academic exercise confined to scientific laboratories: The more we know about the brain, and the more people who know it, the better our chances of finding solutions to problems such as CTE.

IN THIS CHAPTER, WE'LL CONSIDER HOW THE BRAIN WORKS, and what happens when it doesn't. First, we'll introduce the basic unit of information processing in the brain, the neuron. Neurons are the starting point of all behavior, thought, and emotion. Next, we'll consider the anatomy of the central nervous system, focusing especially on the brain. We'll then examine the interplay between genetics and the environment, and the role they play in directing behavior. Finally, we'll discuss methods that allow us to study both damaged and healthy brains.

neurons Cells in the nervous system that communicate with each other to perform information-processing tasks.

cell body (soma) Component of the neuron that coordinates information-processing tasks and keeps the cell alive.

dendrite Component of the neuron that receives information from other neurons and relays it to the cell body.

axon Component of the neuron that carries information to other neurons, muscles, or glands.

myelin sheath An insulating layer of fatty material.

glial cells Support cells found in the nervous system.

Neurons: The Origin of Behavior

An estimated 1 billion people watch the final game of World Cup soccer every 4 years. That's a whole lot of people, but to put it in perspective, it's only a little over 14% of the estimated 7 billion people currently living on earth. But scientists estimate that there are as many as 86 *billion* nerve cells (von Bartheld et al., 2016) in your brain. All of your thoughts, feelings, and behaviors spring from cells in the brain that take in information and produce some kind of output trillions of times a day. These cells are **neurons,** *cells in the nervous system that communicate with each other to perform information-processing tasks*.

Learning Outcomes

WHAT YOU NEED TO KNOW

- Explain the function of neurons.
- Outline the components of the neuron.
- Describe the functions of the three major types of neurons.

Components of the Neuron

During the 1800s, Spanish physician Santiago Ramón y Cajal (1852–1934) used a new technique for staining neurons in the brain (DeFelipe & Jones, 1988) (see **FIGURE 3.1**). He discovered that neurons are complex structures composed of three basic parts: the cell body, the dendrites, and the axon (see **FIGURE 3.2**). Like cells in all organs of the body, neurons have a **cell body** (also called the *soma*), the largest *component of the neuron that coordinates the information-processing tasks and keeps the cell alive*. The cell body contains a *nucleus,* which houses chromosomes that contain your DNA, the genetic blueprint of who you are. The cell body is enclosed by a porous cell *membrane* that allows some molecules to flow into and out of the cell.

Unlike other cells in the body, neurons have two types of specialized extensions of the cell membrane that allow them to communicate: dendrites and axons. **Dendrites** *receive information from other neurons and relay it to the cell body*. The term *dendrite* comes from the Greek word for "tree"; indeed, most neurons have many dendrites that look like tree branches. The **axon** *carries information to other neurons, muscles, or glands*. Axons can be very long, even stretching up to a meter from the base of the spinal cord down to the big toe.

In many neurons, the axon is covered by a **myelin sheath,** *an insulating layer of fatty material*. The myelin sheath is composed of **glial cells** (named for the Greek word for "glue"), which are *support cells found in the nervous system*. Glial cells serve a variety of roles (von Bartheld et al., 2016). Some glial cells digest parts of dead neurons, others provide physical and nutritional support for neurons, and still others form the myelin that insulates the axons of nearby neurons and allows those neurons to carry information more efficiently. In fact, *demyelinating*

