2

Behavioral Neuroscience

CHAPTER OUTLINE

THE BODY'S COMMUNICATION NETWORKS
- The Nervous System
- The Endocrine System

THE NEURON
- Structure of the Neuron
- The Neuron in Action
- How Neurons Communicate
- Neurotransmitters

THE BRAIN
- Tools of Behavioral Neuroscience
- Regions of the Brain
- The Split Brain

PROSPECTS FOR THE FUTURE
- The Brain's Capacity for Growth and Reorganization
- Repairing the Damaged Brain: New Frontiers

LEARNING OBJECTIVES

2.1 Explain the steps taken by the brain and body to prepare for a reaction.

2.2 Apply the parts of a neuron and neurotransmitters to the process of electrochemical communication.

2.3 Summarize and synthesize the methods utilized to understand the parts and operation of the brain.

2.4 Identify the nature of plasticity in the brain and how it can be applied to understanding brain injuries.

What's Your Prediction: One Brain or Two?

The SITUATION

You've seen pictures of the human brain, so you likely have a fairly good sense of what it looks like. The brain has two halves: a right hemisphere and a left hemisphere. Each is actually nearly a copy of the other; as you may know, the whole brain works together, but the right and left sides (or "hemispheres") have different strengths. The left side tends to be a literal interpreter (e.g., the literal meaning of the words you read in a novel), whereas the right side tends to be more of a subjective interpreter (e.g., how you imagine the characters and setting as you read the novel). Incredibly, each hemisphere largely controls the opposite side of the body: the right hemisphere processes the left side of the body, and the left hemisphere processes the right side of the body.

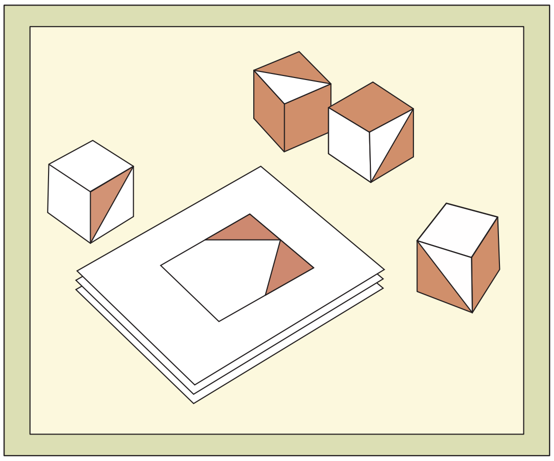
You're only mildly interested. But wait. What if the two halves of a person's brain were physically separated from each other? Would each side compensate for the loss of function on its own, or would the person flounder? This sounds like one of those hypothetical problems that philosophers like to ponder, but it's real. On rare occasions, people who suffer life-threatening seizures undergo a radical form of surgery in which the cable of nerves that connect the brain's right and left hemispheres is completely severed. In these

<< Scott Camazine & Sue Trainor/Science Source

"split-brain" patients, the two sides of the brain can no longer communicate. The question is: What is the effect?

Now imagine the following situation. The year is 1961 and you are assisting with an experiment in which a split-brain patient by the name of W.J. agrees to take part. After your introductions, you show W.J. a series of cards, each containing a red-and-white geometrical pattern, and a set of cubes—each containing two red sides, two white sides, and two mixed sides divided along the diagonal. His task is to arrange the blocks in squares that match the patterns on the cards (see Figure 2.1). Oh, there's one hitch. You tell W.J. that he can use only one hand to assemble the blocks. On some cards, you tell him to use his right hand and keep the left hand tucked under the table. On other cards, you tell him to use only his left hand. Can W.J. match the patterns? Does it matter which hand he uses?

FIGURE 2.1 The Block-Design Task Given to W.J.



Make a PREDICTION

Reread the situation and examine the clues given earlier about the human brain, the type of surgery that W.J. had, and the nature of the task he is being asked to complete. Also keep in mind that W.J. is a normal and intelligent man—at least he was before the surgery. Putting all these pieces together, do you think he is able to complete the task with his right hand? What about with his left hand? Make two predictions, one for each hand.

	YES	NO
Left-hand success	_____	_____
Right-hand success	_____	_____

The RESULTS

Before W.J. was tested, researchers Michael Gazzaniga and Roger Sperry were not sure what to expect. W.J. seemed normal in conversation, but perhaps both sides of an integrated brain are needed for complex mental activities. Or perhaps one side is sufficient if it's the one that specializes in the task at hand. The result was dramatic: W.J. could assemble the block patterns with his left hand, but not with his right hand. In fact, as his right hand struggled, the left hand occasionally snuck up from under the table to help out!

What Does It All MEAN?

W.J. was the first split-brain patient ever tested, but others later confirmed the basic result: The left hand succeeded at the spatial block-design task because the left hand is controlled by the "spatial" right hemisphere. Yet the right hand was clueless because it is controlled by the left hemisphere and was unable to receive signals from the right side after the surgery. This case study involving W.J. shows that the brain's two hemispheres specialize in different types of mental activities—something we normally don't notice because the hemispheres are connected and both sides are involved in everything we do. More important, this study shows that when the two halves are disconnected, they act as two separate brains. Reflecting on the implications, Gazzaniga (1992) notes that "each half brain seemed to work and function outside of the conscious realm of the other" (p. 122).

Case studies such as this have played a major role in our understanding of the human brain and its links to the body and the mind. The brain is a complex anatomical structure, and researchers today have many tools at their disposal to study how it works. In this chapter, we'll examine the human brain, how it's built, its place in the nervous system, and the psychological functions that it serves.

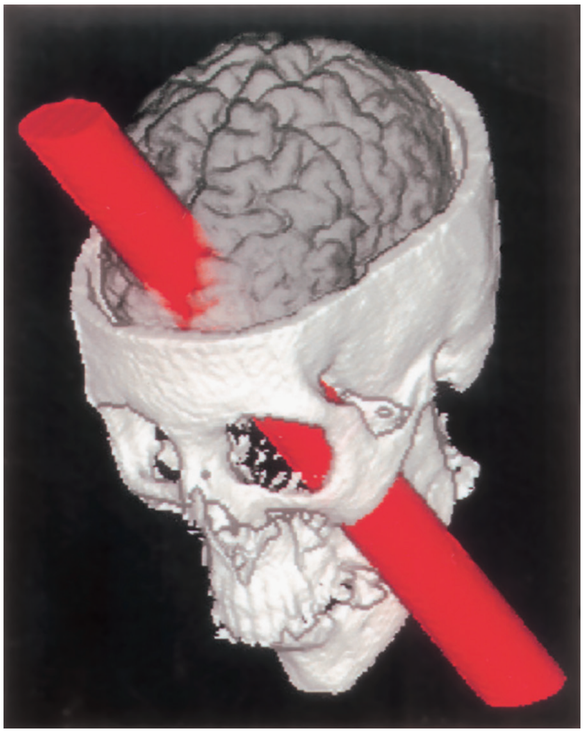
At 25 years of age, Phineas Gage was a supervisor for the Rutland & Burlington Railroad in Vermont. He was bright, well liked, and energetic. On the afternoon of September 13, 1848, Gage and his coworkers were in Vermont blasting rock to pave the way for new railroad tracks. To do this, they drilled holes in the rock and packed the holes with gunpowder and sand, using a 3-foot-long rod called a tamping iron. A spark suddenly ignited the powder, causing an explosion that propelled the rod upward like a missile. As shown in Figure 2.2, the rod (which was 1.25 inches in diameter at one end but came to a sharp point at the other end) pierced Gage's left cheek behind the eye, exited the front-top part of his skull, flew 50 feet into the air, and landed in a pile of dirt, covered with blood and brain matter.

Gage was catapulted backward to the ground, where he began to shake. To everyone's amazement, he was still alive. Minutes later, with blood pouring down his face, Gage was sitting up, moving about, and talking to those around him. Doctors soon stopped the bleeding, cleaned out the loose bits of bone and brain tissue, and packed the wound. Within a few months, Gage was back at work. He showed no loss of intellectual ability. But the front part of his brain, the area known as the frontal lobes, was badly damaged (Figure 2.3). As a result, this normally soft-spoken, controlled, and considerate young man had become irritable, demanding, unable to plan for the future, and unrestrained—at times engaging in gross profanity. In many ways, Gage was not a social being. According to his doctor, the change in Gage's personality was so profound that he was "no longer Gage." To complete the sad story: Gage lost his job, traveled with P. T. Barnum's circus, and exhibited his skull and tamping iron all over the country. Twelve years after the accident, Gage died at age 37. To this day, however, his case remains important in the history of brain science (Fleischman, 2002; Harlow, 1868; MacMillan, 2000; Thiebaut de Schotten et al., 2015).

Psychologists now know that the frontal lobes are involved in thinking, planning, setting goals, and inhibiting impulses. But the case of Phineas Gage told us much more. It told us that the human brain and nervous system are not a single or simple entity but rather an integrated "system" consisting of different specialized parts. And it told us that the links among the brain, the mind, and behavior can be revealed by the effects of damage to specific structures. These points set the stage as we begin to explore the biological roots of the human experience. As we'll learn, all aspects of our

■ **FIGURE 2.2** Phineas Gage's Skull

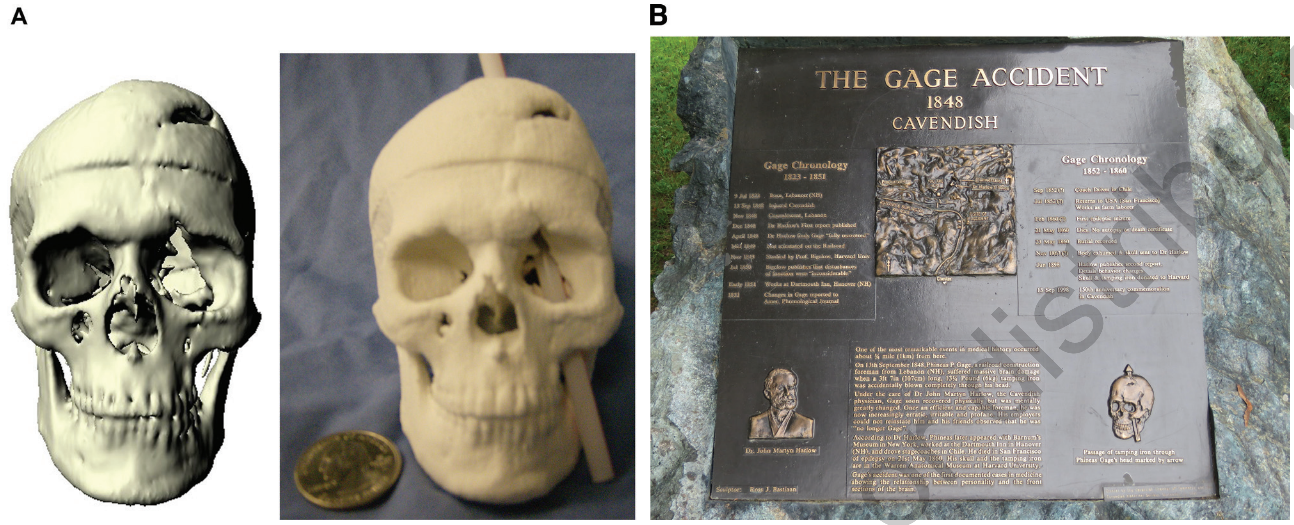
Using photographs and measurements of Gage's skull and computerized images of normal brains, Hanna Damasio and her colleagues (1994) plotted the possible paths of the tamping iron and produced this computerized reconstruction of the damage to the prefrontal cortex of Gage's skull. Gage's skull and tamping iron are now on display on the fifth floor of the Harvard Medical School Library.



Source: Reprinted with permission from H. Damasio, T. Grabowski, R. Frank, A. M. Galaburda, and A. R. Damasio, "The Return of Phineas Gage: Clues About the Brain From a Famous Patient," Science, 264, pp. 1102–1105. © 1994. Reprinted by permission from AAAS.

FIGURE 2.3 Three-Dimensional Plaster Life Mask of Phineas Gage

(A) Recognizing the historic value of his case, doctors in Boston made this three-dimensional plaster mask 1 year after the accident by having Phineas close his eyes and inserting straws into his nose so he could breathe while liquid plaster was poured over his face. You can see the large scar on his forehead. (B) In 1998, the small town of Cavendish, Vermont (72 miles north of one author's home in Williamstown, Massachusetts), memorialized Phineas Gage by dedicating a plaque in his honor. The plaque tells the story of what happened and its significance for the study of behavioral neuroscience.



Source: Kelley DJ, Farhoud M, Meyerand ME, Nelson DL, Ramirez LF, et al. (2007) "Creating Physical 3D Stereolithograph Models of Brain and Skull." PLoS ONE 2(10): e1119. doi:10.1371/journal.pone.0001119. Licensed under Creative Commons CC BY 2.5.

Source: Roadside plaque in Cavendish, Vermont memorializing Phineas Gage by Daniel G. Axtell, licensed under CC BY-SA 4.0 https://creativecommons.org/licenses/by-sa/4.0/deed.en.

existence—every sight, sound, taste, and smell, every twitch, every movement, every feeling of pleasure or pain, all our dreams, learned associations, memories, thoughts, emotions, and even our personalities and social interactions—are biological events. Behavioral neuroscience is the subfield of psychology that focuses on these links (Breedlove & Watson, 2017; Kandel et al., 2000).

The Body's Communication Networks

2.1 Explain the steps taken by the brain and body to prepare for a reaction.

- How do the sensory organs, muscles, and other parts of the body prepare for action?
- What are the body's communication networks, and how does the brain act as a central command center?

The human brain weighs only about 3 pounds. With its gnarled mass of cells, it feels like a lump of jelly and looks like an oversized, wrinkled gray walnut. The brain is an extraordinary organ—capable of great feats and more complex than any computer. It is one of those "miracles" of life that inspire philosophers and scientists alike.

The Nervous System

The brain is the centerpiece of the body's nervous system, an elaborate electrochemical communication network that connects the brain and spinal cord to all sensory organs, muscles, and glands. The nervous system is divided into two major parts: central and peripheral. The **central nervous system (CNS)** consists of the brain and the spinal cord. The spinal cord is a long tubular column of neural tissue surrounded by a ring of bone that runs from the lower back up to the base of the skull. Basically, the spinal cord is a transmission cable filled with nerve fibers and pathways—and it serves

central nervous system (CNS) The network of nerves contained within the brain and spinal cord.

as an "information superhighway." Later in this chapter, we'll learn that the spinal cord transmits signals from sense organs and muscles below the head up to the brain and funnels signals from the brain to the rest of the body. Injury to the spinal cord can cause partial or complete paralysis.

> The world's heaviest known brain—belonging to a 30-year-old male in 1992—weighed 5 lb. 1 oz. The lightest healthy brain—belonging to a man from Ireland who died in New York in 1907 at age 46—weighed 1 lb. 8 oz. (Guinness World Records, 2002)

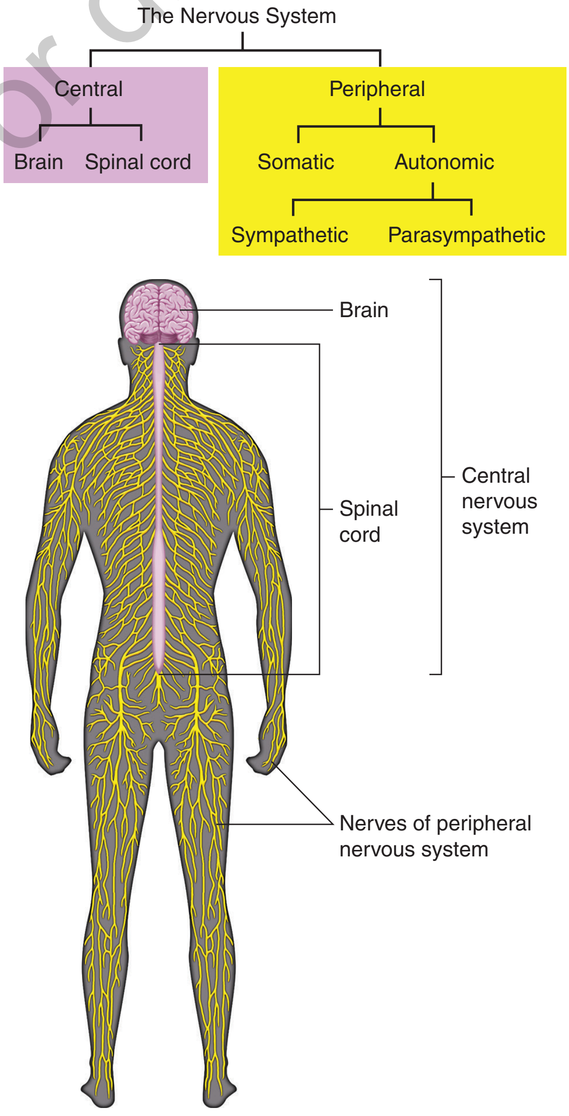
peripheral nervous system (PNS) The network of nerves that radiate from the central nervous system to the rest of the body. The PNS comprises the somatic and autonomic nervous systems.

somatic nervous system The branch of the peripheral nervous system that transmits signals from the sensory organs to the CNS and from the CNS to the skeletal muscles.

autonomic nervous system The branch of the peripheral nervous system that connects the CNS to the internal muscles, organs, and glands.

The **peripheral nervous system (PNS)** consists of all the nerves that radiate from the CNS to the rest of the body—from the top of the head out to the fingers, toes, and skin. The peripheral nervous system is divided into two components: somatic and autonomic. The nerves of the **somatic nervous system** transmit signals (such as sights, sounds, tastes, smells, and pain) from the sensory organs and skin to the CNS. They also relay motor commands from the CNS to the skeletal muscles of the arms, legs, torso, and head, thus directing the body's voluntary movements. The nerves in the **autonomic nervous system** connect the CNS to all of the smooth *involuntary* muscles and organs (such as the heart, stomach, and liver) and to the body's many glands, which secrete hormones (as discussed next). As the term *autonomic* implies, this system automatically regulates internal states such as heartbeat, blood pressure, body temperature, digestion, hormone levels, and glucose levels in the blood. As we'll learn later in this book, people can learn to use biofeedback, yoga, and other techniques to exert some control over these bodily functions.

