show lower brain activity in both the frontal and parietal cortexes when the target and nontarget rare events (red circles and blue squares) are shown, because they are not attending well to any of the stimuli in the task. The results of the Barron et al. (2011) study showed that participants with high levels of mind wandering had lower levels of brain activity in response to both the red circles and blue squares, supporting the idea that participants were not attending to the task while their minds were wandering (see Figure 2.15). The researchers concluded from these data that suppression of the external events (i.e., not paying attention to the rare events, regardless of whether a response is required) contributes to mind wandering. This study shows how EEG/ERP studies can be used to test competing theories about cognitive processes.

FIGURE 2.14 ■ Graphs of Brain Activity From the Barron et al. (2011) Study

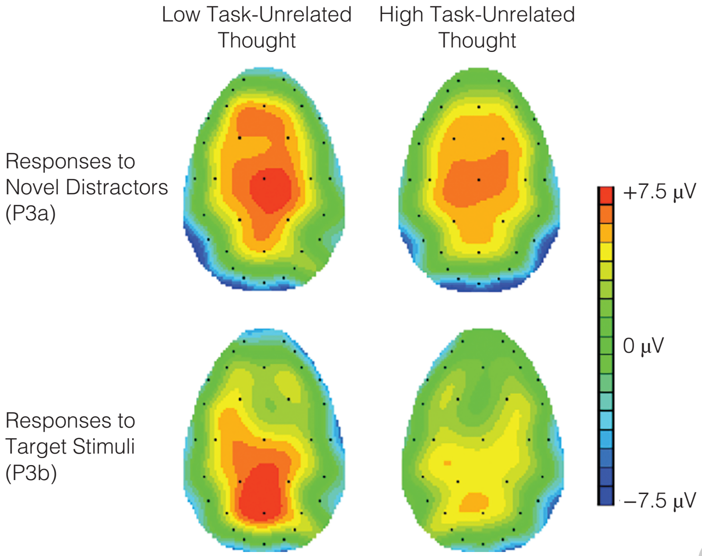


The graphs show the ERPs (collapsed across participants) measured in three regions: the frontal (Fz), the central (Cz), and the parietal (Pz). Beginning near 300 ms after the onset of novel stimuli (dark blue lines), results show increased activity in both the frontal and central regions (relative to the other stimulus types). This peak pattern is sometimes referred to as P300.

Source: Barron et al. (2011, Figure 1).

Brain imaging techniques are also frequently used in cognitive neuroscience studies. An example of this type of study was done by Segaert et al. (2012) to investigate the link in processing between language production and language comprehension. The similarities and differences between language production and comprehension have been a topic of interest as researchers in this area develop and test theories that explain how these processes occur (see Chapter 8 for more discussion of language comprehension

FIGURE 2.15 ■ Brain Activity Comparison Across Conditions in the Barron et al. (2011) Study



The left two topographical maps show P300 ERPs for participants who reported few task-unrelated thoughts (low mind wandering) in the novel and target conditions. The right two maps are of participants who reported high numbers of task-unrelated thoughts. These high wanderers had lower levels of brain activity compared to the low wanderers.

Source: Barron et al. (2011, Figure 2).

and production processes). Segaert et al. (2012) used fMRI recordings to test the idea that the same brain areas are active during syntactic processing (i.e., understanding how words fit together grammatically in sentences) in both language comprehension and production. Participants were asked to complete a task of either comprehending a sentence or producing a sentence when a verb and a picture were presented. The color of the verb (green or gray) indicated whether a comprehension trial or a production trial was used. Then fMRI scans of the participants' brains were taken during the task. The researchers examined the change in brain activity when the same syntactic structure of sentences was repeated in the trials to see if adaptation to the structure (i.e., lowered brain activity) would be seen. They then compared the adaptation effects across the comprehension and production trials to see if adaptation was similar across speaking and listening trials. Adaptation to the repeated syntactic structure of the sentences was found in both comprehension and production trials. In addition, the same level of adaptation was found in both speaking and listening trials. The researchers concluded that the same brain activity contributes to syntactic processing in both comprehension and production of language.