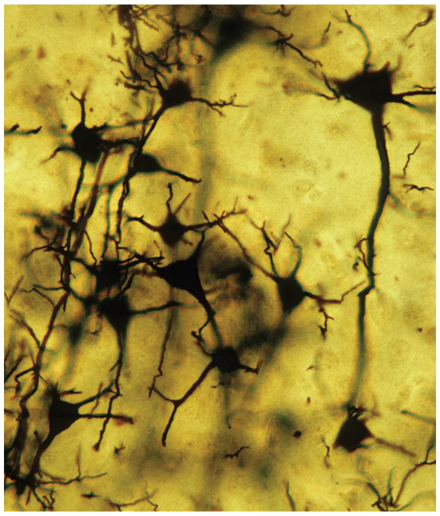

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Figure 3.1
Golgi-Stained Neurons Santiago Ramón y Cajal used a Golgi stain (like the one shown here) to highlight the appearance of neurons. He was the first to see that each neuron is composed of a body with many threads extending outward toward other neurons. In a surprising finding, he also saw that the threads of each neuron do not actually touch other neurons.

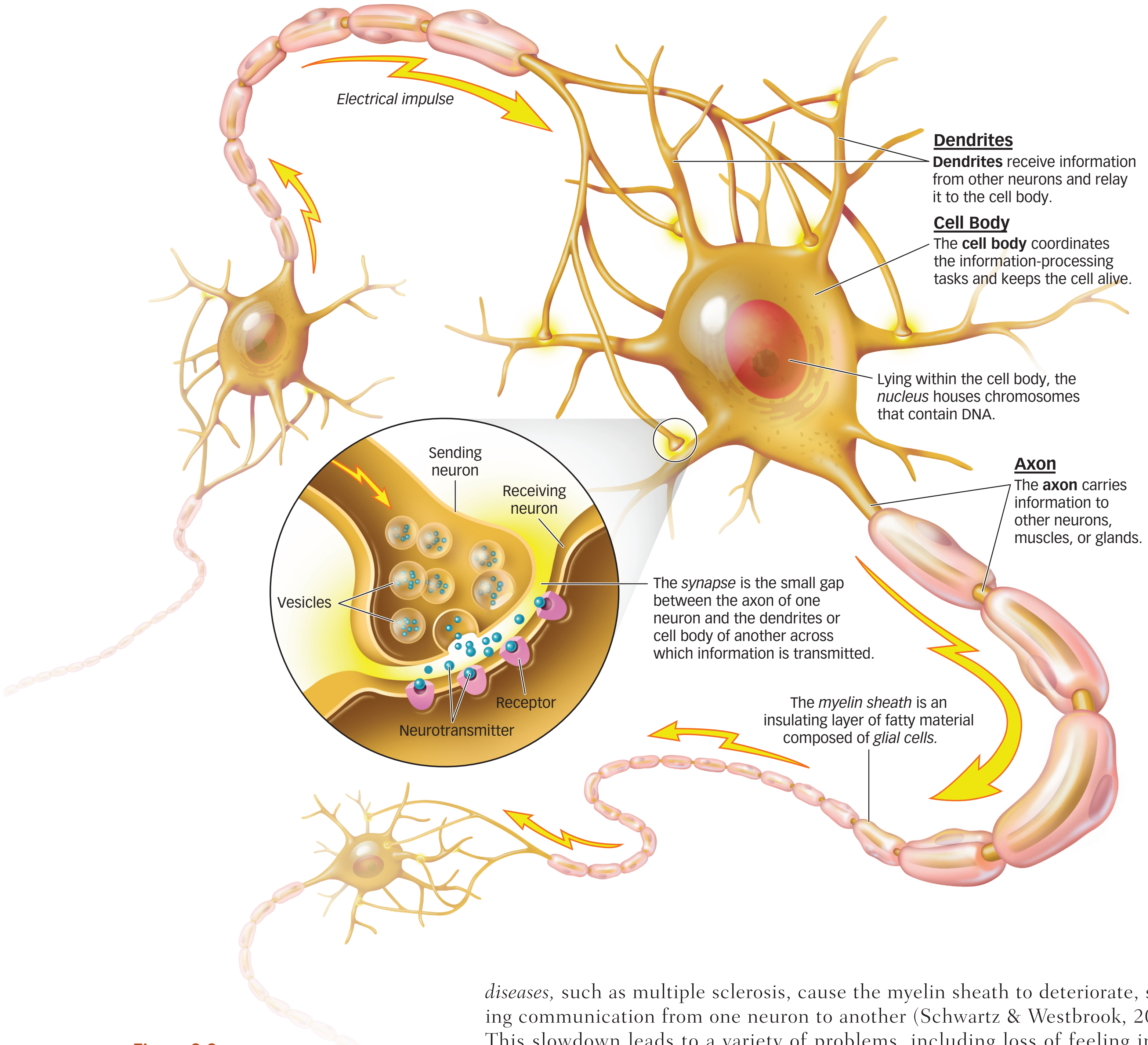

Figure 3.2
Components of a Neuron A neuron is made up of three parts: a cell body, dendrites, and an axon. Notice that neurons do not actually touch one another: There is a small synaptic space between them across which information is transmitted.

synapse The junction or region between the axon of one neuron and the dendrites or cell body of another.

diseases, such as multiple sclerosis, cause the myelin sheath to deteriorate, slowing communication from one neuron to another (Schwartz & Westbrook, 2000). This slowdown leads to a variety of problems, including loss of feeling in the limbs, partial blindness, and difficulties in coordinated movement and cognition (Butler et al., 2009).

Ramón y Cajal also observed that the dendrites and axons of neurons do not actually touch each other. There's a small gap between the axon of one neuron and the dendrites or cell body of another. This gap is part of the **synapse,** *the junction or region between the axon of one neuron and the dendrites or cell body of another* (see Figure 3.2). Many of the billions of neurons in your brain have a few thousand synaptic junctions, meaning that the adult human brain has trillions of synapses. As you'll read shortly, the transmission of information across the synapse is fundamental to communication between neurons, a process that allows us to think, feel, and behave.

Neurons Specialized by Function

There are three major types of neurons, each performing a distinct function: sensory neurons, motor neurons, and interneurons.