■ **FIGURE 2.4** Divisions of the Nervous System



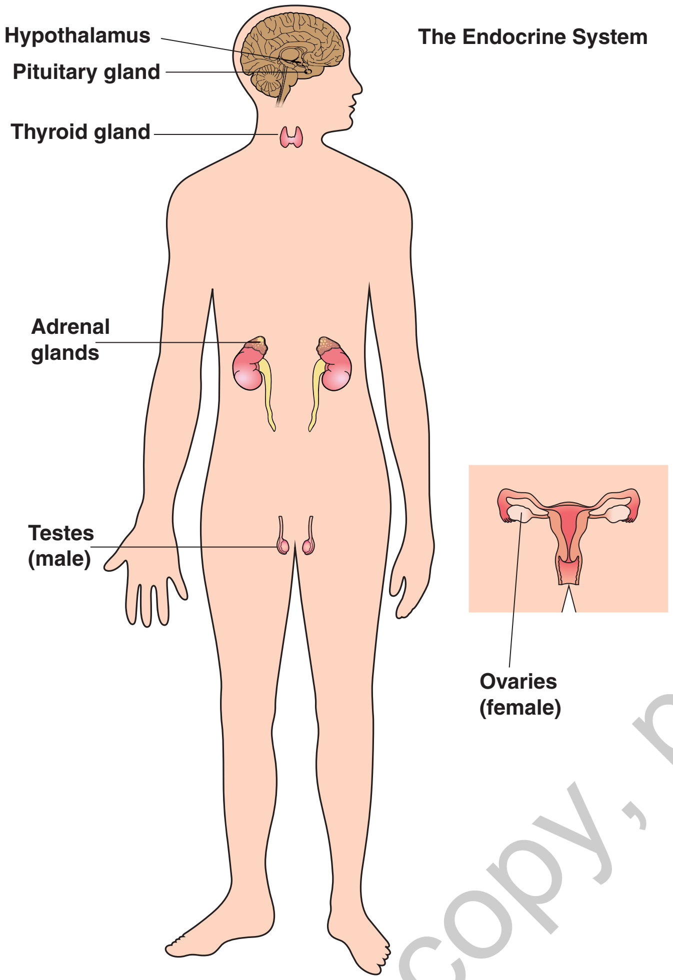
Source: Adapted from Biological Foundations of Human Behavior, by J. Wilson, 2003, Belmont, CA: Wadsworth.

The autonomic nervous system itself has two parts: sympathetic and parasympathetic. In light of the functions served by these subsystems, they may be thought of as the body's "departments of war and peace." The **sympathetic nervous system** energizes the body for action. In times of stress, the sympathetic nervous system directs the adrenal glands, which rest atop the kidneys, to secrete more of the hormones epinephrine and norepinephrine (also known as *adrenaline* and *noradrenaline*), thereby increasing the heart rate and heightening physiological arousal. The pupils dilate to let in more light, breathing speeds up to bring in more oxygen, and perspiration increases to cool down the body. When action is no longer necessary, such as when the stress subsides, the **parasympathetic nervous system** takes over and restores the body to its pre-energized state. The heart stops racing, the pupils contract, breathing slows down, and energy is conserved. The blood levels of epinephrine and norepinephrine slowly diminish, and the body relaxes, cools down, and returns to normal. These systems play a vital role in the experience of emotion.

To summarize, the nervous system is divided into two parts, central and peripheral. The CNS contains the brain and spinal cord. The PNS is further subdivided into the somatic and autonomic systems. In turn, the autonomic system contains both sympathetic (arousing) and parasympathetic (calming) divisions. This overview of the nervous system is presented in Figure 2.4.

FIGURE 2.5 Major Endocrine Glands

Taking commands from the hypothalamus, the glands of the endocrine system regulate growth, reproduction, metabolism, and behavior by secreting hormones into the bloodstream. These hormones are carried to certain "target organs" throughout the body.



The Endocrine System

Closely linked to the nervous system is the body's second communication system. The **endocrine system** is a collection of ductless glands that regulate growth, sexual development, reproduction, metabolism, mood, and certain aspects of behavior by secreting chemical messengers called **hormones** (the word *hormone* means to "set in motion"). Hormones are produced in tissue and secreted into the bloodstream, which then carries them to "target organs" throughout the body. Compared to the speedy transmission of impulses through the nervous system, hormonal messages may take several seconds, hours, or even days to take effect. Once they do, however, the impact is often long lasting. Dozens of hormones are produced by the body. Some of the major glands, along with their locations and their functions, are illustrated in Figure 2.5.

As we'll learn later, a small but important structure in the brain called the hypothalamus controls the endocrine system through the **pituitary gland**, a pea-size gland that sits at the base of the brain. The pituitary can be thought of as the master gland of the endocrine system. Upon command from the control center in the brain, the pituitary releases a hormone that stimulates the production of hormones in other endocrine glands. In turn, many hormones flow from the bloodstream back to the brain, which sends a signal to the hypothalamus that more or less additional secretion is needed. The importance of hormone regulation for the maintenance of the body is apparent when an endocrine gland malfunctions in some way. For example, when a thyroid gland produces too little hormone, people become easily tired and sensitive to cold. When the thyroid produces too much of the hormone, people tend to get nervous and irritable and lose weight.

Notice that there is a constant flow of communication between the nervous system and the endocrine system. Indeed, the brain regulates the release of hormones the same way that a thermostat maintains the temperature of a room. If you set a thermostat to 70 degrees and the temperature dips below that level, the heat comes on until the room tops 70, at which point the thermostat shuts itself off. Similarly, if a hormone drops below a certain level, the hypothalamus signals the pituitary and other glands that more is needed. Then once the hormone levels are sufficient, the hypothalamus signals the pituitary gland to stop the additional release of hormones. With the brain in command, the nervous system and the endocrine system work together.

sympathetic nervous system The division of the autonomic nervous system that heightens arousal and energizes the body for action.

parasympathetic nervous system The division of the autonomic nervous system that reduces arousal and restores the body to its pre-energized state.

endocrine system A collection of ductless glands that regulate aspects of growth, reproduction, metabolism, and behavior by secreting hormones.

hormones Chemical messengers secreted from endocrine glands, into the bloodstream, to various organs throughout the body.

The Neuron

2.2 Apply the parts of a neuron and neurotransmitters to the process of electrochemical communication.

- What are neurons and how are they constructed?
- How do neurons transmit information from one neuron to the other?

- How do neurons transmit information throughout the body?
- What are neurotransmitters, and what do they contribute to the process?

pituitary gland A tiny gland in the brain that regulates growth and stimulates hormones in other endocrine glands at the command of the hypothalamus.

From a broad overview of the nervous system, we now turn to its specific parts. We begin with the tiny but numerous building blocks and the electrical and chemical impulses that fire throughout the body. In humans and other animals, the nervous system consists of two main types of cells: nerve cells and glial cells.

Playing the lead role in this system are the nerve cells, known as **neurons**. Neurons send and receive information throughout the body in the form of *electrochemical signals*. There are three types of neurons. **Sensory neurons** send signals from the senses, skin, muscles, and internal organs to the CNS. When you see an awesome sunset, scrape your knee, or enjoy the flavor of a terrific meal, messages fire from your eyes, knee, and taste buds. These messages are then relayed up to the brain. **Motor neurons** produce motion and transmit commands the other way around—from the CNS to the muscles, glands, and organs. Once the sunset, injured knee, and delicious food "register," you and your body react. Finally, **interneurons** serve as neural connectors within the CNS. Among their functions is to link input signals from the sensory neurons to output signals from the motor neurons.

neurons Nerve cells that serve as the building blocks of the nervous system.

sensory neurons Neurons that send signals from the senses, skin, muscles, and internal organs to the central nervous system.

motor neurons Neurons that transmit commands from the central nervous system to the muscles, glands, and organs.

interneurons Central nervous system neurons that connect sensory inputs and motor outputs.

No one knows for sure how many neurons there are in the human brain, but researchers estimate that the number is between 100 and 200 billion—as many as the number of stars in our galaxy. If you were to count one neuron every second, you would need 6,000 years to count them all. Even more mind-boggling is the fact that each neuron is linked to more than a thousand other neurons, thus providing each of us with literally trillions of connections among the neurons in the brain. It's important to realize that individual neurons are not distributed evenly or haphazardly throughout the body. Rather, they cluster into interconnected working groups known as **neural networks**. Much like habits, neural cell connections are strengthened by usage and experience, allowing for fast and efficient communication within networks.

neural networks Clusters of densely interconnected neurons that form and strengthen as a result of experience.

The nervous system also has a supporting cast of smaller cells called **glial cells**, or neuroglia. The word *neuroglia* is derived from the Latin and Greek words meaning "nerve glue." These cells are so named because they provide structural support, insulation, and nutrients to the neurons, thereby "gluing" the system together. They also play a role in the development and repair of neurons and the speed of the neural signals throughout the system. Glial cells are much smaller than the neurons they support. But because they outnumber neurons 10 to 1, they constitute about half of the brain's total mass (Breedlove & Watson, 2017; Kandel et al., 2000).

glial cells Nervous system cells, also called neuroglia, that provide structural support, insulation, and nutrients to the neurons.

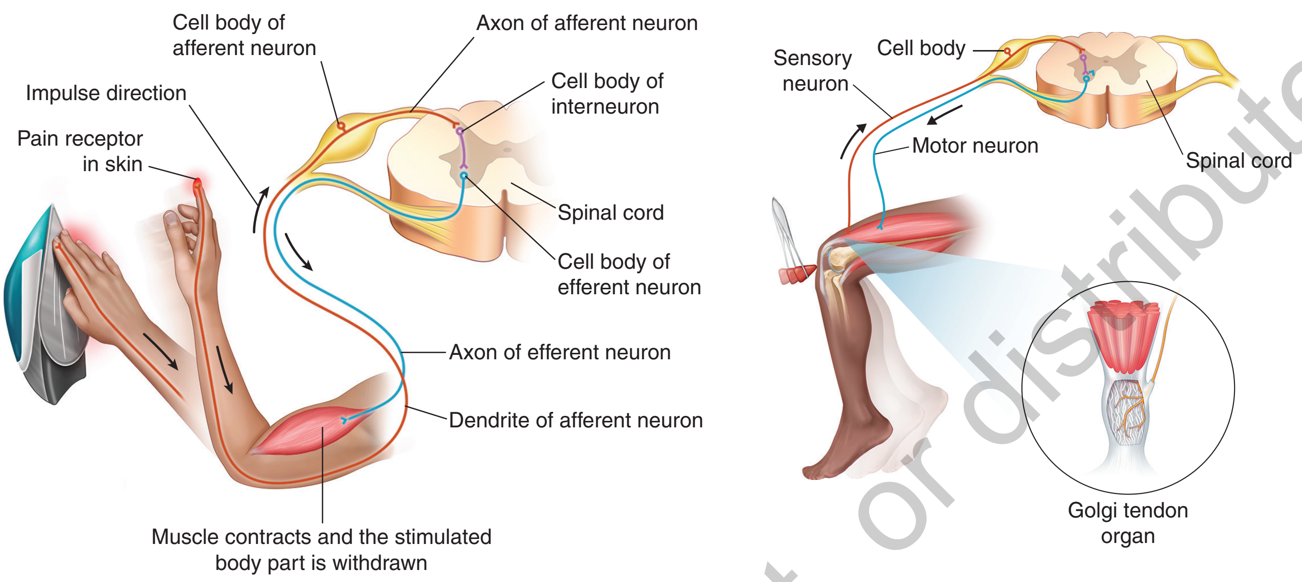
To appreciate how various neurons work together within the nervous system, let's trace the neural pathway of a simple **reflex**, defined as an automatic response to external sensory stimulation. You are probably familiar with the "knee-jerk" reflex elicited during a medical checkup. The doctor uses a rubber mallet to tap your patellar tendon, located just below the knee, causing your leg to kick forward. You don't have to think about it; the reaction is immediate and automatic. How? As shown in Figure 2.6, the knee stretches your thigh muscle, which sends a sensory signal to the spinal cord, which sends a motor signal right back to the thigh muscle. Tap, kick! This two-step chain of events takes only 50 milliseconds because it does not involve higher mental processes in the brain.

reflex An inborn automatic response to a sensory stimulus.

Reflexive behaviors can be very adaptive. When your hand touches a hot iron or the thorn of a rose bush, a sensory neuron sends a quick message to the spinal cord and connects to an interneuron, which activates a motor neuron, causing your hand to pull away. The entire reaction takes place in the spinal cord—before you and your brain feel the pain and before too much damage is done.

In the case of more complex forms of behavior—say, driving a car, working on a math problem, playing a musical instrument, talking to a friend, or reading this fascinating sentence—more extensive activity is needed than is possible within the spinal cord. Sensory inputs travel toward the spinal cord (via the somatic nervous system), but they are then forwarded up to the brain and "processed" before a behavioral "decision" is reached. This decision is sent back down through the spinal cord and out to the muscles, which results in behavior. Most of the behaviors that interest psychologists are of this sort.

FIGURE 2.6 The Withdrawal and Knee-Jerk Reflexes



A The Withdrawal Reflex

Touch a hot object, and your hand will immediately pull away. In this case, sensory and motor neurons are linked by an interneuron.

B The Knee-Jerk Reflex

A tap on the knee sends a sensory signal to the spinal cord, which sends a motor signal back to the muscle. Tap, kick!

Source: Amanda Tomasikiewicz/Body Scientific International.

Structure of the Neuron

The neuron is a lot like other cells in the body. It is surrounded by a membrane and has a nucleus that contains genetic material. What makes the neuron so special is its ability to communicate. Everything that we do and all that we know depends on the transfer of signals from one neuron to another.

It's hard to describe the dimensions of a "typical" neuron because these cells come in hundreds of different shapes and sizes, largely depending on their specific function. But the various neurons do have certain structural features in common. As illustrated in Figure 2.7, every neuron has a roundish **soma**, or cell body, which stores the nucleus of the cell and maintains a chemical balance. Connected to the cell body are two types of branched fibers, or tentacles. The **dendrites** (derived from the Greek word for "tree") *receive* impulses from sensory organs or other neurons. The more dendrites there are, the more information can be received. The **axon** (so named because of its axle-like shape) *sends* the impulse from the neuron to other neurons. Some axons are short and stubby; others are several feet long and slender (some run from the spine down to the muscles of your big toe). At the end of each axon are branches with knob-like tips called axon terminals. As we'll learn, these tips contain vital chemical substances to be released onto other cells. Many axons are also covered with the myelin sheath, a shiny white layer of fatty cells. Produced by the glial cells, the myelin sheath is tightly wrapped around the axon to insulate it. This insulation helps to speed up the movement of electrical impulses by preventing leakage. The importance of this insulation can be seen in multiple sclerosis, a disease in which the **myelin sheath** degenerates, slowing signals to the muscles and resulting in the eventual loss of muscle control. To summarize, neural signals travel from the dendrites, through the soma (cell body), down the axon, and into the axon terminals.

soma The cell body of a neuron.

dendrites Extensions from the cell body of a neuron that receive incoming impulses.

axon Extension of the cell body of a neuron that sends impulses to other neurons.

myelin sheath A layer of fatty cells that is tightly wrapped around the axon to insulate it and speed the movement of electrical impulses.

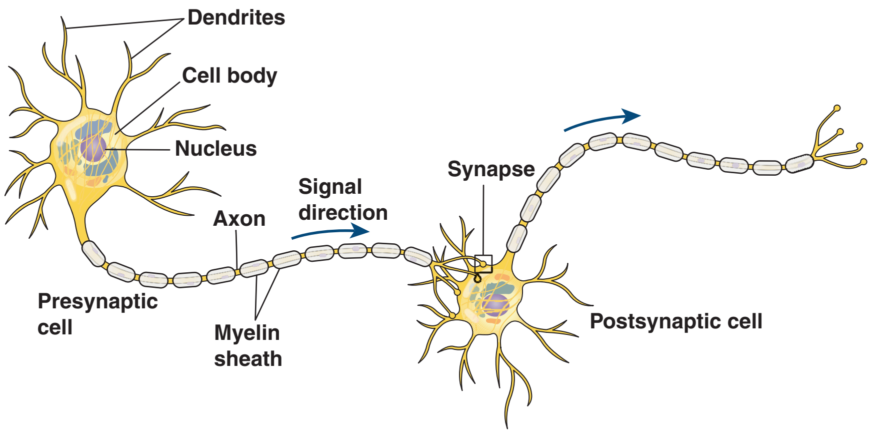


FIGURE 2.7 Structure of the Neuron

Every neuron consists of a soma, or cell body, and two types of branched fibers. Dendrites receive electrical impulses from sensory organs or other neurons and the axon relays these impulses to other neurons or muscles. As shown, many axons are insulated with the myelin sheath, a fatty layer that speeds the movement of the impulses.

The Neuron in Action

To understand how messages are transmitted from the axon of one neuron to the dendrites of another, you need to know that these messages occur in the form of electrical impulses. Here is a brief lesson on the electricity of the nervous system.

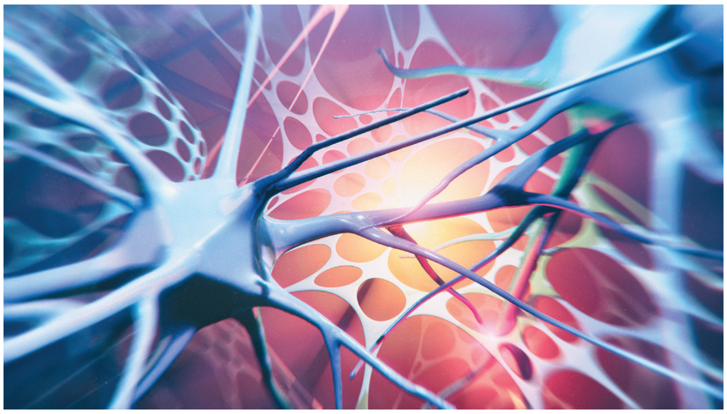
Every neuron is covered by a membrane, a semipermeable skin that permits some chemicals to pass through more easily than others. Dissolved in fluid on both sides of the membrane are electrically charged particles called *ions*. Three kinds of ions are most important: sodium (positively charged ions that do not pass easily through the membrane and thus remain concentrated outside the cell), potassium (positively charged ions that cross easily and are concentrated inside the cell), and negatively charged ions that are trapped permanently inside the cell. When a neuron is at rest, the inside of the cell has a negative charge relative to the outside, making it a store of potential energy.

When the dendrites of a neuron are stimulated, usually by other neurons, this delicate balance is suddenly altered. The semipermeable membrane opens ion channels, permitting the positively charged sodium ions outside the cell to rush in. For an instant, the charge inside the cell becomes less negative and, as a result, may trigger an **action potential**—a quick burst of electrical energy that surges through the axon like a spark along a trail of gunpowder. Depending on the neuron, most impulses travel at speeds ranging from 2 miles an hour up to 200 miles an hour, which is faster than a car but 3 million times slower than the speed of electric current passing through a wire. At top speed, then, it takes an action potential one-hundredth of a second to run along an axon from the spinal cord to a muscle in the finger or toe. After an impulse has passed, the positive ions inside the cell are then pumped back to the outside of the membrane. The neuron returns to its resting state and is once again ready for action.

action potential An electrical impulse that surges along an axon, caused by an influx of positive ions in the neuron.

The stimulation of a neuron does not always trigger the firing of an electrical impulse. At any given moment, a neuron may be receiving signals at its dendrites from very few or from hundreds, even thousands, of other neurons. Whether the neuron fires depends on the sum total of signals impinging on it. Only if the combined signals exceed a certain minimum intensity, or **threshold**, does the neuron's membrane break down and begin to transmit an electrical impulse. If it does not, no impulse is created. In other words, the action potential is an *all-or-none response*. Either it fires or it does not. This effect is like firing a gun. If you squeeze the trigger past a certain point (the threshold), bang! The bullet is launched. If not, nothing happens. You can't half-shoot, and you can't vary the intensity of the shot.

threshold The level of stimulation needed to trigger a neural impulse.


iStock.com/koto_feja

Neurons transmit electrochemical signals throughout the body.