Brain recording technologies have allowed cognitive neuroscientists to gain important knowledge about the connection between brain function and cognitive processes. Pulvermüller (2010b) outlined the four key questions that can be answered by cognitive neuroscience research: (1) What brain activity occurs during specific cognitive tasks? (2) When does the brain activity occur during a task (e.g., at stimulus presentation or after a delay when processing has begun)? (3) How does the brain activity occur (e.g., in specific networks of brain areas)? and (4) Why does particular brain activity occur (i.e., testing hypotheses about how the processing occurs in particular cognitive tasks)? Thus, there is a large advantage in using brain recording techniques in cognitive neuroscience research to learn about these specific aspects of cognitive functioning. However, some disadvantages exist as well. One disadvantage is that not all cognitive tasks are easily adapted to the brain recording techniques. The neuroscientific study of insight (i.e., that "aha" moment when you suddenly realize how to solve a problem; see Chapter 11), for example, has been difficult to conduct because it is hard to predict when insight will occur for a specific problem. Luo and Knoblich (2007) describe the difficulties in using fMRI and EEG techniques to study the process of insight and some of their methods to adapt insight studies to brain recording techniques. Another disadvantage is the limited availability of brain scan technology.

Because MRI machines are expensive and also serve as a medical tool, it can be difficult for researchers to obtain time available for use of these devices. EEG machines are relatively cheaper and more readily available for research, but their use can be time-consuming for running participants. Thus, although these recording techniques represent significant advances in our ability to connect cognitive function with brain activity, they are not without drawbacks.

Another area where progress has been made in investigating how brain activity translates into specific behaviors is in patterns of activity related to the identification of simple objects. For example, some studies have shown that a unique pattern of brain activity accompanies the identification of objects such as faces and houses (Grill-Spector, 2008). In fact, researcher Marcel Just and his colleagues (Mitchell et al., 2008) have been developing a "mind reading" program that can identify a word a person is looking at simply from the pattern of brain activity seen in an fMRI scan of the person's brain.

The research highlighted here is promising in making specific connections between predictable brain activity and cognitive behavior. However, one criticism is that the behaviors being examined are too simple (e.g., choosing to press a button, looking at a word). It may be much more difficult and maybe impossible to make such precise connections between brain activity and more complex behaviors, such as driving, having a conversation, and imagining yourself in a situation you have never been in. Yet, innovative techniques are being developed along with the refinement of current techniques for the future. Thus, research in this area will continue to connect cognition and brain activity.

STOP AND THINK

2.5 What type of brain activity is detected in PET and fMRI scans? Why is an fMRI scan preferred to a PET scan in most cases?

2.6 Does research that makes connections between brain activity and cognitive task performance provide causal information or merely correlational information? Explain your answer.

2.7 Suppose that you were interested in learning about the brain areas involved in memory processing. You are specifically interested in testing whether the retrieval of accurate and false memories relies on the same underlying processes in brain function. Describe a study using one of the brain recording techniques described in this chapter that would test this question.

THINKING ABOUT RESEARCH

As you read the following summary of a research study in psychology, think about the following questions:

1. Explain how this study used recordings of brain activity to test a theoretical description of a cognitive process.
2. What was the primary manipulated variable in this experiment? (Hint: Review the Research Methodologies section in Chapter 1 for help in answering this question.)
3. Do you think the researchers would have achieved similar results if they had used EEG instead of fMRI in this study? Why or why not?
4. Explain why it was important for the researchers to show that participants were slower in performing the nonfocal than the focal prospective memory task.
5. Explain why it was important for the researcher to show that the participants were equally accurate in the internal-only condition and the internal-plus-external attention conditions.

Study Reference

Cona, G., Chiossi, F., Di Tomasso, S., Pellegrino, G., Piccione, F., Bisiacchi, P., & Arcara, G. S. (2020). Theta and alpha oscillations as signatures of internal and external attention to delayed intentions: A magnetoencephalography (MEG) study. *NeuroImage, 205*, 116295. https://www.un.org/sites/un2.un.org/files/wmr_2020.pdf, p. 44.

Purpose of the study: The researchers' goal was to map brain activity in two tasks that differed in the type of attention they required. One task required internal attention and the other task required external attention. Brain electrical activity was recorded using the MEG technique. The researchers predicted that the brain activity patterns would differ across the two tasks due to the different kinds of attention they relied on.