- **Sensory neurons** *receive information from the external world and convey this information to the brain via the spinal cord*. They have specialized endings on their dendrites that receive signals for light, sound, touch, taste, and smell. For example, the endings of sensory neurons in our eyes are sensitive to light.
- **Motor neurons** *carry signals from the spinal cord to the muscles to produce movement*. These neurons often have long axons that reach to muscles at our extremities.
- **Interneurons** *connect sensory neurons, motor neurons, or other interneurons.* Most of the nervous system is composed of the interneurons. Some carry information from sensory neurons into the nervous system, while others carry information from the nervous system to motor neurons, and still others perform a variety of information-processing functions within the nervous system.

The Electrochemical Actions of Neurons: Information Processing

Our thoughts, feelings, and actions depend on neural communication. Neurons use both electrical and chemical signals to communicate. First, an electric signal is *conducted* inside the neuron, from the dendrites to the cell body, and then down the axon. Second, a chemical signal is *transmitted* from one neuron to another, across the synapse. Together, these stages are what scientists generally refer to as the *electrochemical action* of neurons. Let's look at each stage in more detail.

Learning Outcomes

WHAT YOU NEED TO KNOW

- Describe how an electric signal moves down an axon.
- Outline the steps in synaptic transmission.
- Explain how drugs mimic neurotransmitters.

Electric Signaling: Conducting Information Inside a Neuron

The neuron's cell membrane has small pores that act as channels to allow *ions* to flow in and out of the cell. Ions are atoms or molecules that carry a small positive (+) or negative (–) electric charge. The flow of ions across the neuron's cell membrane creates the conduction of electric current within the neuron.