The firing of an electrical impulse is as quick as the blink of an eye, but it has profound significance. Information in the nervous system is made up of action potentials. Every thought, dream, or emotion you have, every action you take, and every decision you make is coded in the form of action potentials. For neuroscientists, cracking the action potential code is a key to understanding the language of the nervous system and unlocking new discoveries about the biology of our minds and behavior.

How Neurons Communicate

A neural impulse races from the receiving dendrites (the starting line), through the cell body, and down the axon. What happens when the signal reaches the axon terminals? And how does it then get to the dendrites of the next neuron? The transmission of messages in the nervous system is like a relay race. When the impulse reaches the end of one cell, it passes the electrochemical baton to the next cell or to a muscle or gland. How is this accomplished? Scientists used to think that the branching axons and dendrites of adjacent neurons always touched, thus enabling impulses to travel seamlessly, the way an electrical current crosses two extension cords that are plugged together. We now know that this is not the main way it works. Rather, there is a narrow gap between neurons that is roughly one-millionth of an inch wide. This gap is called a **synapse**, from a Greek word meaning "point of contact." The question is: How does the impulse cross this synaptic gap to the next neuron?

synapse The junction between the axon terminal of one neuron and the dendrites of another.

neurotransmitters Chemical messengers in the nervous system that transmit information by crossing the synapse from one neuron to another.

receptors Specialized neural cells that receive neurotransmitters.

The answer has to do with the action of **neurotransmitters**. When an electrical impulse reaches the knob-like axon terminal, it forces the release of chemical messengers called neurotransmitters—so named because they aid in the *transmission* of information from one *neuron* to another. These chemical substances are manufactured by the neuron and stored in tiny round packets called synaptic vesicles. Upon release, the neurotransmitters literally squirt across the synaptic gap and bind to specialized **receptors** on the dendrites of the receiving neuron or on muscles or glands.

There are different types of neurotransmitters. Some will excite (fire) an action potential in the next neuron, whereas others will inhibit (restrain the firing of) the next action potential. It's a truly remarkable process. There are many different neurotransmitters and many different types of receptors, each with its own shape. This fact is significant because a neurotransmitter binds snugly only to certain receptors, the way a key fits only one lock. The entire electrochemical process is illustrated in Figure 2.8.

Neurotransmitters

Anxiety, feelings of calm, sadness, depression, pain, relief, memory disorders, drowsiness, hallucinations, paralysis, tremors, and seizures all have something in common: a link to the activity of neurotransmitters. The human nervous system is a prolific chemical factory. There are possibly as many as 100 different neurotransmitters in the human nervous system that provide extremely precise communication (Herculano-Houzel, 2009).

The activities of certain neurotransmitters—where in the body they're produced, their effects on mind and behavior, and their responsiveness to drugs—are well understood. (See Table 2.1, which describes many important neurotransmitters discussed in this book.)

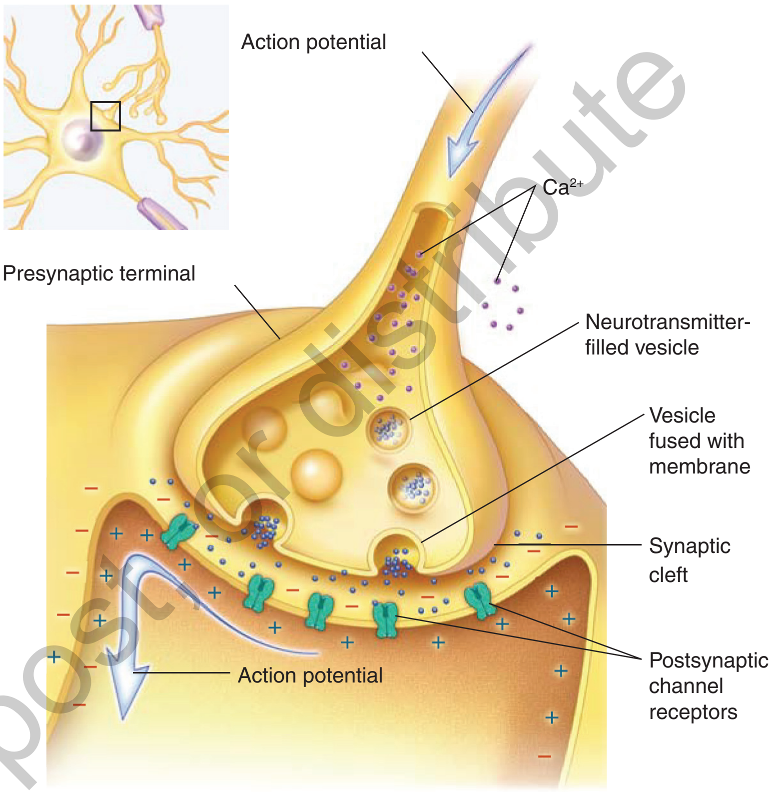
acetylcholine (ACh) A neurotransmitter found throughout the nervous system that links the motor neurons and muscles.

The first substance identified as a neurotransmitter was **acetylcholine (ACh)**, which is found throughout the nervous system and is most concentrated in the parts of the brain that control motor behavior. Using powerful electron microscopes, researchers can see the sacs that store and release ACh molecules and have found that ACh is the chemical key that links the motor neurons and muscles. Thus, whenever you walk, talk, dance, ride a bike, throw a ball, or take a breath, ACh is released. What would happen if you somehow blocked the release of all ACh in the system? Think about the link that would be severed, and you'll have the answer. Curare, a poison that some South American Indians put on the tips of their hunting arrows, blocks the ACh receptors, causing complete paralysis of the skeletal muscles. Consider the opposite condition. What would happen if you were to flood the synapses between motor neurons and muscles with ACh? The toxic bite of a black widow spider does just that, resulting in violent muscle contractions, sometimes even death. ACh may also play a role in the formation of new memories.

Another neurotransmitter, **dopamine**, is also involved in the regulation of movement. Parkinson's disease, a motor disorder that is characterized by hand tremors, stooped posture, slowness, and a loss of control over one's voluntary movements, is caused by the death of neurons that produce dopamine. For people with this disease, the symptoms can often be eased with l-dopa, a chemical substance that the neurons convert into dopamine, which replenishes the supply.

FIGURE 2.8 How Neurons Communicate

When an impulse reaches the axon terminal, it forces the release of neurotransmitters, which are stored in tiny vesicles. These chemicals squirt across the synaptic gap and bind to receptors on the receiving neuron. There are different neurotransmitters. Each fits only certain receptors, the way a key fits only one lock.



Source: Carolina Hrejsa/Body Scientific International.

Table 2.1 Major Neurotransmitters

NEUROTRANSMITTER	FUNCTION
Acetylcholine (ACh)	Links motor neurons and muscles. Also facilitates learning and memory. Patients with Alzheimer's disease have an undersupply of ACh.
Dopamine	Concentrated in the brain, it is linked to muscle activity. A shortage can cause Parkinson's disease; an excess of dopamine receptors is linked to symptoms of schizophrenia and many addictive behaviors (e.g., drug use, gambling).
Endorphins	Distributed throughout the CNS, these natural opiates relieve pain.
Norepinephrine	Widely distributed in the CNS, it increases arousal. Too much may produce a manic state; too little may lead to depression.
Serotonin	Produced in the brain, it lowers activity levels and causes sleep. Too little is linked to depression.
GABA (gamma aminobutyric acid)	Produced in the brain, it lowers arousal and reduces anxiety. It is the main inhibitory neurotransmitter in the nervous system.

dopamine A neurotransmitter that is produced in the midbrain and is involved in the control of voluntary movements as well as reward-motivated behavior.

ALFRED PASIEKA/Science Source

Micrograph of neurotransmitters in synaptic vesicles (top) squirting across the synaptic gap (center) to a receiving neuron (bottom).

We'll learn later in this chapter that a promising new approach is to implant healthy tissue containing dopamine into the brain of patients with Parkinson's disease. Indeed, many people who suffer with schizophrenia have an oversupply of dopamine receptors in the brain. Their symptoms can often be treated with drugs that block the activity of dopamine. Dopamine also plays an important role in drug addiction via a pathway called the *mesolimbic tract*, sometimes referred to as the "reward region" of the brain. Dopamine seems to drive motivation to consume "comfort foods"; for individuals with substance abuse problems, dopamine may drive increased drug use. Specifically, dopamine drives what is called *incentive salience*—it makes foods and drugs more salient or noticeable to drive a desire or incentive to consume or use them.

Another exciting discovery is that the brain produces its own morphine, a painkiller. As part of a research study, Candace Pert and Solomon Snyder (1973) injected laboratory animals with morphine, a powerful and addictive painkilling drug derived from opium. To their surprise, the researchers found that the morphine bound to certain receptors in the brain the way neurotransmitters do. This discovery is only mildly interesting, you may think. But wait. Why would the brain have receptors for a chemical produced outside the body? Doesn't a special receptor for morphine mean that the brain produces its own morphine-like substance? The answer is yes, and the neurotransmitter is called an **endorphin** (from the words *endogenous*, which means "internal," and *morphine*). Since this discovery, researchers have found that endorphins and their receptors, and other similar substances, are distributed throughout the central nervous system (Cooper et al., 2002; Sprouse-Blum et al., 2010).

endorphin A morphine-like neurotransmitter that is produced in the brain and is linked to pain control and pleasure.

LEARNING CHECK

Nerve Racking

Match each part of the nervous system in the left column with the activity it regulates.

1.	Sensory neuron	a.	Heightens arousal and energizes the body for action
2.	Motor neuron	b.	Regulates aspects of growth, reproduction, metabolism, and behavior by secreting hormones
3.	Myelin sheath	c.	Transmits information by crossing the synapse
4.	Sympathetic nervous system	d.	Sends signals from the senses, skin, muscles, and internal organs to the central nervous system
5.	Parasympathetic nervous system	e.	Insulates the axon and speeds electrical impulses
6.	Endocrine system	f.	Transmits commands from the central nervous system to the muscles, glands, and organs
7.	Neurotransmitter	g.	Reduces arousal and restores the body to its pre-energized state

(Answers: 1. d; 2. f; 3. e; 4. a; 5. g; 6. b; 7. c)

What triggers the release of endorphins? What triggers sensations of pain and discomfort, such as physical injury or the labor pains that precede childbirth (Akil, 1982)? Research has shown that women with higher endorphin levels in the bloodstream are less sensitive to pain and less likely to experience premenstrual mood problems such as tension, irritability, and depression (Barbosa et al., 2013; Straneva et al., 2002). Over the years, some researchers have speculated that the exhilarating and intense “runner’s high” described by many long-distance runners and bicyclists might result from the release of endorphins (Farrell et al., 1982). Yet others note that while exercise seems to be addictive for some people, factors such as genes, gender, training status, hormonal status, and more need to be considered to understand the possible role of endorphins (Heijnen et al., 2016). For now, the causes and effects of endorphins are not clearly understood. It is clear, however, that the human body comes equipped with a natural, built-in pharmacy for pain relief.

The Brain

2.3 Summarize and synthesize the methods utilized to understand the parts and operation of the brain.

- How do psychologists study activity in the human brain?
- Do different parts specialize in certain functions or operate as an integrated system?
- Does each side of the brain have its own “mind”? How could this hypothesis be tested, and what do you think would be the result?

Encased in a hard, protective skull, the brain is the crown jewel of the nervous system. It weighs only about 3 pounds and constitutes only l/45th of the human body’s average weight. But, as we saw earlier, it contains billions of neurons and trillions of synaptic connections. For those who are interested only in anatomy, it was easy to determine the physical *structure* of the brain by dissecting brains removed from dead animals and from humans who had donated their bodies to science. For behavioral and cognitive neuroscientists, however, the task is more challenging: to determine the *functions* of the living brain and to understand its influences on the way we think, feel, and behave.

Tools of Behavioral Neuroscience

Before the term *neuroscience* had ever been uttered, Viennese physician Franz Joseph Gall (1758–1828) founded **phrenology**, the pseudoscientific theory that psychological characteristics are revealed by bumps on the skull. Apparently, as a young boy, Gall “noticed” that his friends who had the best memories also had prominent eyes and large foreheads. From this he speculated that the brain structure involved in verbal memory must lie behind the eyes. Similarly, Gall believed that speech, math ability, aggression, and other traits are “localized” in certain regions of the brain. In believing that there were many parts to the brain and that the parts were involved in different mental functions, Gall was on the right track. In using bumps on the skull to find these links, however, he was very much on the wrong track (Damasio, 1994; Zola-Morgan, 1995).

phrenology The pseudoscientific theory that psychological characteristics are revealed by bumps on the skull.

To fully understand and evaluate what researchers currently know about the human brain, it helps to be aware of *how* they arrive at that knowledge—the methods they use and why they use them. Thanks in part to advances in medical and computer technology, today’s behavioral neuroscientists are like explorers on a new frontier. As we’ll learn, four types of research methods are commonly used: clinical case studies, experimental interventions, electrical recordings, and imaging techniques.

CLINICAL CASE STUDIES

One approach to studying the brain is the clinical case study, in which researchers observe people with brain damage resulting from tumors, diseases, head injuries, or exposure to toxic substances. In the case of Phineas Gage, discussed earlier, massive damage to the frontal lobes was followed by changes in his personality (specifically, an inability to control impulses), yet his intellectual abilities remained unchanged. Thus, the case showed that the frontal lobes are involved in the control of behavior.

Clinical evidence is tantalizing and often enlightening, but it cannot provide the sole basis for behavioral neuroscience. One drawback is that when one part of the brain is damaged, nearby neurons sometimes sprout new branches, and other structures sometimes take over the function. Another drawback is that natural injuries are seldom localized, so the resulting deficit may not really be traceable to a single structure. A third drawback of case studies in brain and behavior is that they often cannot be used to establish cause and effect. In a fascinating use of the case study method, neuroscientist Sandra Witelson gained access to the brain of physicist Albert Einstein, one of the greatest geniuses of modern history. When Einstein died in 1955, the pathologist who did the autopsy removed the brain and preserved it in a jar. More than 40 years later, Witelson and her colleagues (1999) compared Einstein's brain tissues with those of other men who had died at a similar age. They found that the overall size of Einstein's brain was about average, but a region used in visuospatial and mathematical thinking was 15% wider than the others tested. It may be tempting to conclude from this result that Einstein was born with a brain uniquely gifted for physics, but the researchers were quick to suggest another possibility—perhaps this region of Einstein's brain grew *because* he used it so often. Clinical evidence alone cannot solve the puzzle.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In 1873, Mark Twain visited Lorenzo Fowler, a phrenologist. "I found Fowler on duty," Twain wrote, "amidst the impressive symbols of his trade . . . marble white busts, hairless, every inch of the skull occupied by a shallow bump, and every bump labeled in black letters." Fowler sold hundreds of busts like these. The one shown here can be seen at the Smithsonian Institution in Washington, DC.

EXPERIMENTAL INTERVENTIONS

A second method of brain research is to "invade" the brain through an experimental intervention and then measure the effects on behavior. One invasive technique, often used by animal researchers, is to purposely disable, or "lesion," a part of the brain by surgically destroying it. Often this is done by anesthetizing an animal, implanting an electrode into a specific site in the brain, and passing a high-voltage current through it to burn the tissue.

Another technique is to administer drugs that are suspected of affecting neurotransmitters and other activity in the brain. Over the years, this approach has been used to test the effects of many substances (e.g., alcohol, caffeine, adrenaline, nicotine, and the sex hormones testosterone and androgen) on the brain and behavior.

Yet another form of intervention is through the use of electrical brain stimulation. In these studies, a microelectrode is inserted in the brain and a mild electrical current is used to "activate" the neurons in a particular site. Most of these experiments are conducted with animals, but on occasion, clues are derived from human brain-surgery patients. How does this occur? Since no two brains are exactly alike, brain surgeons often must "map" a patient's brain so they don't accidentally destroy key functions. Toward this end, the patient is given a local anesthetic and kept awake for the procedure.

ELECTRICAL RECORDINGS

The most exciting advances in behavioral neuroscience arise from techniques that are not invasive to the human subject. In 1929, German psychiatrist Hans Burger invented a machine that could detect, amplify, and record waves of electrical activity in the brain using metal disc electrodes pasted to the surface of the scalp. The instrument is called an

electroencephalograph (EEG), and the information it provides is in the form of line tracings called *brain waves* (see Figure 2.9).

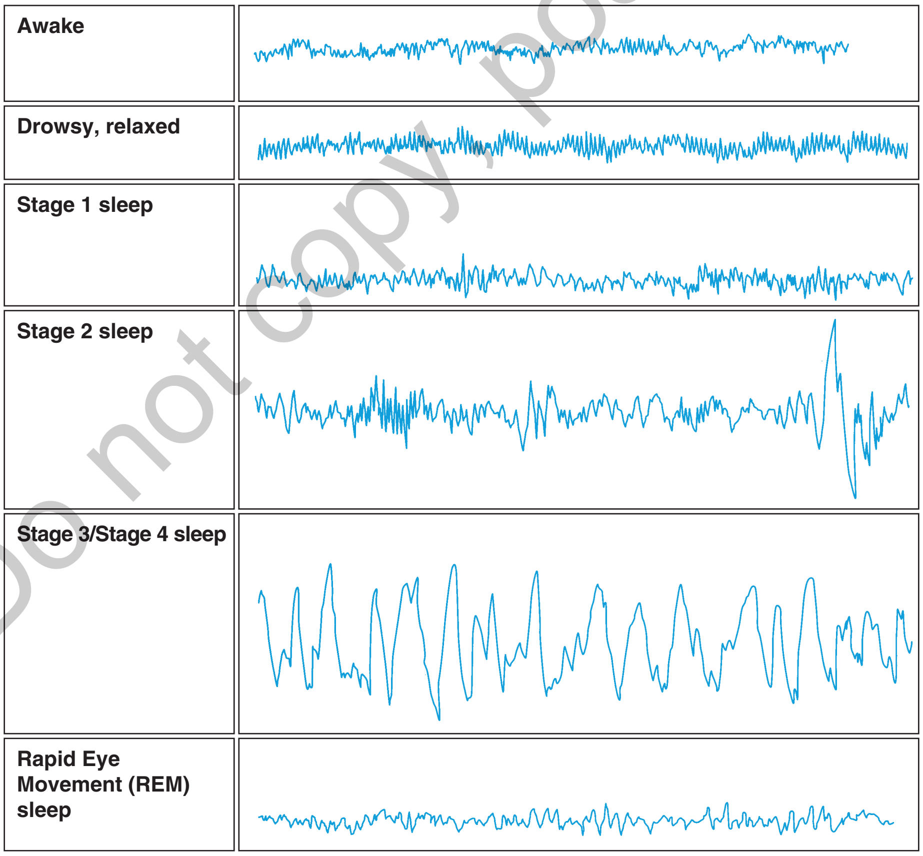
electroencephalograph (EEG) An instrument used to measure electrical activity in the brain through electrodes placed on the scalp.