Method of the study: Participants were 21 healthy young adults. The participants were asked to complete a lexical decision task, where letter strings were presented for word/non-word judgments. This task only requires internal attention to one's mental lexicon (see more in Chapter 8). This task was performed on its own and also performed with additional tasks. One of the additional tasks involved pressing a separate key when the syllable "pra" was present in any of the letter strings. This task requires external attention to scan for this syllable within the stimuli (while also making a judgment about whether the string of letters was a word/nonword). The other additional task involved pressing a separate key when three specific words were presented with a different key to be pressed for each word. This task used internal attention to monitor for and notice the specific words and then remember which corresponding key to press. Participants completed the tasks while positioned in an MEG device to record brain activity during the tasks. The recorded activity was then mapped onto an MRI of the participants' brains to determine the location of the activity.

Results of the study: The brain activity results revealed a different pattern of activity for the external and internal attention tasks. Specifically, compared with blocks of trials where the lexical decision task was completed on its own, the external attention task was consistent with a reduction in activity over time on each trial, whereas the internal attention task was consistent with increases in activity over time on each trial. In addition, no performance difference was found across the two tasks—participants were equally likely in the two tasks to complete the correct responses to the specific words and the syllable they were given for the additional tasks.

Conclusions of the study: From the recordings of brain activity seen in this study, the researchers concluded that tasks that differ in their required attention produce different brain activity patterns, such that tasks using internal attention (keeping a task in their immediate memory) is associated with an increase in a specific type of electrical activity, but tasks using external attention (monitoring stimuli for a specific feature, like a syllable) is associated with a decrease in a different type of electrical activity.

CHAPTER REVIEW

- **How is the examination of brain activity involved in the study of cognition?**

  A number of brain activity recording techniques are used by cognitive neuroscientists to better understand how brain activity is tied to cognition. All rely in some way on neuron activity, with some (single-cell recordings, EEG) measuring the electrical signals from neurons and others (PET, fMRI) recording images of neuron activity in larger areas of the brain.

- **How do case studies of individuals with cognitive deficits inform us about the connection between cognition and brain function?**

  Individuals who have suffered a brain lesion can help us connect cognitive deficits to specific areas of the brain. By examining the area(s) of the lesion and which cognitive deficits the individuals have, researchers can make hypotheses about the primary function of different areas of the brain. Much of the early knowledge of localization of function in the brain came from such clinical case studies.

- **What can be learned about cognition through measurements of neuron activity in the brain?**

  Like clinical case studies, researchers can connect specific brain areas with cognitive abilities. However, measurements of brain activity also allow researchers to provide better tests of hypotheses about brain function because experiments can be conducted with brain activity as the dependent measures.

CHAPTER QUIZ

1. Which brain recording technique(s) is (are) often limited to laboratory animals because it (they) requires the insertion of a recording needle into the brain?
   a. NIRS
   b. EEG/ERP
   c. fMRI
   d. single-cell recording
   e. both (a) and (b)
2. Which brain recording technique(s) measures a change in blood flow to different areas of the brain?
   a. PET scan
   b. EEG/ERP
   c. fMRI
   d. single-cell recording
   e. both (a) and (b)
3. What is meant by localization and lateralization of brain function?
4. Describe some disadvantages of using clinical case studies to connect brain function and cognition.
5. From Phineas Gage, researchers learned that the ____________ lobe of the brain is important for reasoning abilities and control of emotion.
   a. frontal
   b. parietal
   c. temporal
   d. occipital
6. In which lobe of the brain is visual information primarily processed?
   a. frontal
   b. parietal
   c. temporal
   d. occipital
7. In what ways is the single-cell recording technique different from other brain recording techniques?
8. How do brain recording techniques allow for experiments that cannot be done with clinical case study patients?
9. When EEG recordings are connected to the timing of the presentation of a stimulus, it is called ____________________.
10. The MEG technique provides better ____________ than EEG.
11. The ______ brain imaging technique is non-invasive, portable, and is often used together with other brain recording techniques.
12. Which recording techniques can also be used to excite or inhibit brain activity?

KEY TERMS

Axon (p. 25)
Dendrites (p. 25)
Electroencephalography (EEG) (p. 31)
Event-related potential (ERP) (p. 31)
Functional magnetic resonance imaging (fMRI) (p. 35)
Hippocampus (p. 24)
Lateralization (p. 28)
Localization (p. 28)
Magnetic resonance imaging (MRI) (p. 34)
Magnetoencephalography (MEG) (p. 31)
Neuron (p. 25)
Positron emission tomography (PET) (p. 35)
Single-cell recording (p. 30)
Synapse (p. 25)
Transcranial magnetic stimulation (TMS) (p. 32)
Transcranial direct current stimulation (tDCS) (p. 32)