The Resting Potential: The Origin of the Neuron's Electrical Properties

Normally (when a neuron is "at rest"), some ions, such as positively charged potassium ions (K^+) and negatively charged protein ions (A^-), are more abundant *inside* the neuron than outside in the fluid-filled space between neurons (see **FIGURE 3.3a**). Other ions, such as positively charged sodium ions (Na^+), are more abundant *outside* the neuron. The net result is that the inside of the neuron has a slight negative electric charge, relative to the outside. This small imbalance is known as the **resting potential,** *the difference in electric charge between the inside and outside of a neuron's cell membrane*. The resting potential is usually about –70 millivolts. By comparison, a typical AA battery has about 1.5 volts (1,500 millivolts).

One reason for the difference in concentrations of ions inside and outside the neuron's cell membrane is that special channels in the cell membrane restrict the movement of the ions in and out of the cell. But, like the floodgates of Hoover Dam, which hold back the Colorado River until they are released, these channels in the

sensory neurons Neurons that receive information from the external world and convey this information to the brain via the spinal cord.

motor neurons Neurons that carry signals from the spinal cord to the muscles to produce movement.

interneurons Neurons that connect sensory neurons, motor neurons, or other interneurons.

resting potential The difference in electric charge between the inside and outside of a neuron's cell membrane.