As we'll learn in later chapters, researchers using the EEG have found that brain waves differ depending on whether a person is excited, relaxed, pensive, drowsy, or asleep. The EEG can also be used for diagnosing brain damage from tumors, strokes, infections, and various neurological disorders. For example, people with epilepsy have seizures because a certain portion of the brain is overexcitable and prone to fire in a wild manner, setting off electrical spikes or "explosions." The EEG may even be useful for diagnosing psychological disorders such as attention-deficit/hyperactivity disorder, schizophrenia, and depression (Howells et al., 2018; Lazarev, 2006).

There are limits, however, to what EEG recordings can tell us. The problem is that the EEG merely summarizes all the electrical activity of billions of neurons firing along the brain's surface. Thus, as one group of researchers put it, "We are like blind men trying to understand the workings of a factory by listening outside the walls" (quoted by Hassett, 1978). For greater precision, some animal researchers use microelectrodes, wires with tips so tiny that they can stimulate or record the activity of a single cell.

BRAIN-IMAGING TECHNIQUES

When people think about the wonders of high technology, what comes to mind is global communication satellites and giant-size telescopes that can spy on the distant galaxies of the universe. But recent advances in technology have also enabled us to turn the scientific eye on ourselves, to inner recesses of the human brain never previously seen. Designed to provide visual images of the live human brain, without our ever having to lift a scalpel, this new technology uses computers to combine thousands of still "snapshots" into models of the brain in action. As described in *Images*



Source: Christopher M. Sinton , Robert W. McCarley. "Neurophysiological Mechanisms of Sleep and Wakefulness: A Question of Balance." Semin Neurol 2004; 24(3): 211-223 DOI: 10.1055/s-2004-835067.

FIGURE 2.9 The EEG

Through electrodes on a subject's scalp, the electroencephalograph records electrical activity in the brain and displays the output in line tracings called brain waves. Varying in their frequency (cycles per second) and amplitude (voltage), EEG patterns differ according to a person's mental state. Shown here are brain wave patterns for each of the stages of sleep, which will be introduced in Chapter 4.

of Mind (Posner & Raichle, 1997), there are several basic types of imaging techniques. Three of the most common, all popularly known by their initials, are CT, PET, and MRI.

computerized tomography (CT) scan A series of X-rays taken from different angles and converted by computer into an image that depicts a horizontal slice of brain.

First introduced to medicine in the 1970s, the **computerized tomography (CT) scan** is a computer-enhanced X-ray of the brain. In this technique, X-ray beams are passed through the head at 1-degree intervals over a 180-degree arc, and a computer is used to convert this information into an image that depicts a horizontal slice of the brain. This technique takes advantage of the fact that when a highly focused beam of X-rays is passed through the body, the beam is affected by the relative density of the tissue through which it passes. While CT scans do use X-rays that can be harmful in certain doses, CT scans are invaluable for diagnosing tumors and strokes and for identifying brain abnormalities in people who suffer from schizophrenia and other psychological disorders.

positron emission tomography (PET) scan A visual display of brain activity, as measured by the amount of glucose being used.

A second revolutionary imaging technique, one that can be used to map activity of the brain over time, is the **positron emission tomography (PET) scan**. Because glucose supplies the brain with energy, the level of activity in a given region of the brain can be measured by the amount of glucose it burns. After a tiny amount of radioactive glucose is injected into the brain, the scanner measures the amount of glucose consumed in different regions. The results are then fed to a computer, which produces an enhanced color picture that can be used to not only infer mental processes but also assist with understanding clinical and mental health outcomes (Silverman et al., 2008; Vaquero & Kinahan, 2015). Can the PET scan actually spy on our thought processes? In a way, yes. In these scans, "hot" colors such as red, orange, and yellow indicate more activity, whereas cool colors such as violet, blue, and green mean less activity.

Using the PET scan, psychologists have made some interesting discoveries. One is that it may be possible to distinguish among different types of psychological disorders by measuring brain activity (Masdeu, 2011; Vaquero & Kinahan, 2015). For example, researchers had patients with schizophrenia relax with their eyes closed and press a button whenever they started to hear imaginary voices and when they stopped hearing these voices. The result: On PET scans, hallucinating lit up certain areas of the brain more than others (Silbersweig et al., 1995). Today, researchers are using PET scans to identify anomalies in brain structure and function that can be used to identify and predict the severity of schizophrenia (Marques et al., 2017).

magnetic resonance imaging (MRI) A brain-scanning technique that uses magnetic fields and radio waves to produce clear, three-dimensional images.

An advanced technique, called **magnetic resonance imaging (MRI)**, is similar to a CT scan but instead of using an X-ray, MRI passes the subject's head through a strong but harmless magnetic field to align the brain's atoms. A quick pulse of radio waves is then used to disorient the atoms, which give off detectable signals as they return to normal. As shown in Figure 2.11, the MRI can produce clear and detailed pictures of the brain's soft tissues (Grover et al., 2015). Particularly important today is a high-speed version of MRI known as *functional MRI* (fMRI), used to take moving pictures of the brain in action. The method is noninvasive and does not involve the use of radioactive materials, so researchers can do hundreds of scans on the same person to get detailed information about a particular brain's activity.

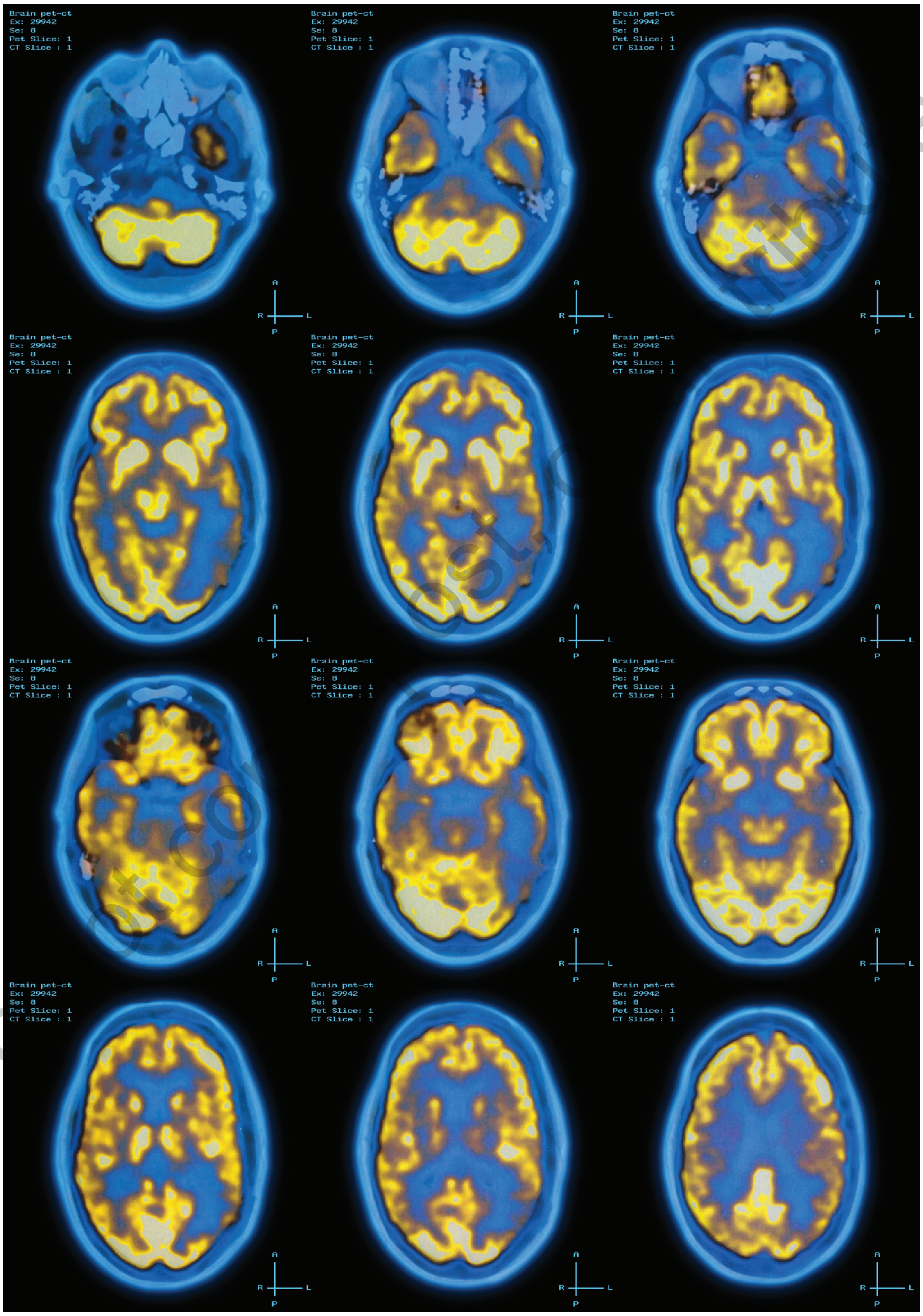
This new technology is generating tremendous excitement among psychologists who are interested in attention, perception, memory, and other cognitive processes (D'Esposito, 2002; Rana et al., 2016). Early in its use, researchers said, "This is the wonder technique we've all been waiting for," and called it "the most exciting thing to happen in the realm of cognitive neuroscience in my lifetime" (Blakeslee, 1993). It is still just as exciting today.

Regions of the Brain

The human brain is a unique product of evolution. In some ways, it is similar to the brains of "lower" animals; in other ways, it is quite different. Salmon, caribou, and migrating birds have navigational abilities unparalleled in our own species. Dogs, cats, and certain other mammals have senses of hearing and smell that are downright superhuman. Yet no other animal on the planet can solve problems, think about itself and the future, or communicate as we do. As we'll learn, these relative strengths and weaknesses can be traced to the unique structure of the human brain.

FIGURE 2.10 PET Scans

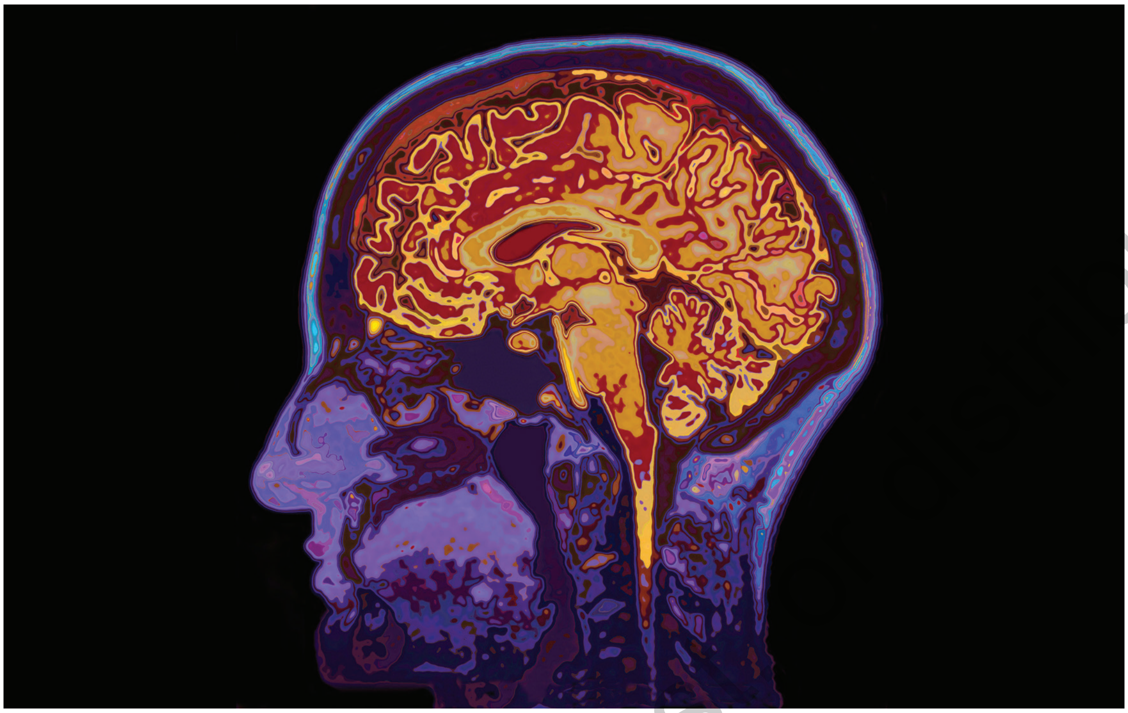
After radioactive glucose has been injected into the brain, a scanner measures how much glucose is consumed in different regions. The results are displayed in a computer-enhanced picture in which hotter colors (red, orange, yellow) indicate more activity.



Source: iStock.com/Cginspiration.

FIGURE 2.11 The MRI

Magnetic resonance imaging yields the best resolution for visualizing brain structures.



Source: Ian Allenden/Alamy Stock Photo.

Mark Harmel/Alamy Stock Photo

In this fMRI study, the participant is inside the magnet and the result is a vivid picture of the brain's activity.

Although the brain is a single organ containing interconnected pathways of nerve fibers, neuroscientists have found that there are really three mini-brains rolled into one. The *brainstem* is the old "inner core" that rests atop the spinal cord and helps to regulate primitive life-support functions such as breathing, heartbeat, and muscle movements. Surrounding the brainstem, the *limbic system* provides an increased capacity for motivation, emotional responses, and basic forms of learning and memory. In the *cerebral cortex*, the wrinkled outer layer of the brain, "higher" mental processes enable more complex forms of learning, memory, thought, and language. The cerebral cortex is the last part to develop in an individual. It also developed last in the species as a whole (see Figure 2.12).

THE BRAINSTEM

As the spinal cord enters the skull, it enlarges into the **brainstem**, the primitive inner core. As illustrated in Figure 2.13, the brainstem contains three key structures: the medulla, the pons, and the reticular formation. Located just above the spinal cord, the **medulla** controls some of our most vital, involuntary functions—swallowing, breathing, and heart rate—and contributes to muscle control. It's also a "crossover" point where nerves from one side of the brain connect to the opposite side of the body. There's nothing particularly exotic about the medulla, but if it were severed, blood pressure would drop to zero, breathing would stop, and death would soon follow. Just above the medulla is a bulbous structure called the **pons** (meaning "bridge"), which helps to connect the lower and higher regions of the brain. The pons also has neurons that play a role in sleep and arousal. Damage

brainstem The inner core of the brain that connects to the spinal cord and contains the medulla, pons, and reticular formation.

medulla A brainstem structure that controls vital involuntary functions.

pons A portion of the brainstem that plays a role in sleep and arousal.

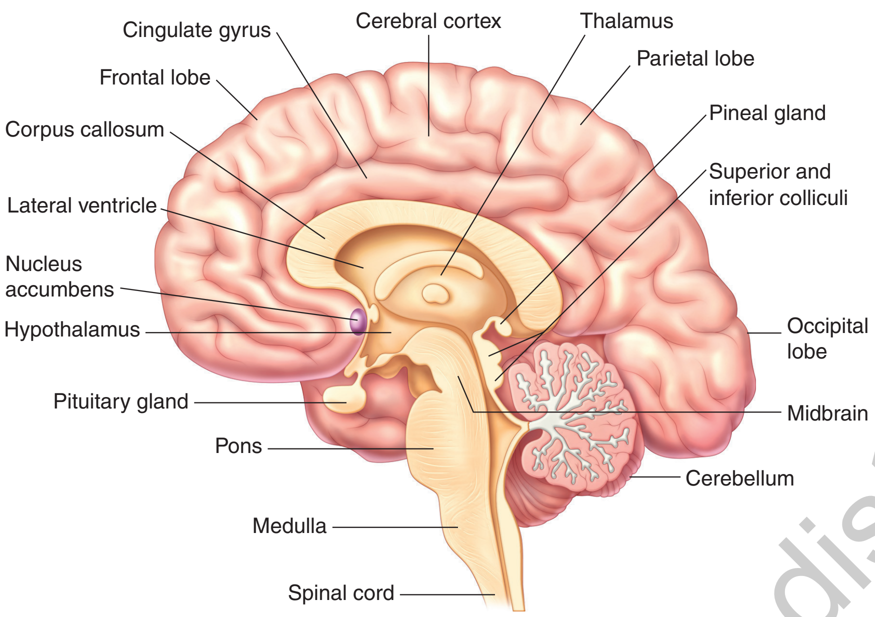


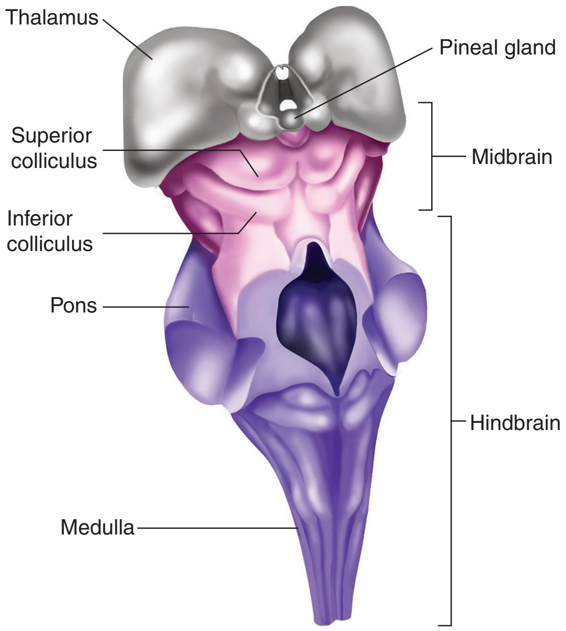
FIGURE 2.12 The Human Brain

There are three main regions of the human brain. The brainstem is the old "inner core" that controls life-support functions. The limbic system regulates motivation, emotion, and basic forms of learning and memory. The cerebral cortex, which features the wrinkled outer layer of the brain, controls "higher" mental processes that enhance learning, memory, thought, and language.

to this area can put a person into a coma. Finally, the **reticular formation** is a netlike group of nerve cells and axons that project throughout the brain and help to control sleep, arousal, and attention. It is here that sensory information is filtered in or out of our consciousness.

FIGURE 2.13 The Brainstem

The brainstem is the most primitive structure of the brain. Resting atop the spinal cord, it contains the medulla, pons, and reticular formation and is attached to the cerebellum.



Also attached to the back of the brainstem is the **cerebellum**, a peach-sized structure that means "little brain." Figure 2.12 shows that the cerebellum resembles a miniature brain attached to the brain, wrinkles and all. This structure is one of the oldest in the nervous system and is highly developed in fish, birds, and lower mammals. It plays a role in learning and memory, but its primary functions (like that of certain other structures distributed throughout the brain) is balance and the coordination of muscle movements. In this regard, the cerebellum is like a sophisticated computer. It receives and integrates information from all the senses, considers the positions of the limbs, and makes rapid-fire calculations as to which muscle groups must be activated in order to run, jump, dance, break a fall, or throw a ball (Houk et al., 1996). The cerebellum is also activated by certain aspects of music. In a study of eight conductors listening to Bach, PET scans revealed that when the expected rhythm was altered, blood flow to parts of the cerebellum increased, even though the conductors had not moved a muscle (Parsons & Fox, 1998). Even among ordinary research participants, those trained to learn complex rhythms—compared to those exposed to random sequences—exhibit more activity in parts of the cerebellum (Ramnani & Passingham, 2001).