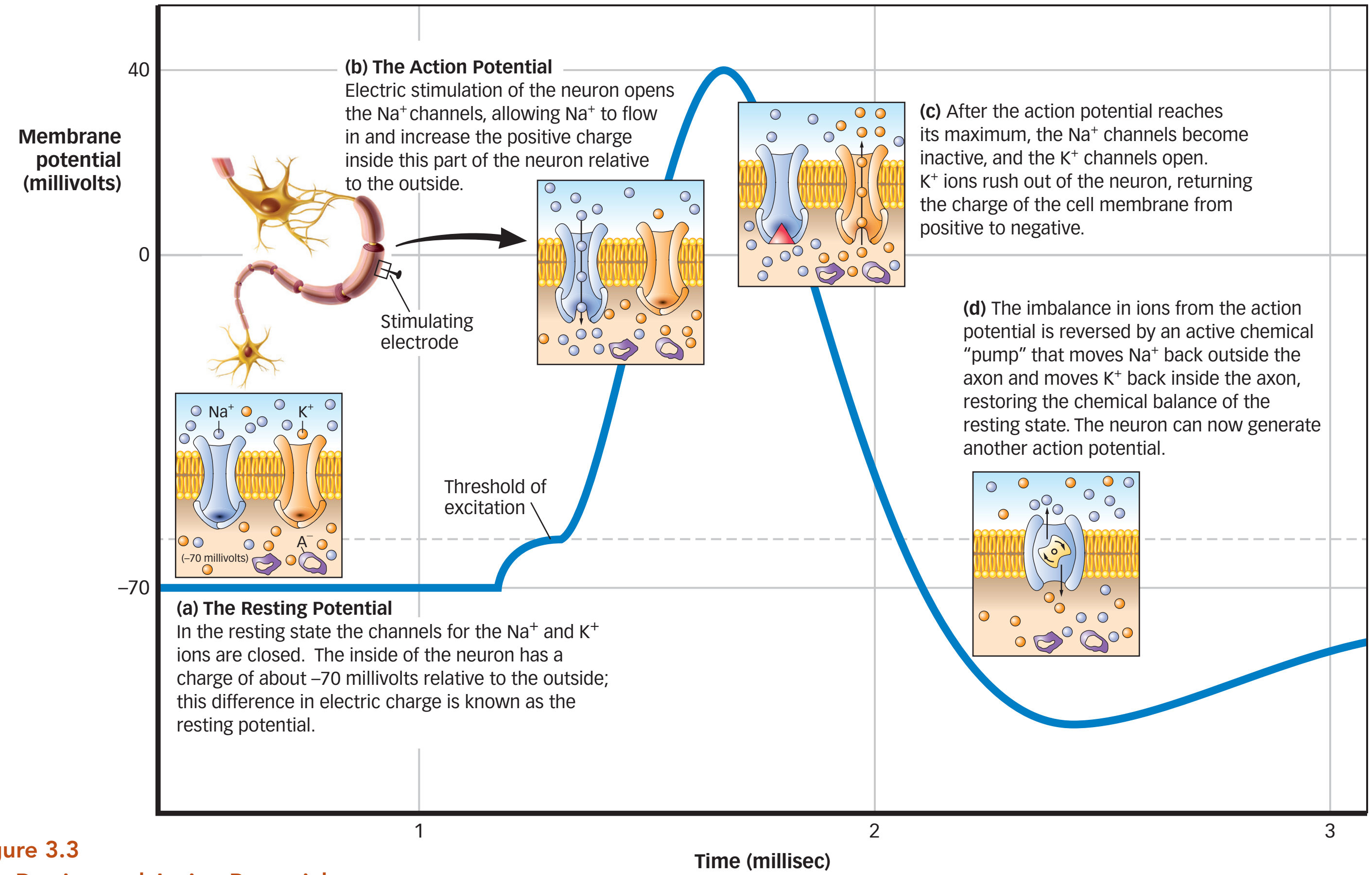

Figure 3.3
The Resting and Action Potentials Neurons have a natural electric charge called a resting potential. Electric stimulation causes an action potential.

cell membrane can be opened, allowing ions to rush across the membrane in a fraction of a second.

The Action Potential: Sending Signals Across the Neuron

When an axon is stimulated with an electric shock, it can set off a much larger electrical impulse that travels down the axon in a wave (Häusser, 2000; Hodgkin & Huxley, 1939). This electric impulse is called an **action potential,** *an electric signal that is conducted along the length of a neuron's axon to a synapse*. The action potential is a fundamental basis for just about everything that we think, feel, or do, and so it is important to understand how it works.

The action potential occurs only when the electric shock reaches a certain level, or *threshold*. Above that threshold, increases in the electric shock will *not* increase the strength of the action potential. The action potential is *all or none*: Electric stimulation below the threshold fails to produce an action potential, whereas electric stimulation at or above the threshold always produces the action potential and always at the same strength. Because of the rapid, all-or-nothing nature of an action potential, scientists sometimes say that a neuron "fires" when it produces an action potential. (By way of analogy, a revolver ejects one bullet at a constant velocity whenever the trigger is pulled with sufficient force. Pulling on the trigger with sufficient force causes the revolver to fire—but, beyond that point, extra force on the trigger will not cause the bullet to be ejected more forcefully or at greater speed; the firing event is all-or-nothing.)

action potential An electric signal that is conducted along the length of a neuron's axon to a synapse.

The Action Potential Moves Across the Neuron in a Domino Effect The action potential occurs due to changes in the axon's membrane channels. During the resting potential, the membrane channels for sodium ions are closed. However,

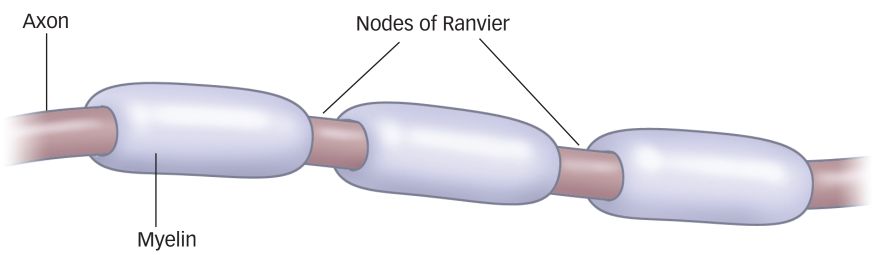

Figure 3.4
Myelin and Nodes of Ranvier Myelin is formed by a type of glial cell. It wraps around a neuron's axon to speed the movement of the action potential along the length of the axon. Breaks in the myelin sheath are called the nodes of Ranvier. The electric impulse jumps from node to node, thereby speeding the conduction of information down the axon.

when the electrical charge across the cell membrane reaches the threshold, sodium channels in that area of the cell membrane open up like the floodgate of a dam, and Na^+ ions rush in almost instantaneously (see Figure 3.3b). This inrush of positively charged ions causes the local electric charge to surge from −70 millivolts to +40 millivolts in less than one millisecond.

And this starts a domino effect. As the first Na^+ ions rush in, they spread inside the cell, increasing the electric charge in neighboring areas too. When the electric charge in those areas reaches the threshold, channels in the adjacent cell membrane open and let in more Na^+ ions, spreading the charge even farther. Just as one domino knocks over another, the influx of Na^+ ions triggers nearby channels to open, and the process repeats down the entire axon.

In many neurons, the conduction of the action potential is greatly increased by the presence of a myelin sheath around the axon. The myelin sheath prevents electric current from leaking out of the axon, in much the same way as insulation covers the wires on a power cord to keep the electric current from leaking out. Myelin clumps around the axon with little break points between clumps, looking kind of like sausage links. These breakpoints are called the *nodes of Ranvier,* after the French pathologist Louis-Antoine Ranvier, who discovered them (see **FIGURE 3.4**). The current seems to "jump" quickly from node to node (Poliak & Peles, 2003). This process helps speed the flow of information down the axon.

The action potential always spreads onward, never backward, because the Na^+ channels in each region of the axon are temporarily inactivated after the action potential passes over them, just as a domino that has already been knocked over cannot be knocked over twice. This brief period of inactivation is called a **refractory period,** *the time following an action potential during which a new action potential cannot be initiated.* During the refractory period, the electrical and chemical balance of the neuron is restored. To restore the electrical balance, Na^+ channels inactivate themselves for several milliseconds, stopping the inrush of Na^+ ions, and K^+ channels open, allowing excess K^+ ions in the cell to escape (see Figure 3.3c). The rapid exit of positively charged K^+ ions returns the electrical charge of the membrane to a negative state. Then, to restore the chemical balance, a series of special channels, called ion pumps, work to redistribute the ions (e.g., pushing all that excess Na^+ back out of the cell and pulling some K^+ back in), until the concentrations are rebalanced and the resting potential is restored (see Figure 3.3d). At this point, the dominoes are set back up—and ready to be knocked over again if triggered. The entire process is so fast that some neurons fire more than 100 times in a single second.

Chemical Signaling: Transmission Between Neurons

When the action potential reaches the end of an axon, it crosses the synaptic gap by relying on a bit of chemistry. Although a neuron has only one axon, it may have hundreds or even thousands of branches that reach out to other neurons and organs. Axons usually end in **terminal buttons,** *knoblike structures that branch out from*

refractory period The time following an action potential during which a new action potential cannot be initiated.

terminal buttons Knoblike structures that branch out from an axon.