Alongside the cerebellum are the **basal ganglia**, large masses of gray matter that are involved in the coordination of slower, more deliberate movements such as turning your head or reaching for an object. Damage to the cerebellum and basal ganglia can make it difficult to coordinate various motor behaviors. The reason drunken drivers can't pass the roadside test given by the police

reticular formation A group of nerve cells in the brainstem that helps to control sleep, arousal, and attention.

cerebellum A primitive brainstem structure that controls balance and coordinates complex voluntary movements.

basal ganglia Masses of gray matter in the brain that help to initiate and coordinate deliberate movements.

("Close your eyes, put out your arms, and touch your nose with the index finger") is that alcohol affects these areas.

THE LIMBIC SYSTEM

limbic system A set of loosely connected structures in the brain that help to regulate motivation, emotion, and memory.

Continuing up from the brainstem is a ring of loosely connected structures collectively known as the **limbic system**. Just above the inner core, yet surrounded by the cerebral cortex, the limbic system contains several structures that play a role in the regulation of motivation, emotion, and memory. Brain researchers disagree as to which structures actually qualify as "limbic" and whether they really form a unified "system." Still, the key structures here include the thalamus, the amygdala, the hippocampus, and the hypothalamus (see Figure 2.14).

thalamus A limbic structure that relays neural messages between the senses and areas of the cerebral cortex.

The Thalamus. Directly atop the brainstem, and buried like the pit inside a peach, is the **thalamus** ("inner chamber"). The thalamus is a sensory relay station that directs neural traffic between the senses and the cerebral cortex. All input from what you see, hear, taste, and touch is received in the thalamus and then sent for processing to the appropriate region of the cortex. For example, there's a special nucleus located in the thalamus that receives visual input from the optic nerve behind the eye and sends the information to the visual cortex. It's interesting that the sense of smell completely bypasses the thalamus because it has its own private relay station that directs input from the nose to the olfactory bulb, which sits near areas that control emotion. This may explain why perfume, cookies baking in the oven, freshly cut grass, and other scents often arouse powerful emotions in us.

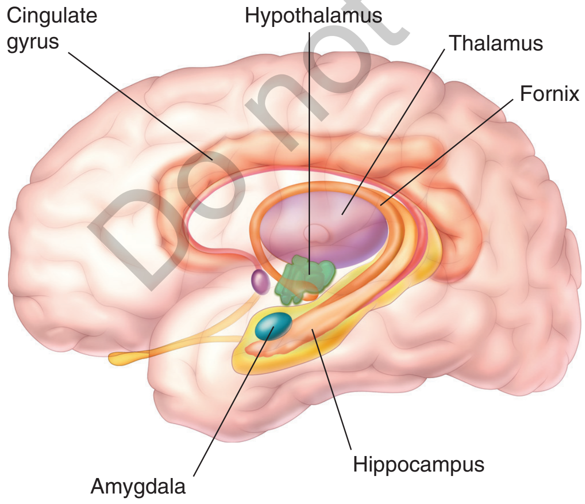
amygdala A limbic structure that controls fear, anger, and aggression.

hippocampus A limbic structure that plays a key role in the formation of new memories.

The Amygdala. The **amygdala** is an almond-shape bulge that has at times been called an "aggression center." This phrase oversimplifies both the behavioral functions of the amygdala and the biological roots of aggression. But there is a link, and experiments have shown that stimulation of the amygdala can produce anger and violence, as well as fear and anxiety (Davis, 1992). In fact, experiments suggest that the amygdala plays a more general role in learning, memory, and the experience of both positive and negative emotions (Rolls, 1999; Tyng et al., 2017).

FIGURE 2.14 The Limbic System

Just above the inner core, yet surrounded by the cerebral cortex, the limbic system plays a role in motivation, emotion, and memory. As shown, this system is composed of many structures, including the thalamus, amygdala, hippocampus, and hypothalamus.



In 1937, psychologists Heinrich Kluver and neurosurgeon Paul Bucy found that lesions of the temporal lobe, including the amygdala, calmed ferocious rhesus monkeys. Later experiments on other wild animals revealed the same mellowing effect. Can amygdala lesions be used to treat people who are uncontrollably violent? Case studies have suggested that they can (Mark & Ervin, 1970). We'll learn in Chapter 14, however, that the use of psychosurgery—operating on the brain as a way to alter behavior—raises profound ethical questions (Pressman, 1998; Valenstein, 1986).

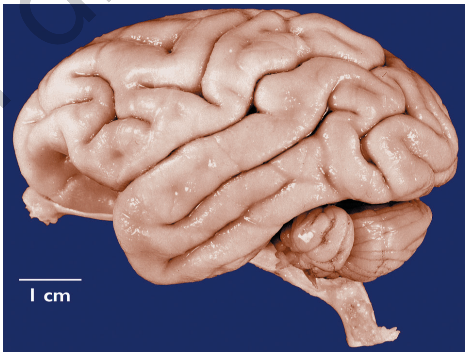
The Hippocampus. The largest structure in the limbic system is the **hippocampus**, which is Greek for "seahorse," whose shape it roughly resembles. Research reveals that the hippocampus plays a key role in the formation of new memories. In rats, monkeys, and many other animals, hippocampal lesions cause deficits in memory. In fact, when the structure is removed from black-capped chickadees—food-storing birds whose brains have an unusually large hippocampus compared to nonstoring birds—they lose the natural ability to recover food they had previously stored (Hampton & Shettleworth, 1996). In humans, brain scans reveal that the hippocampal area is shrunken in people with severe memory loss, even while surrounding areas of the brain are intact (Squire, 1992). As we'll learn in Chapter 6, long-term memories are not necessarily stored in the hippocampus, but they may well be formed there (Opitz, 2014; Van Petten, 2004).

The Hypothalamus. At the base of the brain, there is a tiny yet extraordinary limbic structure called the **hypothalamus** (which means "below the thalamus"). The hypothalamus is the size of a kidney bean, weighs only about half an ounce, and constitutes less than 1% of the brain's total volume. Yet it regulates the body's temperature and the activities of the autonomic nervous system, controls the endocrine system by triggering the release of hormones into the bloodstream, helps regulate basic emotions such as fear and rage, and is involved in basic drives such as hunger, thirst, sleep, and sex. The hypothalamus is also home to one of the brain's true "pleasure centers," an area associated with regulating feelings of pleasure when it is stimulated (Rolls, 1999; Wise, 1996). If you had to sacrifice an ounce of brain tissue, you wouldn't want to take it from the hypothalamus.

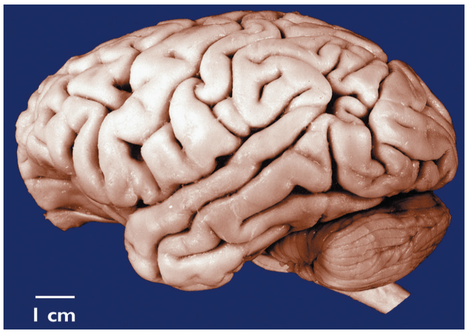
FIGURE 2.15 The Cerebral Cortex in Animals

From fish and birds to mammals, primates, and humans, there is an increase in the relative size and wrinkling of the cerebral cortex.

A Armadillo brain



B Monkey brain



C Chimpanzee brain

Source: Used with permission from http://www.brains.rad.msu.edu, and http://brainmuseum.org, supported by the US National Science Foundation.

THE CEREBRAL CORTEX

The **cerebral cortex** is the outermost covering of the brain. Its name is derived from the words *cerebrum* (which is Latin for "brain") and *cortex* (which means "bark"). It is the newest product of evolution, overlaid on the older structures. If you were to examine the cerebral cortex of various species, you would see that the more complex the animal, the bigger the cerebral cortex is relative to the rest of the brain. You would also notice that in complex animals, the cortex is wrinkled, or folded in on itself, rather than smooth and it is lined with ridges and valleys. This wrinkling allows for more tissue to fit compactly inside the skull (just as crumpling up a piece of paper allows one to squeeze it into a small space).

As shown in Figure 2.15, the cerebral cortex is virtually absent in all fish, reptiles, and birds. Yet the cerebral cortex is present in mammals (particularly in primates, dolphins, and whales) and is the most highly developed in humans. In volume, it constitutes 80% of the human brain (Kolb & Whishaw, 1990). Whenever you read, write, count, speak, reflect on the past, think about the future, or daydream about being rich and famous, billions of neurons are firing in the cerebral cortex.

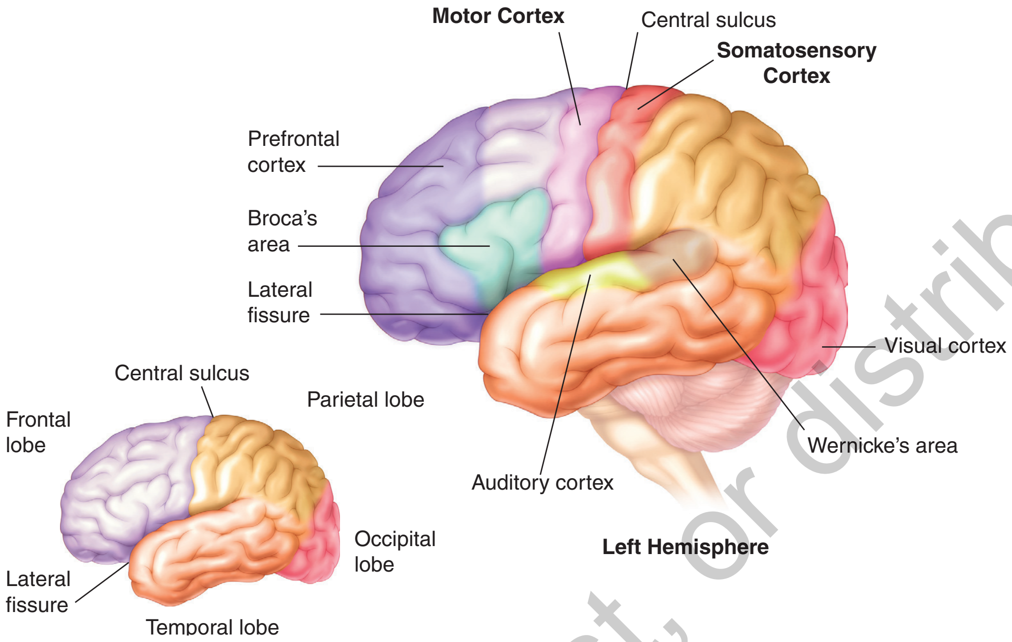
The cortex is divided into left and right hemispheres, and each hemisphere is further divided along deep grooves, called fissures, into four sections called lobes. These are the *frontal lobes* (in front, just behind the forehead), the *temporal lobes* (at the temples, above the ears), the *parietal lobes* (in the back, at the top of the skull), and the *occipital lobes* (in the back, at the base of the skull). Although these regions describe the anatomy of the cerebral cortex, most psychologists prefer to divide the areas of the brain according to the functions they serve. As shown in Figure 2.16, the functional regions include the sensory areas of the cortex, the motor cortex, the association cortex, and two special areas where language is processed and produced.

hypothalamus A tiny limbic structure in the brain that helps regulate the autonomic nervous system, endocrine glands, emotions, and basic drives.

cerebral cortex The outermost covering of the brain, largely responsible for higher-order mental processes.

FIGURE 2.16 The Cerebral Cortex

The cortex is divided along deep grooves, or fissures, into four lobes. Within these lobes, areas are further distinguished by their functions. These include the sensory areas (visual, auditory, and somatosensory), the motor area, the association areas, and two special areas—Broca's area and Wernicke's area—where language is processed and produced.



Sensory and Motor Areas. While operating on his hundreds of patients with epilepsy, Wilder Penfield stimulated exposed parts of the cortex with a tiny electric probe and thereby "mapped" the human cortex in 1947. One of Penfield's great discoveries was that certain areas of the brain specialize in receiving sensory information. When he touched the occipital lobe in the back of the brain, patients "saw" flickering lights, colors, stars, spots, wheels, and other visual displays. This area is the primary visual cortex—and damage to it can leave a person blind. Or damage to a specific part of it may result in a more specific visual deficit. For example, in *The Man Who Mistook His Wife for a Hat*, Oliver Sacks (1985) tells a story about a patient who suffered occipital lobe damage. As this patient looked for his hat while preparing to leave Sacks's office, he grabbed his wife's head and tried to lift it. Suffering from visual agnosia—an inability to recognize familiar objects—this patient had apparently mistaken his wife for a hat.

Penfield discovered other sensory areas in the cortex as well. When he stimulated a small area of the temporal lobe, called the auditory cortex, the patients "heard" doorbells, engines, and other sounds. Indeed, damage in this area can cause deafness. And when Penfield stimulated a narrow strip in the parietal lobe, the **somatosensory cortex**, patients "felt" a tingling of the leg, hand, cheek, or other part of the body. In general, Figure 2.17 shows that the more sensitive to touch a body part, the larger the cortical area devoted to it. Today, researchers continue to study this system in an effort to uncover "the brain's own body image" (Umeda et al., 2019).

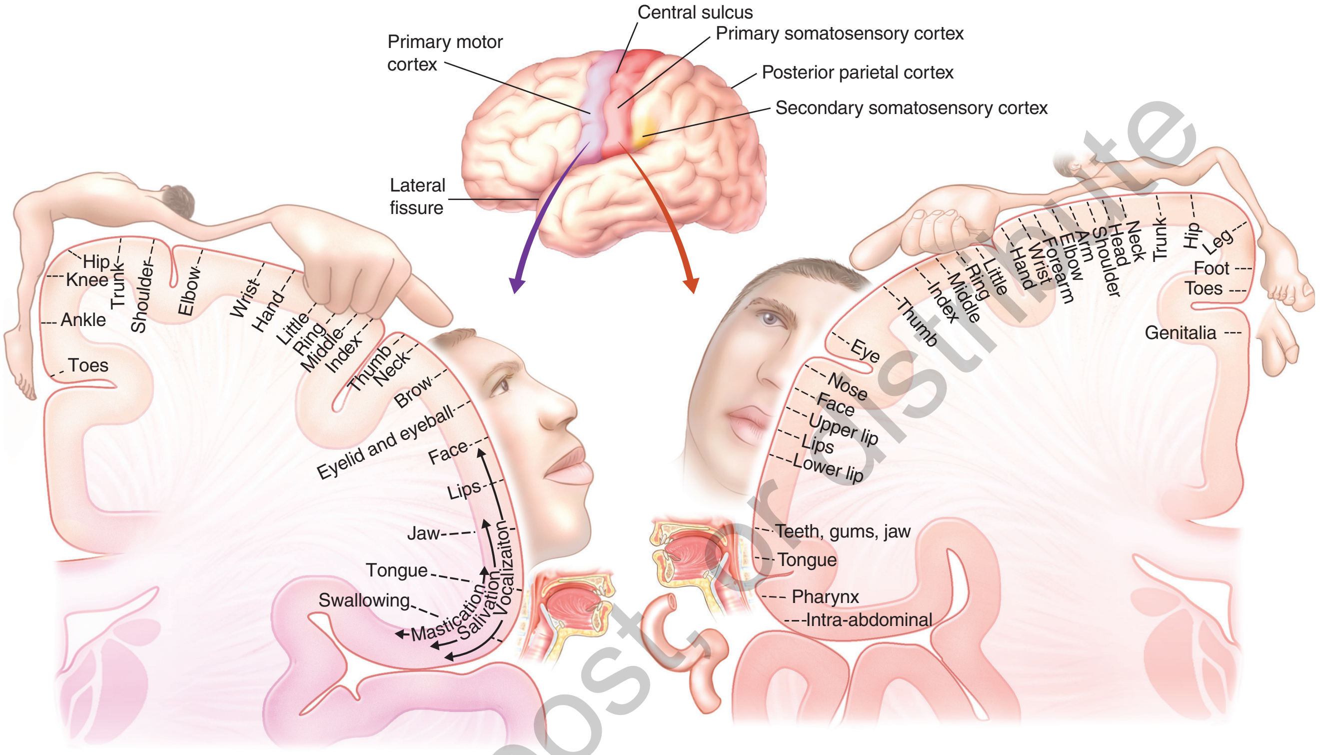
somatosensory cortex The area of the cortex that receives sensory information from the touch receptors in the skin.

Mirroring the somatosensory cortex is another narrow strip that specializes in the control of motor functions. Once again, much of what we know came from Penfield's work. Stimulating different parts of this strip triggers movement in different parts of the body. Stimulate the top, and a leg twitches; stimulate the bottom, and the tongue or jaw moves. All 600 muscles of the human body are represented in this area, called the **motor cortex**. As in the somatosensory cortex, the greater the need for precise control over a body part, the larger its area in this strip. Thus, Figure 2.17 shows more surface area devoted to the face, hands, and fingers than to the arms and legs.

motor cortex The area of the cortex that sends impulses to voluntary muscles.

FIGURE 2.17 The Somatosensory and Motor Areas

Each part of the body is represented in the somatosensory (right) and motor (left) cortex. Note that the amount of tissue devoted to a body part does not correspond to its actual size. Rather, more area is devoted to parts that are most sensitive to touch (such as the lips) and in need of fine motor control (such as the thumbs).



Source: Adapted from The Cerebral Cortex of Man by W. Penfield and T. Rasmussen, 1950, New York: Macmillan. © 1950 Gale, a part of Cengage Learning, Inc.

Try This!

AUTONOMIC PILOT

To learn how the autonomic nervous system (which regulates involuntary functions like heartbeat) can react to external stimuli, **TRY THIS:** Measure your typical heartbeat before starting the experiment. Next, sit silently in a darkened, candlelit room for half an hour. Choose a quiet time of day, turn off your phone, and try to reduce all possible distractions or interruptions. Clear your mind and try to concentrate on your own breathing, making it deep, slow, and even.

At the end of the half hour, test your pulse again. Was it lower than when you started? By how much? What other techniques would you suggest for slowing or accelerating your "automatic" functions?

Association Areas. The cerebral cortex does more than just process sensory information and direct motor responses. There are also vast areas that collectively make up the **association cortex**. These areas communicate with both the sensory and motor areas and house the brain's higher mental processes. Electrical stimulation of these sites does not elicit specific sensations or motor twitches in specific parts of the body, so it's hard to pin these areas down. But damage to the association cortex can have devastating results. In the frontal

association cortex Areas of the cortex that communicate with the sensory and motor areas and house the brain's higher mental processes.

lobes, such damage can change someone's personality, as in the case of Phineas Gage. In other association areas, damage can impair specific kinds of memories, distort our spatial awareness, render us oblivious to emotions, or cause odd speech deficits (Saper et al., 2000).

Language Areas. For the most part, our ability to adapt to life's demands through learning, memory, and thought processes is spread throughout the regions of the cortex. But language—a complex activity for which humans, and in some ways only humans, are uniquely prepared—is different. Carved within the cortex are two special areas dedicated to language. One plays a role in the production of speech; the other, comprehension. In 1861, French physician Paul Broca observed that people who have suffered damage in part of the frontal lobe of the left hemisphere lose the ability to form words to *produce* fluent speech. The words sputter out slowly, and what is said is often not grammatical ("Buy milk store"). This region of the brain—now known to be important for speech production and comprehension (Flinker et al., 2015)—is called **Broca's area** (Schiller, 1992). Interestingly, while Broca, in a narrow sense, did "discover" this region in his research, it was actually another researcher, Ernest Auburtin (representing Jean-Baptiste Bouillaud), who is credited for his 1861 discovery of Broca's area as being associated with speech (Thomas, 2001).

A few years later in 1874, German neurologist Carl Wernicke found that people with damage to the temporal lobe (subsequently called **Wernicke's area**) lose their ability to comprehend speech. In short, people with language disorders, or aphasias, demonstrate that there are at least two distinct cortical centers for language. Interestingly, these two areas are connected by a neural pathway, thus forming part of a language circuit within the brain (Brown & Hagoort, 1999; Geschwind, 1979).

Broca's area A region in the left hemisphere of the brain that directs the muscle movements in the production and comprehension of speech.

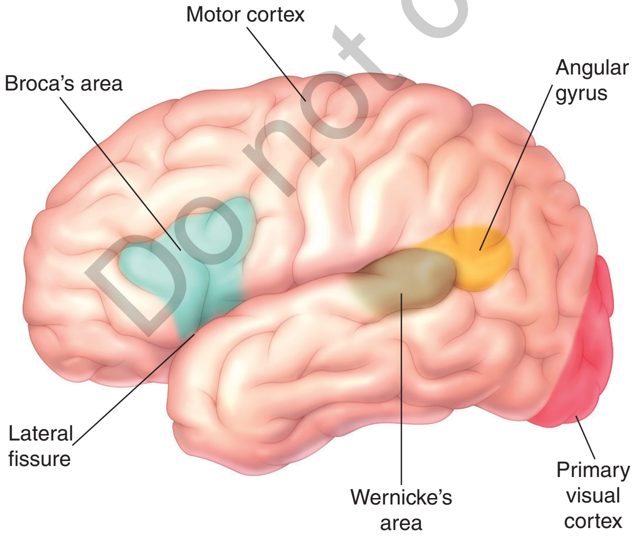
Wernicke's area A region of the brain that is involved in the comprehension of language.

The Integrated Brain. Even though Penfield was able to pinpoint or "map" various locations in the cortex that house sensory and motor functions, we mustn't overstate the case for localization. Although different cortical regions *specialize* in certain functions, the healthy human brain operates as an *integrated* system. This point is illustrated by the role of the brain in language, whereby different cortical areas are activated depending on whether a word is read, spoken, written, or presented in music—or even whether it is a verb or a noun (Caramazza & Hillis, 1991). Consider what it takes simply to repeat the written word *ball*. From the eyes, the stimulus must travel for processing to the visual cortex. The input must then pass through the angular gyrus to be recorded, to Wernicke's area to be understood, and then to Broca's area, where signals are sent to the motor cortex, which drives the muscles of your lips, tongue, and larynx so that you can repeat the word (see Figure 2.18).

It's also important to note that this model may not accurately describe the ways in which different brain regions interact to produce language. Figure 2.18 seems to suggest that the neural events related to language occur in serial fashion, one step at a time. In fact, evidence suggests that language and other complex mental processes may be more accurately represented by *parallel* models in which neural signals move along several routes at once and are processed simultaneously (Peterson et al., 1989). As in an orchestra, it takes the coordinated work of many instruments, often playing together, to make music.

FIGURE 2.18 Language Processing

Although different regions specialize in certain functions, the brain operates as an integrated system. The "simple" act of speaking a written word, for example, requires a coordinated effort of the eyes, the visual cortex, and angular gyrus, Wernicke's area, Broca's area, and the motor cortex.



LEARNING CHECK

Brain Teasers

Match each part of the brain in the left column with its description in the right.

1. Motor cortex	a. Directs muscle movements in the production and comprehension of speech.
2. Cerebral cortex	b. Relays neural messages between the senses and areas of the cerebral cortex.
3. Somatosensory cortex	c. The outermost covering of the brain.
4. Pons	d. Region of the brain involved in the comprehension of language.
5. Broca's area	e. Brainstem structure that controls vital involuntary functions.
6. Wernicke's area	f. Receives sensory information from touch receptors in the skin.
7. Thalamus	g. Sends impulses to voluntary muscles.
8. Medulla	h. Portion of the brainstem that plays a role in sleep and arousal.

(Answers: 1. g; 2. c; 3. f; 4. h; 5. a; 6. d; 7. b; 8. e)

The Split Brain

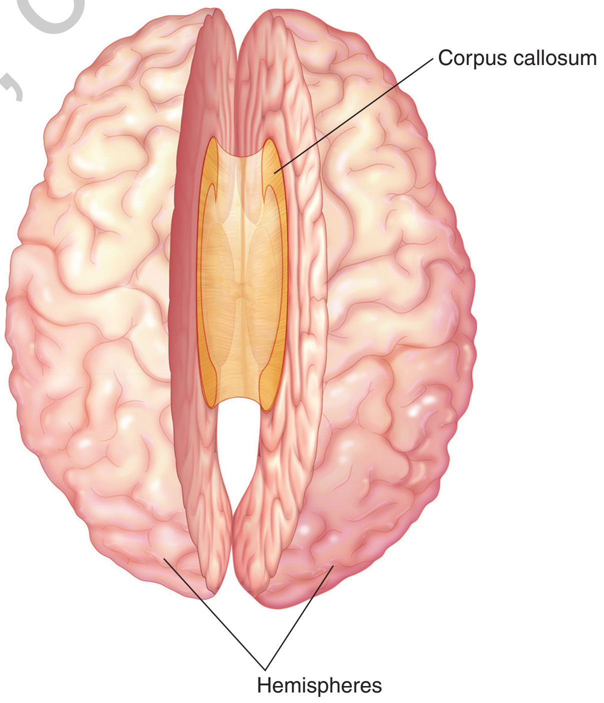
A remarkable feature of the human brain is that each hemisphere is basically a copy of itself. For each structure in the right brain, there is a corresponding structure in the left side of the brain. For example, we introduced many regions of the brain, including the hippocampus, amygdala, hypothalamus, thalamus, association areas, language areas, and sensory and motor areas. For each structure, there is one region in our right brain and in the same corresponding stereotaxic location in the left brain. This organization has interesting implications, which we discuss in this section for split-brain cases.

Split-Brain Studies. For people with severe epilepsy, seizures are the brain's equivalent of thunder-and-lightning storms. A seizure usually starts in one small area, but it quickly spreads across the brain from one side to the other. The experience can be terrifying and at times life-threatening. In the past, neurosurgeons tried to control the problem by removing the overactive area, but these operations had only limited success. To prevent the seizures from spreading, a more radical approach was needed. The goal was to separate the two hemispheres. The method was to cut the **corpus callosum**, a 4-inch-long, quarter-inch-thick bundle consisting of millions of white nerve fibers that join the two hemispheres (see Figure 2.19). This **split-brain** surgery often eliminates epileptic seizures, as hoped. But are there psychological side effects? Was Fechner right in proposing that a split brain, in which the link between the two hemispheres is severed, contains two separate minds?

Before we examine the effects of split-brain surgery, let's consider the divisions of labor within the brain. Recall that the left hemisphere receives sensory input from, and sends motor commands to, the right side of the body (hands, legs, arms, and so on), whereas the right hemisphere communicates with the left side of the body. Processing visual and auditory input is somewhat

FIGURE 2.19 The Corpus Callosum

The corpus callosum contains millions of nerve fibers and joins the left and right hemispheres.

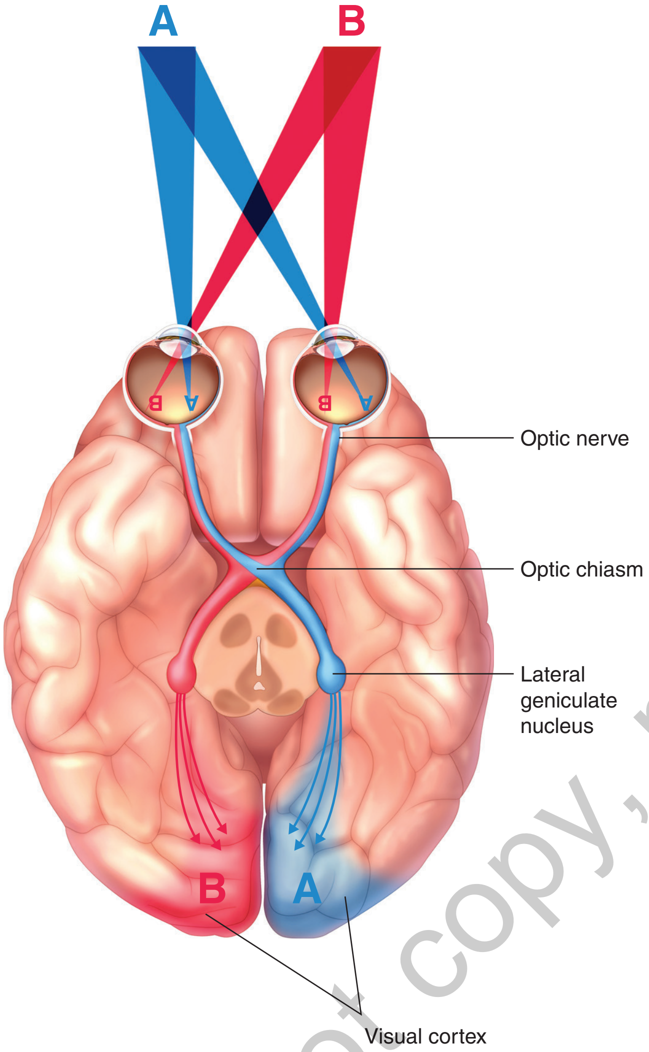


corpus callosum A bundle of nerve fibers that connects the left and right hemispheres.

split brain A surgically produced condition in which the corpus callosum is severed, thus cutting the link between the left and right hemispheres of the brain.

FIGURE 2.20 Visual Processing

Both eyes send information to both hemispheres, but images in the right half of the visual field are sent to the left hemisphere, and images in the left half of the visual field are sent to the right hemisphere. Each image is instantly sent to the other side through the corpus callosum.



more complex. Both eyes send information to both hemispheres, but images in the right half of the visual field are sent to the left hemisphere, and images in the left half of the visual field are sent to the right hemisphere. In other words, if you're looking straight ahead at someone, images on the left are sent by both eyes to the right hemisphere, and images on the right are sent by both eyes to the left hemisphere (see Figure 2.20). Auditory inputs are also sent to both hemispheres, but sounds received in one ear register in the opposite hemisphere first.

If your brain is intact, then this odd crossover arrangement poses no problem because information received by each hemisphere is quickly sent to the other side through the corpus callosum. By sharing information in this manner, the two sides of the brain work as a team. But what happens when the neuron-filled highway that connects the hemispheres is severed?

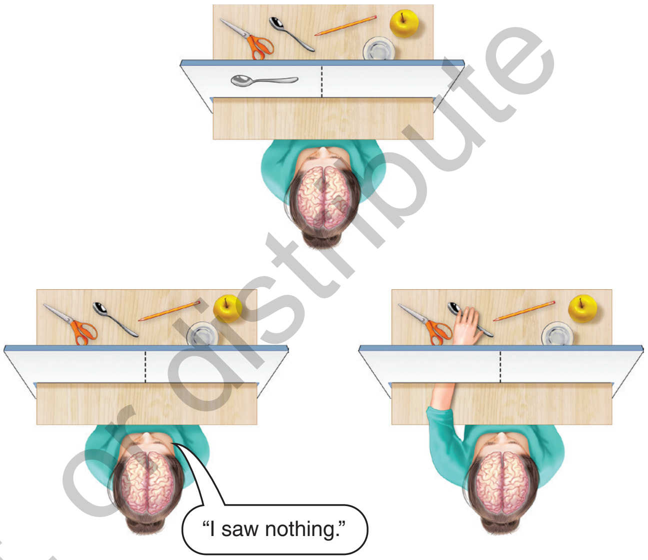
Roger Sperry (who was awarded a Nobel Prize in 1981 and died in 1994), Michael Gazzaniga (his student), and others have helped bring this picture into focus through an ingenious series of studies, such as the one cited at the beginning of this chapter. These studies involved split-brain patients, and the basic procedure was to present information to one hemisphere or the other, and then to measure what the subject "knew" by testing each hemisphere separately. You can view this for yourself by going to **You and Psychological Science! Split-Brain Patient Processing Experiment**.

In one study, Sperry (1968) asked a female patient, identified as N.G., to stare at a black dot in the center of a screen. Then, for only a fraction of a second, he flashed a picture of a spoon either to the right or left of the dot and asked, "What do you see?" The result was fascinating. When the image was shown in the right visual field and thus sent to the left hemisphere, N.G. was quick to reply that she saw a spoon. But when the image was presented on the left side and sent to the right hemisphere, she could not say what she saw. Why not? As noted earlier, speech is controlled by the left hemisphere. If an image in the right side of the brain cannot cross over to the left side, then the person cannot transform what is seen into words. But wait. How do we know that N.G. actually saw the spoon? Maybe the right hemisphere is just stupid. To probe further, Sperry asked N.G. to reach behind a screen and feel an assortment of objects, such as a pencil, an eraser, a key, and a piece of paper. "Which of these did you see before?" Sperry asked. Easy. When N.G. touched the objects with her left hand (which sent the sensations to the right hemisphere), she selected the spoon. The right side knew all along it had seen a spoon, but only the left side could say so (see Figure 2.21).

In a second, similar study, Gazzaniga (1967) had split-brain patients stare at a black dot and flashed the word *teacup* on the screen. The letters *tea* were presented to the left visual field (the right hemisphere), and *cup* was presented to the right visual field (the left hemisphere). If you were the subject—and if your corpus callosum was intact—you would see the full word, *teacup*. But the split-brain patients reported seeing only *cup*, the portion of the word that was flashed to the left hemisphere. Again, how do we know they actually saw the second part of the word? When told to choose between the two parts by pointing with the left hand, they pointed to tea, the letters sent to the right hemisphere. As in the spoon study, each hemisphere was in touch with only half of the total input. Under normal circumstances, stimuli reaching both hemispheres are blended to form a unified experience. Disconnected, each hemisphere has a mind of its own.

FIGURE 2.21 Sperry's Split-Brain Experiment

When the image of a spoon was projected to the right hemisphere, the split-brain patient could not say what she saw. Yet when she felt various objects with her left hand, she selected the spoon. The right side knew all along that it saw the spoon, but only the left side could say so (Sperry, 1968).



In a third study, Jerre Levy and others (1972) took pictures of faces, cut them vertically in half, and pasted different right and left halves together. These composite photographs were then presented rapidly on slides. As in other studies, subjects stared at a center dot so that half of the image fell on either side. When asked what they saw, subjects who looked at the stimulus presented in Figure 2.22 said it was a child. Because they were forced to respond in words, the left hemisphere dominated, causing them to name the image in the right visual field. But when subjects were told to point to the face with the left hand, they pointed to the woman wearing glasses, whose image was projected on the left side. Remarkably, split-brain patients did not seem to know that the composite face was unusual.

Cerebral Lateralization. Split-brain research has generated tremendous excitement in behavioral neuroscience. When the corpus callosum is severed, most (although not all) input to one hemisphere is trapped, unable to pass to the other side. As a result, neither hemisphere knows quite what the other is doing. But what about the day-to-day operations of a normal and healthy brain, corpus callosum and all? We know that speech is usually located in the left hemisphere, but are there other asymmetries in the human brain? Are other functions similarly *lateralized*? Does one side or the other control math, music, or the ability to recognize faces?

Using an array of tools, researchers have uncovered many strands of evidence for **cerebral lateralization** in the normal human brain (Corballis, 2014; Davidson & Hugdahl, 1995; Springer & Deutsch, 1998). As we learned, the left hemisphere largely controls verbal activities—including reading, writing, speaking, and other aspects of language. Studies also show that people recognize words, letters, and other verbal stimuli faster when these stimuli are sent directly to the left hemisphere. Those who are hearing impaired also appear to rely on the left hemisphere more than the right for reading sign language (Corina et al., 1992; Sakai et al., 2005). Finally, PET scans show that different regions of the left hemisphere (and some areas of the right hemisphere as well) "light up" depending on whether subjects are listening to words that are spoken (hearing), reading words on a screen (seeing), saying words aloud (speaking), or coming up with related words (thinking). A sample PET scan appears in Figure 2.23 (Peterson & Fiez, 1993).

cerebral lateralization The tendency for each hemisphere of the brain to specialize in different functions.

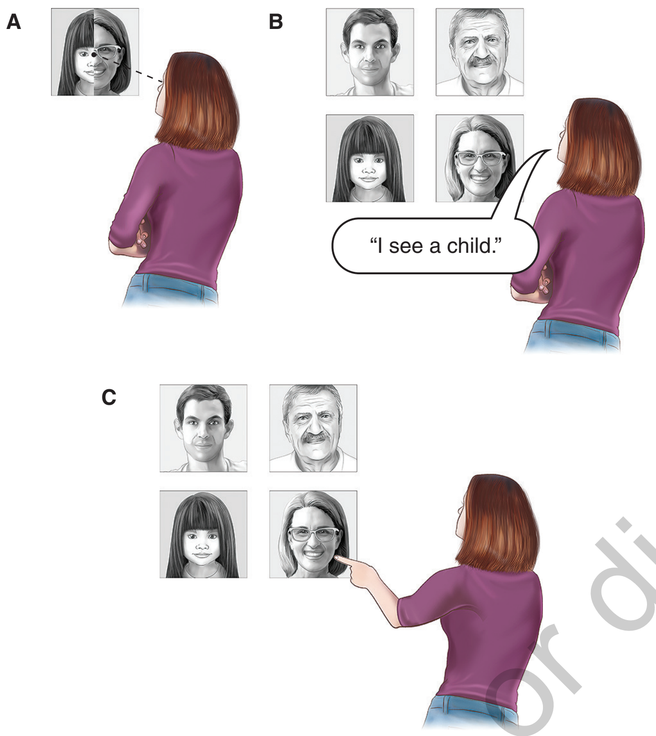


FIGURE 2.22 Levy's Split-Brain Experiment

(A) Split-brain subjects stared at a dot and viewed a composite of two faces. (B) When asked what they saw, subjects chose the child—the image sent to the verbal left hemisphere. (C) But when subjects pointed to the face with the left hand, they chose the woman with glasses—whose image was received by the right hemisphere (Levy et al., 1983).