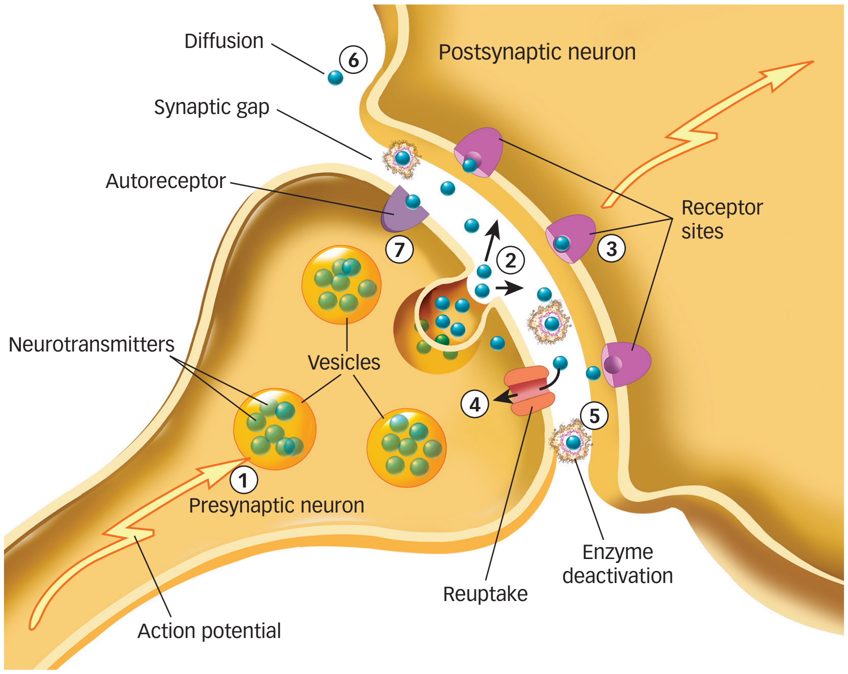

Figure 3.5
Synaptic Transmission (1) The action potential travels down the axon and (2) stimulates the release of neurotransmitters from vesicles. (3) The neurotransmitters are released into the synapse, where they float to bind with receptor sites on a postsynaptic neuron, initiating a new action potential. The neurotransmitters are cleared out of the synapse by (4) reuptake into the sending neuron, (5) being broken down by enzymes in the synapse, or (6) diffusion away from the synapse. (7) Neurotransmitters bind to autoreceptors on the sending neuron, stopping the release of more neurotransmitters.

an axon. Each terminal button is filled with tiny *vesicles* or bags that contain **neurotransmitters,** *chemicals that transmit information across the synapse to a receiving neuron's dendrites*. The dendrites of the receiving neuron contain **receptors,** *parts of the cell membrane that receive the neurotransmitter and either initiate or prevent a new electric signal*.

The action potential in the sending neuron, or *presynaptic neuron*, travels down the length of the axon to the terminal buttons, where it stimulates the release of neurotransmitters from vesicles into the synapses. The neurotransmitters quickly float across the synapse and bind to receptor sites on the nearby dendrite of the receiving neuron, or *postsynaptic neuron*. The sending and receiving of chemical neurotransmitters is called *synaptic transmission* (see **FIGURE 3.5**), and it ultimately underlies your thoughts, emotions, and behavior. When the postsynaptic neuron receives a neurotransmitter, it may activate nearby ion channels, which can either raise or lower the voltage across the membrane. Depending on the combination and timing of the neurotransmitters acting on the neuron, the voltage inside the cell body membrane may reach the threshold and trigger a new action potential. In this way, the neurotransmitters' chemical messages create an electrical signal, and the electrochemical process of neuronal communication continues.

Neurotransmitters and receptor sites act like a lock-and-key system. Just as a particular key will fit only in a particular lock, so too will only some neurotransmitters bind to specific receptor sites on a dendrite. The molecular structure of the neurotransmitter must fit the molecular structure of the receptor site.

After the chemical message is relayed to the postsynaptic neuron, the neurotransmitters must stop acting on neurons; otherwise, there would be no end to the signals that they send. Neurotransmitters leave the synapse through three processes (see Figure 3.5).

1. *Reuptake* occurs when neurotransmitters are absorbed by the terminal buttons of the presynaptic neuron's axon or by neighboring glial cells.
2. Neurotransmitters can be destroyed by enzymes in the synapse in a process called *enzyme deactivation,* in which specific enzymes break down specific neurotransmitters.
3. *Diffusion* occurs when neurotransmitters drift out of the synapse and can no longer reach receptors.

Neurotransmitters can also bind to receptor sites on the presynaptic neuron called *autoreceptors*. Autoreceptors detect how much of a neurotransmitter has been released into a synapse and may stop the release of more.

neurotransmitters Chemicals that transmit information across the synapse to a receiving neuron's dendrites.

receptors Parts of the cell membrane that receive the neurotransmitter and either initiate or prevent a new electric signal.