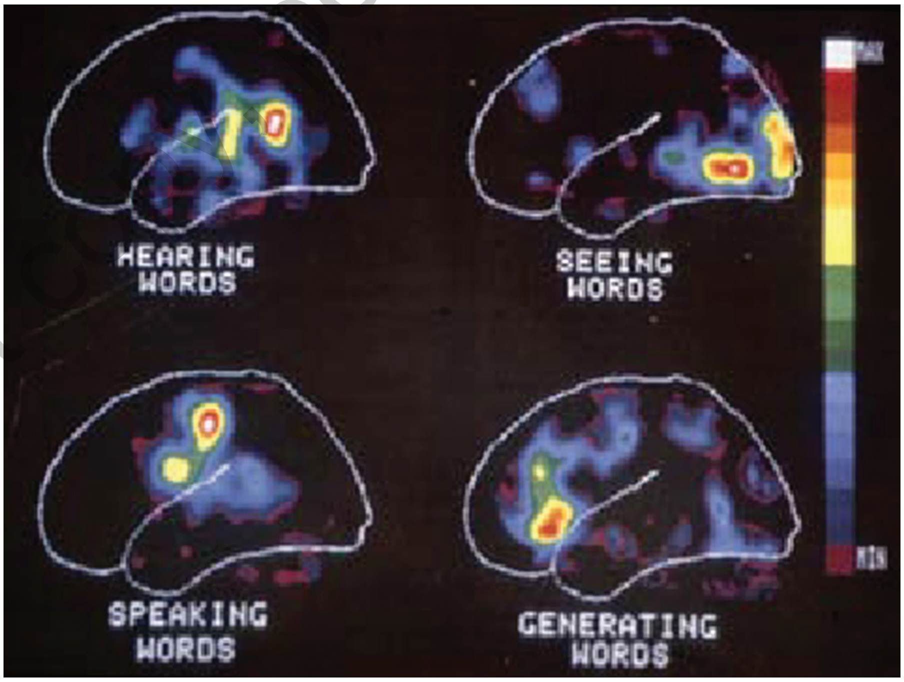


FIGURE 2.23 The Talking Left Hemisphere

PET scans show that a single word activated different left-hemisphere areas depending on whether it was heard, seen, spoken, or thought about. Notice that these "lit-up" areas are in the auditory cortex, visual cortex, Broca's area, and frontal lobes, respectively.

Whereas the left hemisphere is a verbal specialist, there is now converging evidence that the right hemisphere plays a vital role in nonverbal activities such as visual-spatial tasks, music, and the recognition of other people's faces and emotional states. Laboratory studies show that people are usually faster at locating dots, drawing three-dimensional objects, and recognizing faces when the material is presented to the right hemisphere than to the left (Bradshaw & Nettleton, 1981). Clinical case studies also illustrate this point (Corballis et al., 2002). For example, Gazzaniga (1985) instructed a split-brain patient to draw a cube and found that he produced a better drawing with the left hand than with the right—even though he was right-handed. Right hemisphere damage may also cause people to lose their sense of direction while driving, have trouble locating items in a familiar supermarket, or even get lost in their own homes (Newcombe & Ratcliff, 1990).

In some cases, right hemisphere damage caused by a stroke or an accident triggers a disruption of spatial awareness called "neglect" (Vallar, 1998). People with neglect syndrome lose all awareness of the left side of space—including the left side of their own bodies. When asked to bisect a horizontal line, these patients draw the line to the right of center. In actual life tasks, they may comb their hair only on the right side of the head, shave only the right side of the face, or eat food only if it's on the right side of the plate (see Figure 2.24).

The evidence clearly suggests that there is specialization, with the left side more verbal and the right side more visual and spatial. But some researchers believe that the key difference between the two hemispheres is not in *what* kind of input is processed but in *how* that input is processed. In essence, research suggests that the left hemisphere processes information in analytical, piecemeal style—as used in word analogies, arithmetic, and logical problem solving—and that the right hemisphere processes information in a more global, holistic style—as used in music, art, and various forms of creative expression. In one study, for example, Gazzaniga tested a split-brain patient's perceptions of a painting that depicted a face made up of a pattern of small fruits. When the image was presented to the right hemisphere, the patient reported seeing the face, but when the same image was shown to the left hemisphere, he perceived only the fruits. The right side saw the whole; the left side saw the parts (see Reuter-Lorenz & Miller, 1998).

Regardless of how the differences between left and right hemispheres are characterized, it's important not to overstate the case for lateralization. Neither hemisphere has exclusive control over certain functions, and both sides can process different kinds of information (Efron, 1990). As we'll see in the coming pages, our brains are highly adaptive—and often capable of reorganization. If one

FIGURE 2.24
Neglect Syndrome

A patient with a stroke in the right hemisphere was asked to copy model pictures. Like many patients with neglect syndrome, he almost completely overlooked the left side of each drawing.

side is damaged, the other often compensates for the lost functions. Even with old age, which brings about a decline in certain cognitive functions, people compensate by using both sides of the brain. As a result, older adults are more bilateral than younger adults, meaning they are less likely to exhibit left-right differences in specialization (Cabeza, 2002; Woytowicz et al., 2020).

LEARNING CHECK

Right or Left?

How well do you know your right from your left (brain hemispheres, that is)? Put an X in the box on the left side of the question to answer “left” or on the right side to answer “right.”

	1. “Neglect syndrome” is a result of damage to which hemisphere?	
	2. Which hemisphere is the first to register sounds received in the right ear?	
	3. According to research, which hemisphere processes information in a more analytical, piecemeal style?	
	4. Which hemisphere processes information in a more global, holistic style?	
	5. Which hemisphere has more to do with music?	
	6. Which hemisphere has more to do with recognizing people’s faces?	
	7. Which hemisphere sends motor commands to your right hand?	
	8. Damage to which hemisphere would be more likely to disrupt your sense of direction?	

(Answers: 1. right; 2. left; 3. left; 4. right; 5. right; 6. right; 7. left; 8. right)

Prospects For the Future

2.4 Identify the nature of plasticity in the brain and how it can be applied to understanding brain injuries.

- Is the adult brain fixed in its structure, or does it have a capacity to change as a result of experience?
- Is it possible for people to recover functions lost to brain damage?
- Can healthy tissue be transplanted from one brain into another?

The human brain is a remarkable organ. It is organized with a specificity that allows researchers to compare differences in brain structure and function across the human species. Yet it is also adaptive to change—to facilitate not only learning but also recovery of function when injuries occur. In this section, we introduce the human brain as an adaptive organ capable of changing over time and recovering from injury.

The Brain’s Capacity for Growth and Reorganization

The human brain is an impressive organ. Encased in a hard protective skull, the human brain is complex and has a great deal of **plasticity** (from the word *plastic*)—a capacity to change as a result of usage, practice, and experience (Huttenlocher, 2002; Nelson, 1999).

plasticity A capacity to change as a result of experience.

THE BENEFIT OF PLASTICITY: GROWTH THROUGH EXPERIENCE

Psychologists used to believe that the neural circuits of the adult brain and nervous system were fully developed and no longer subject to change. Then a series of provocative animal experiments showed that this is not so. Mark Rosenzweig (1984) built an “amusement park” for rats to examine the effects of an enriched environment on neural development. Some rats lived together in a cage filled with ladders, platforms, boxes, and other toys, whereas others lived in solitary confinement. The enriched rats developed heavier, thicker brains with more dendrites and synapses than those who were deprived. In fact, the growth can be quite specific. Rats flooded with visual stimulation formed 20% more synaptic connections per neuron in the visual cortex than those who were raised in darkness (Greenough et al., 1987). "Acrobatic" rats trained to run between pylons on elevated runways formed new synaptic connections in the cerebellum, the structure involved in balance and motor coordination (Greenough et al., 1990). Similar results in birds, mice, squirrels, and monkeys of different ages have confirmed a basic point: Experiences spark the growth of new synaptic connections and mold the brain's neural architecture (Colangelo et al., 2019; Kolb & Whishaw, 1998).

What's Your Prediction?

Most people in the world are right-handed. Yet psychologist Lee Salk (1962) once noticed that mothers tend to hold their infants on the left side of their body. Is this true? Shouldn't most people, being right-handed, prefer the right arm for something as precious as a human baby? What about books, boxes, and other objects? Imagine you are holding a 3-month-old baby in one arm. Are you using your right arm or left? Now imagine that you're holding an antique vase or a shoebox. Which arm are you using now? Jason Almerigi and others (2002) tested 300 college students. What percentage do you think saw themselves using the right arm for a baby—25%, 50%, 75%, more? What about for inanimate objects? The result confirmed Salk's observation: Although 76% said they'd use the right arm to hold objects, 66% said they'd use the *left* arm for an infant. This result is found consistently—not just for imaginary tasks, but in actual practice (Harris, 2002). How can this be explained? Is it possible that people hold infants on the left arm in order to free up the right hand? The preference is clear, but at this point more research is needed to determine the reason for it.

Plasticity has profound practical implications for human development and adaptation. Reorganization within the brain can help people compensate for other types of loss as well. For example, brain-imaging studies have shown that in people who are blind, the visual cortex—which is deprived of visual input—is activated by other types of stimulation such as sound and touch (Sadato et al., 1999). Similarly, in people who are deaf, the auditory cortex becomes activated in response to touch (Levanen et al., 1998). These findings illustrate "cross-modal plasticity," which may help to explain a common observation that when people lose their sight or hearing, their other senses become sharpened as a result.

Neural plasticity has other implications, too. Avi Karni and Leslie Ungerleider (1996) tested the proposition that repeated stimulation of a body part would cause corresponding changes in the human brain. These researchers had six men perform one of two finger-tapping sequences for 10 to 20 minutes every day. After 5 weeks, they had the men tap out both the practiced and nonpracticed sequences. Using fMRI, they found that tapping the practiced sequence lit up a larger portion of the primary motor cortex.

If sheer usage can spark the buildup of new synaptic connections among neurons, then an individual's life experiences should leave a permanent mark on his or her brain. In an interesting test of this hypothesis, researchers autopsied a number of human brains and measured the degree of synaptic branching in Wernicke's area of the left hemisphere. Then they probed into the backgrounds of these deceased subjects and found that the more educated they were, the more branching there was in this language-rich part of the brain (Jacobs et al., 1993). In another study, researchers played tones of varying frequencies for 37 professional musicians and nonmusicians and found that the part of the auditory cortex that responds to sound was more active in the musicians' brain—and it contained 130% more gray matter. Perhaps years of experience had stimulated the growth of extra neurons in this music-sensitive structure (Schneider & Domhoff, 2020).

The recent analysis of Albert Einstein's brain is a case in point. We noted earlier that whereas Einstein's brain was average sized overall, a highly specific region that is active in visuospatial and mathematical thinking was 15% larger than normal. Einstein may well have been born with a brain uniquely gifted for physics. Yet it's possible, as the researchers were quick to point out, that this part of his brain bulked up in size as a result of constant usage (Witelson et al., 1999). "Practice may not always make perfect, but it is likely to make a lasting impression on your brain" (Azar, 1996).

THE COST OF PLASTICITY: THE CASE OF THE PHANTOM LIMB

Plasticity is an adaptive feature of the nervous system. However, recent studies indicate that the brain's plasticity can also be a burden, as in the case of amputation. Psychologists have long been puzzled by phantom pain—the fact that amputees often feel excruciating pain in the area of their lost limb, sensations that would often last for years. To lessen the pain, puzzled physicians and their patients have sometimes resorted to desperate measures such as shortening the stump or cutting sensory tracts in the spinal cord, typically without success. In the past, some interpreted the pain as a form of denial, or wishful thinking; others believed that frayed nerve endings in the stump were inflamed and irritated, thereby fooling the brain into thinking that the limb was still there. It now appears that neither of these explanations is correct and that the phantom pain results, ironically, from the brain's own capacity for reorganization and growth.

This possibility was first raised when Michael Merzenich and his colleagues (1983) severed the nerve of the middle finger in an adult monkey and found that the area of the somatosensory cortex dedicated to that finger did not wither away. Rather, nearby neurons activated by other fingers filled in the dormant region. The sensations produced by these neurons may thus fool the brain into thinking that the limb is still there. Consistent with this account, a study of human amputees revealed that the more cortical reorganization that had occurred, as detected in brain scans, the more pain the patients felt (Flor et al., 1995; Karl et al., 2001).

Repairing the Damaged Brain: New Frontiers

The brain has great capacity for enrichment, but alas, we are mortal and our bodies are fallible. Strokes, spinal cord injuries, diseases that strike at the core of the nervous system, exposure to toxic substances, and addictions to alcohol and other drugs are just some of the causes of brain damage. The possible effects include paralysis, motor disorders, thought and speech disorders, blunted emotion, changes in personality, and a loss of sensory capabilities, consciousness, and memory. (See the *Psychology Applied: Head Injury in Contact Sports* feature.)

NEUROGENESIS

neurogenesis The production of new brain cells.

Scientists used to believe that adult brains do not produce new neurons—that the death of brain cells results in permanent loss. It now appears, however, that the production of new brain cells—a process called **neurogenesis**—continues well beyond infancy. The human brain may acquire billions of new cells between birth and age 6 years, which are incorporated into existing neural circuits and help to construct new ones (Blakeslee, 2000; Gilmore et al., 2018). Neurogenesis may slow in adulthood, but it does not stop completely. The adult brain, too, has special cells that divide and produce new neurons. The discovery of neurogenesis in adults can be traced to the mid-1960s when researchers studying adult mice found new brain cells in the hippocampus, the structure involved in forming new memories. Within a few years, scientists observed this in the brains of other adult mammals, such as guinea pigs and rabbits, and in birds. For instance, new cells are created in the brains of adult canaries that learn new songs and in adult chickadees that store memories for where their winter seed stashes are hidden.

Does all this mean that neurogenesis occurs in the brains of adult humans? Although more evidence is needed, the possibilities are exciting. If you get an ulcer, break a finger, or scrape your knee, new cells will be produced to heal the wound. Scientists of the past assumed that the brain did not have this same capacity to heal itself. Once a neuron is damaged, after all, it is forever disabled. Yet every now and then, we hear stories of "miraculous" recoveries from brain damage. What makes this possible is the adaptive capacity to compensate for loss by strengthening old synaptic connections and by sprouting new axons and dendrites to form new connections. Earlier we saw that healthy brain tissue will sometimes pick up lost functions—which is why children with substantial damage to the left hemisphere learn to speak, and many adults who suffer strokes later recover their speech and motor abilities. Although methodological challenges have constrained the ability of investigators to reach a definitive answer, neurogenesis may also occur in the brains of adult humans, putting us on the verge of exciting new treatments for brain disorders (Kumar et al., 2019).

concussion An alteration in a person's mental state caused by trauma to the head.

Psychology Applied

HEAD INJURY IN CONTACT SPORTS

How often have you seen an athlete take a crushing blow to the head, go down, lie still for a few moments, and then stumble off the field looking dazed? Elite National Football League (NFL) quarterbacks Aaron Rodgers, Patrick Mahomes II, and Russell Wilson have all suffered from concussions. So do thousands of other athletes every year, professionals and amateurs, who play soccer, hockey, and other contact sports. What happens in a concussion, what are its effects, and can they be prevented?

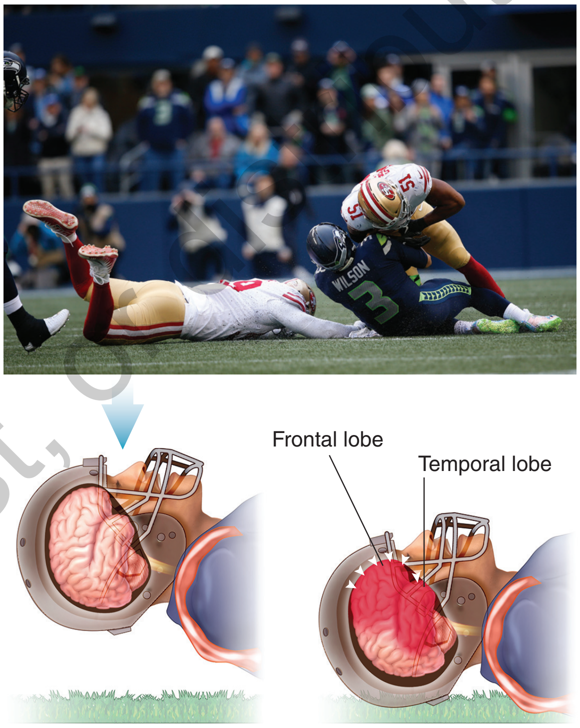
A **concussion** is an alteration in a person's mental state caused by trauma to the head. From a neurological perspective, a concussion occurs when a jarring blow causes axons to become stretched, twisted, or sheared, interrupting signals between neurons (see Figure 2.25). The most common changes in mental state following a concussion are temporary confusion and amnesia, and these symptoms may occur right after the trauma or up to 15 minutes later.

Concussions vary a great deal in their severity. Mild "Grade 1" concussions tend to cause headaches, dizziness, disorientation, blurred speech, and a ringing in the ears. In sports, this type of concussion is difficult to diagnose and is commonly referred to as a "dinger" (athletes like to describe the state as "having their bell rung"). At the other extreme are severe "Grade 3" concussions, which are easy to spot because they cause unconsciousness for a brief or prolonged time. This type of injury can damage the brainstem and disrupt such autonomic functions as heart rate and breathing. Over time, it may also result in such symptoms as persistent headaches, vision problems, memory loss, sleep loss, an inability to concentrate, a lack of tolerance for loud noises and bright lights, fatigue, and anxiety or depressed mood. How can a coach or athletic trainer know that an athlete has just suffered a concussion? Here are some common symptoms (American Academy of Neurology, 1997; Bailes et al., 1998):

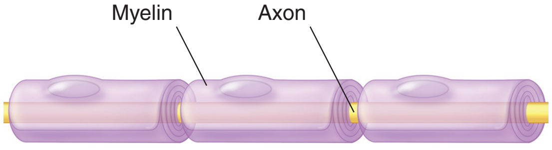
- Stares vacantly into space or looks confused
- Is slow to answer questions
- Is easily distracted and unable to follow instructions
- Slurs speech or talks in gibberish
- Stumbles and cannot walk a straight line
- Is disoriented, often walking in the wrong direction
- Doesn't know the current time, day, or place

FIGURE 2.25 Anatomy of a Concussion

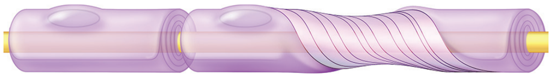
How often have you seen an athlete take a crushing blow to the head, go down, and leave the game? Featured NFL quarterbacks suffer repeated concussions. So do thousands of other athletes each year. But with what effect?



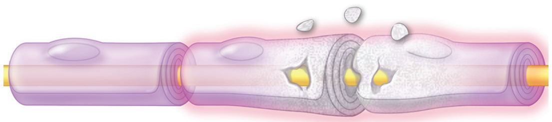
Michael Zagaris/Contributor/Getty Images



In a normal neuron, the axon, which is protected by a myelin sheath, is not broken or otherwise distorted.



After a concussive blow, an axon might twist or bend, interrupting communication between neurons.



If a concussion is severe enough, the axon swells and disintegrates. Less severely damaged axons return to normal.

(Continued)

(Continued)

- Repeatedly asks the same question and forgets the answer
- Becomes highly emotional, crying for no apparent reason

Doctors fear that people who suffer repeated concussions may face lasting cognitive declines. So, what can be done to minimize the damage to athletes? There are three steps to be taken. The first is to require the use of safety equipment that would lessen the risk of getting a concussion. In the NFL, the focus has been largely on improving safety of helmets, head gear, and mouth guards. Many testing methods are now being used to determine equipment safety. A second precautionary step is to change the rules of the game in order to reduce risks of concussions for plays or rules that are "high risk" for concussions. Changes for the NFL include moving the line where a team kicks off from the 30- to the 35-yard line to reduce the number of times a kickoff is returned, expanding the list of "defenseless players" to protect players in vulnerable positions, and reducing the length of the overtime to 10 minutes. A third precautionary step appropriate to all sports is to ensure that any player who takes a blow to the head be sidelined immediately and carefully examined for concussion-like symptoms. For this step, standardized brief examination methods have been developed and a five-step concussion protocol is now implemented in the NFL. In fact, concussion protocols are now implemented in most contact sports—in college and in professional leagues (Deubert et al., 2017; NCAA Sport Science Institute, 2020).

Today, neurologists are wondering if the newest roller coasters can cause similar brain trauma by jostling the brain's soft tissue, causing it to press up against the skull. A few years ago, no roller coaster surpassed 200 feet in height; today, "hypercoasters" reach up to 400 feet. A few years ago, roller coasters gained speed by gravity; today, many are catapulted by motors designed to launch rockets. As thrilling as the rides can be, they subject riders to powerful physical forces—such as gravity, or g-force, jerk, roll, pitch, and yaw. Research is currently being conducted to examine the effects of such forces on the brain (Pieles et al., 2017).

NEURAL TRANSPLANTATION

Is it possible to more effectively restore the brain through medical intervention? For the millions of people each year who are struck by Parkinson's disease, Alzheimer's disease, and other degenerative nerve disorders, can the damaged brain and nervous system be repaired? One exciting development is that researchers have been busy trying to transplant healthy tissue from the central nervous system of one animal into that of another animal in a surgical procedure known as a **neural graft**. In amphibians and fish, researchers demonstrated long ago that it was possible to transplant neurons in coldblooded animals. In classic experiments from the 1940s, Sperry transplanted eyeballs in frogs and found that these grafts formed new pathways to the brain and restored vision. Would neural grafting work as well in warm-blooded mammals? To find out, a team of researchers destroyed a dopamine-producing area of the brainstem (called the *substantia nigra*) in laboratory rats. As they had anticipated, the lack of dopamine caused severe tremors and other symptoms that mimicked Parkinson's disease. Next, researchers implanted healthy tissue from brains taken from rat fetuses, and they observed a 70% decline in symptoms after 4 weeks (Perlow et al., 1979). In later experiments with rats, mice, and primates, researchers also used neural grafting in other regions of the brain to reverse cognitive learning deficits, spatial deficits, and alcohol-induced memory loss (Brasted et al., 2000; Stoker et al., 2017).

neural graft A technique of transplanting healthy tissue from the nervous system of one animal into that of another.


R. McPhedran/Stringer/Hulton Archive/Getty Images

In 1984, 3 years after retiring from boxing, Muhammad Ali was diagnosed with Parkinson's disease. Outside of his Hall-of-Fame boxing career, Ali played an instrumental role in the Civil Rights movement and was a world-recognized advocate who raised awareness for those suffering with Parkinson's disease. He passed away from complications of the disease on June 3, 2016 at the age of 74.

News from animal laboratories is encouraging, but can brain grafts help people suffering from degenerative nerve disorders? In March 1982, a male patient with Parkinson's disease in Stockholm, Sweden, agreed to serve as a human guinea pig. The patient was barely able to move without medication and underwent an experimental operation. The neurosurgeons removed part of his adrenal gland, which produces dopamine, and injected the tissue directly into his brain (Parkinson's disease results from a shortage of dopamine). But the result was disappointing. The patient showed some minor improvement during the first couple of weeks, but he soon reverted to his presurgery state (Backlund et al., 1985). Undiscouraged, others pursued the use of brain grafts in patients with Parkinson's disease, with varying degrees of success.

Recent studies offer an exciting direction for future efforts to repair the damaged brain. Neuroscientists have long held that new nerve cells cannot be produced in the adult brain. New axons and dendrites may sprout, forming new synaptic connections. While the growth of new neurons was once considered impossible, neurogenesis researchers have since discovered that the adult human brain does spawn new nerve cells in the hippocampus, a structure that is important in learning and memory. This discovery, and the possibility that neuroscientists may someday find a way to stimulate the growth and migration of nerve cells, has led some researchers to speculate that the human brain harbors great potential for its own repair (Doidge, 2007; Fawcett et al., 2001).

THINKING LIKE A PSYCHOLOGIST ABOUT BEHAVIORAL NEUROSCIENCE

The study of the split-brain patient described at the outset of this chapter gave us a glimpse into the fascinating and developing world of behavioral neuroscience. This research illustrates why it is valuable to observe individuals who are exceptional in some way and tells us that each region of the brain is involved in different psychological processes. But as we have seen elsewhere in this chapter, researchers use other methods as well, including powerful brain scans, to discover linkages among the brain, the mind, and behavior. Although different areas of the brain act as "specialists," the healthy human brain operates as an integrated system and has the capacity to change as a result of usage, practice, and experience.

To this day, the human brain and nervous system remain one of the great frontiers in science. From the trillions of tiny building blocks, consisting of axons, dendrites, synapses, and neurotransmitters, to the structures of the brainstem, limbic system, and cerebral cortex, there is a solid biological foundation for the study of mind and behavior. The goal, as we'll learn in later chapters, is to understand the links between the human body and psychological processes that range from visual perception to moral development, social aggression, and the health benefits of psychotherapy.

PROCESS OF DISCOVERY: MICHAEL S. GAZZANIGA

Process of Discovery interviews offer a firsthand account of how eminent psychologists, in their own words, came upon their major contributions. These stories, which help learners think like psychologists, are windows into the minds of those who have shaped the field of psychology.

Michael S. Gazzaniga, Splitting the Brain . . . and the Mind

Q: How did you first become interested in psychology?

A: I think it is virtually impossible to not be interested in psychology. For me it started in college, at Dartmouth, when I took a course on emotions, then migrated into studying visual perception. This all came while I was majoring in zoology, which is where I learned about Roger Sperry's work on how neurons grew back in a specific manner. Sperry wrote with

(*Continued*)

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such compelling clarity that I was immediately drawn to his work. He was at Caltech and my home was nearby, so I wrote him to ask for a summer job. He was able to provide one and that summer changed my life. Sperry was doing split-brain work on animals. I was intrigued and became interested in psychological aspects of brain function.

Q: How did you come up with your important discovery?

A: When I returned to Dartmouth, I thought it would be a great idea to test patients that had been operated on to cure their epilepsy at the University of Rochester. These tests would indicate if information presented to one side of the brain would be known to the other side of the brain. I wrote to Sperry with my ideas and he supported my effort. Those studies didn't get done. I, however, was bitten by the intellectual questions, so I applied to graduate school, abandoned medical school plans, and started my work with Sperry. I was there for only moments when Sperry, knowing of my interest in human testing, told me to prepare for a possible patient.

I built a tachistoscope, devised test stimuli, and all the rest. One summer day the first split-brain patient came for preoperative testing. I ran my tests and because his brain was intact, he behaved completely normally, being able to name stimuli presented to either half brain. He was then taken home to await surgery. Dr. Peter Vogel and Joseph Bogen soon operated, and after a recovery period he returned to Caltech for postoperative testing. That is a day I will never forget. The patient was in a wheelchair, and I rolled him into the testing room I had devised. I first showed him a picture in his right visual field and he easily named it. I then showed a picture to his left hemisphere. He said nothing had been presented! The human split-brain research story was born.

Q: How has the field you inspired developed over the years?

A: There are many things that have happened, including the naming of the field, cognitive neuroscience. With the advent of brain imaging, electrical recordings, animal models, and gene expression work, the field has rocketed to a complexity and activity level that is staggering in its importance and yield.

Q: What's your prediction on where the field is heading?

A: It is a risky enterprise to attempt to predict the future. Charles Townes, the Nobel Laureate who invented the laser, once remarked, "The beautiful thing about a new idea is that you don't know about it yet." New ideas will come along as they are needed. In this field, my guess is that computational ideas will come to the front and instruct us on how the nervous system computes and therein generates our psychological lives bounded by reason, perception, language, and emotions.

Michael S. Gazzaniga is Professor of Psychology at the University of California, Santa Barbara, where he is the Director of the SAGE Center for the Study of the Mind.

SUMMARY

Phineas Gage's dramatic brain injury showed that the human brain and nervous system form an integrated system of specialized parts—the concern of *behavioral neuroscience*.

THE BODY'S COMMUNICATION NETWORKS

The body has two communication networks: the nervous system and the endocrine system.

The Nervous System

The human nervous system has two basic parts. The **central nervous system (CNS)** includes the brain and the spinal cord. The **peripheral nervous system (PNS)** consists of the nerves that radiate from the CNS to the rest of the body.

The PNS is further divided into two components. The **somatic nervous system** transmits signals from the sensory organs and skin to the CNS. It also relays motor commands from the CNS to the skeletal muscles. The **autonomic nervous system** connects the CNS to the involuntary muscles, organs, and glands, thus regulating such functions as heartbeat and temperature. The autonomic nervous system has two parts: the **sympathetic nervous system**, which energizes the body for action, and the **parasympathetic nervous system**, which returns the body to its normal state.

The Endocrine System

The **endocrine system** is a collection of ductless glands that regulate growth, metabolism, and other functions by secreting **hormones** into the bloodstream. These secretions are controlled in the brain by the hypothalamus, which signals the **pituitary gland.**

THE NEURON

Neurons, or nerve cells, transmit and receive information throughout the nervous system. **Sensory neurons** transmit information from the senses, skin, muscles, and internal organs to the CNS. **Motor neurons** send commands from the CNS to the muscles, glands, and organs. **Interneurons** serve as connectors within the CNS. Neurons cluster into interconnected working groups called **neural networks**. **Glial cells** help support, insulate, and nourish the neurons. A simple **reflex** like the knee jerk illustrates the speed of neural signals.

Structure of the Neuron

Each neuron has a rounded body, called the **soma**, and two types of branched fibers: **dendrites**, which receive impulses, and an **axon**, which sends impulses through its terminals. Many axons are covered with a **myelin sheath**, a fatty insulating layer that speeds impulses.

The Neuron in Action

A neuron transmits messages by means of an electrical process. When dendrites receive signals of sufficient strength, the cell's membrane breaks down. Positively charged sodium ions rush in, altering the charge inside in such a way that a burst of electrical energy known as an **action potential** surges through the axon as soon as a certain necessary level of stimulation, or **threshold**, is reached.

How Neurons Communicate

To transmit a signal across the **synapse**, the tiny gap between two neurons, the sending neuron releases chemical **neurotransmitters** from vesicles in its axon terminals. These chemicals bind to **receptors** on the dendrites of a receiving neuron. There are many neurotransmitters in the body, and each fits only certain receptors.

Neurotransmitters

Acetylcholine (ACh) is a neurotransmitter that links motor neurons and muscles. ACh has an excitatory effect on muscles. **Dopamine**, in contrast, inhibits muscles and helps control voluntary movements. Alzheimer's disease, Parkinson's disease, and schizophrenia have all been linked to problems with these chemical messengers. Other neurotransmitters called **endorphins** serve as the body's own pain relievers.

THE BRAIN

The basic anatomy of the brain has long been known, but behavioral neuroscientists face the more difficult task of understanding how it functions.

Tools of Behavioral Neuroscience

Although **phrenology** was misguided in linking mental characteristics to bumps on the skull, it correctly supposed that functions are localized in particular parts of the brain.

Today, neuroscientists use four methods to study brain functions: (1) clinical case studies of people with brain damage; (2) invasion of the brain through surgery, drugs, or electrical stimulation; (3) electrical recordings of activity using the **electroencephalograph (EEG)**; and (4) brain-imaging techniques, such as the **computerized tomography (CT) scan**, the **positron emission tomography (PET) scan**, and **magnetic resonance imaging (MRI).**

Regions of the Brain

The brain consists of three main parts: the brainstem, the limbic system, and the cerebral cortex. Each of these comprises several important structures.

The **brainstem** is the inner core. It contains the **medulla**, which controls vital involuntary functions such as breathing; the **pons**, involved in sleep and arousal; and the **reticular formation**, a netlike group of cells that filter sensory information and help control sleep, arousal, and attention. Nearby are the **cerebellum** and **basal ganglia**, which play an important role in balance and coordination.

Above the brainstem is the **limbic system**, which helps govern motivation, emotion, and memory. It includes the **thalamus**, a relay station for sensory information; the **amygdala**, linked to fear, anger, and aggression; the **hippocampus**, which performs a key function in memory formation; and the **hypothalamus**, which helps regulate the autonomic nervous system, emotions, and basic drives.

The outermost 80% of the brain, the wrinkled **cerebral cortex**, controls higher-order mental processes. Anatomically, it consists of two hemispheres and four lobes. It can also be divided into areas based on function: (1) Sensory areas specialize in receiving sensory information. For example, the **somatosensory cortex** receives information from the touch receptors in the skin. (2) The **motor cortex** controls the voluntary muscles. (3) The **association cortex** areas communicate with the sensory and motor areas and house higher mental processes. Within the association cortex, two areas specialize in language. **Broca's area** directs the production and comprehension of speech, and **Wernicke's area** is involved in language comprehension.

The Split Brain

Researchers have investigated Fechner's idea that each side of the brain has its own mind. The studies rely on the fact that the left hemisphere communicates with the right side of the body, and the right hemisphere with the left side. The hemispheres are connected by, and share information through, the **corpus callosum**. Experiments with **split-brain** patients, in whom the corpus callosum has been severed, show that each hemisphere has a somewhat different version of experience.

Other researchers have studied **cerebral lateralization** to determine which functions are lateralized, or controlled by a single side of the brain. The key language centers are in the left hemisphere. The right hemisphere plays a crucial role in nonverbal functions. But the most important distinction may be the style of processing. The left hemisphere seems to rely on analytical processing, whereas the right hemisphere is more holistic.

Research supports the notion that the two hemispheres, when their links are cut, produce separate streams of consciousness. But in the healthy brain, they exchange information so quickly that our mental experience is a seamless whole.

PROSPECTS FOR THE FUTURE

Recent advances in the study of the brain have addressed two questions: Does the adult brain have a capacity to change and adapt as a result of experience, and is it possible to repair a damaged brain?

The Brain's Capacity for Growth and Reorganization

Research shows that the brain has **plasticity**, a capacity to change. Specifically, certain experiences can spark the branching of new dendrites and the growth of new synaptic connections. This enables the brain to compensate for damage, but it also causes people with amputated limbs to experience phantom pain.

Repairing the Damaged Brain: New Frontiers

Advances in understanding the brain have shown that **neurogenesis** continues past infancy and have led to attempts at brain repair. With the **neural graft** procedure, researchers have transplanted brain tissue from one animal into another in an effort to reduce deficits in brain function. Among human beings, the greatest hope may involve the transplantation of fetal tissue, a highly controversial procedure. Contrary to what has been believed, new nerve cells can be produced in the mature brain. With the increased attention paid to **concussions** in sports, more research than ever is being conducted as well to evaluate the effects of trauma to the head and possible treatments for repairing damage.

KEY TERMS

acetylcholine (ACh)
action potential
amygdala
association cortex
autonomic nervous system
axon
basal ganglia
brainstem
Broca's area
central nervous system (CNS)
cerebellum
cerebral cortex
cerebral lateralization
computerized tomography (CT) scan
concussion
corpus callosum
dendrites
dopamine
electroencephalograph (EEG)
endocrine system
endorphin
glial cells
hippocampus
hormones
hypothalamus
interneurons
limbic system
magnetic resonance imaging (MRI)
medulla
motor cortex
motor neurons
myelin sheath
neural graft
neural networks
neurogenesis
neurons
neurotransmitters
parasympathetic nervous system
peripheral nervous system (PNS)
phrenology
pituitary gland
plasticity

pons
positron emission tomography (PET) scan
receptors
reflex
reticular formation
sensory neurons
soma
somatic nervous system
somatosensory cortex
split brain
sympathetic nervous system
synapse
thalamus
threshold
Wernicke's area

CRITICAL THINKING

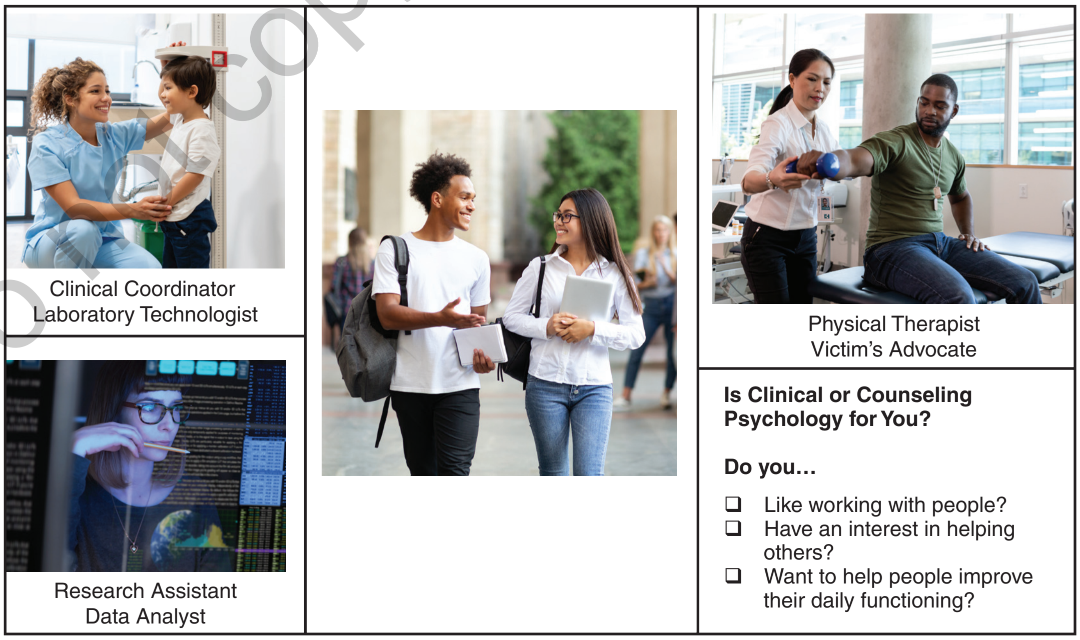
THINKING CRITICALLY ABOUT BEHAVIORAL NEUROSCIENCE

1. What is the difference between the "mind" and the "brain"?
2. Advances in brain-imaging technology allow us to see the human brain at work. What kinds of questions do you think we might be able to answer with these sophisticated techniques?
3. What is your opinion of the right-brain education debate? What is the evidence for and against right- versus left-brain learning? In what ways might lateralized functions and integrated functioning each contribute to the learning process?
4. Research investigating neural plasticity suggests that life experiences can alter the neural circuitry of the brain. What are the advantages and disadvantages of this phenomenon? What are some of the real-world implications of this research (e.g., for child rearing, the treatment of stroke victims, etc.)? Is this notion of plasticity consistent with the evolutionary perspective discussed in the previous chapter? Why or why not?

CAREER CONNECTION

While some psychologists choose to focus on research, others choose to focus their careers on applied psychology and working directly with people and communities. Its near universal application—from counseling and relationships to advertising and business—makes psychology one of the most versatile and valuable majors in all of higher education.

FIGURE 2.26



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