Types and Functions of Neurotransmitters

You might wonder how many types of neurotransmitters are floating across synapses in your brain right now. Today, we know of more than 100, each of which affect thought, feeling, and behavior in different ways. A few major classes of neurotransmitters play key roles in certain fundamental behaviors. We'll summarize those here, and you'll encounter some of these neurotransmitters again in later chapters.

- *Acetylcholine (ACh)* is a neurotransmitter involved in a number of functions, including voluntary motor control. Acetylcholine also contributes to the regulation of attention, learning, sleeping, dreaming, and memory (Gais & Born, 2004; Hasselmo, 2006; Wrenn et al., 2006). Alzheimer's disease, a medical condition involving severe memory impairments (Salmon & Bondi, 2009), is associated with the deterioration of ACh-producing neurons.
- *Dopamine* is a neurotransmitter that regulates motor behavior, motivation, pleasure, and emotional arousal. Because of its role in basic motivated behaviors, such as seeking pleasure or associating actions with rewards, dopamine plays a role in drug addiction (Baler & Volkow, 2006). High levels of dopamine in some brain pathways are linked to schizophrenia (Winterer & Weinberger, 2004), whereas low levels in other areas are linked to Parkinson's disease.
- *Glutamate* is the major excitatory neurotransmitter in the brain, meaning that it enhances the transmission of information between neurons. *GABA (gamma-aminobutyric acid)*, in contrast, is the primary inhibitory neurotransmitter in the brain, meaning that it tends to prevent the firing of neurons. Too much glutamate, or too little GABA, can cause neurons to become overactive, causing seizures.
- Two related neurotransmitters influence mood and arousal: norepinephrine and serotonin. *Norepinephrine* is involved in states of vigilance, or heightened awareness of dangers in the environment (Ressler & Nemeroff, 1999). *Serotonin* is involved in the regulation of sleep and wakefulness, eating, and aggressive behavior (Dayan & Huys, 2009; Kroeze & Roth, 1998). Because both neurotransmitters affect mood and arousal, low levels of each have been implicated in mood disorders such as depression (Tamminga et al., 2002).
- *Endorphins* are chemicals that act within the pain pathways and emotion centers of the brain (Keefe et al., 2001). Endorphins help dull the experience of pain and elevate moods. The "runner's high" experienced by many athletes as they push their bodies to painful limits of endurance can be explained by the release of endorphins in the brain (Boecker et al., 2008).


SAM BARNES/GETTY IMAGES

When long-distance runners complete a marathon, they may experience the subjective highs that result from the release of endorphins—chemical messengers acting in emotion and pain centers that elevate mood and dull the experience of pain.

Each of these neurotransmitters affects thought, feeling, and behavior in different ways, so typical functioning involves a delicate balance of each. Even a slight imbalance—too much of one neurotransmitter or not enough of another—can dramatically affect behavior. People who smoke, drink alcohol, or take drugs (legal or not) are altering the balance of neurotransmitters in their brains.

How Drugs Mimic Neurotransmitters

Many drugs that affect the nervous system operate by increasing, interfering with, or mimicking the manufacture or function of neurotransmitters (Cooper et al., 2003; Sarter, 2006). **Agonists** are *drugs that increase the action of a neurotransmitter*. **Antagonists** are *drugs that diminish the function of a neurotransmitter.*

agonists Drugs that increase the action of a neurotransmitter.

antagonists Drugs that diminish the function of a neurotransmitter.

For example, the drug L-dopa is used to treat Parkinson's disease, a movement disorder characterized by tremors and difficulty initiating movement. Parkinson's disease is caused by the loss of neurons that make the neurotransmitter dopamine by modifying L-dopa produced naturally in the body. Ingesting L-dopa as a drug elevates its concentration in the brain and spurs the surviving neurons to produce more dopamine. In other words, L-dopa acts as an agonist for dopamine by increasing its production. The use of L-dopa has been reasonably successful in the alleviation of Parkinson's disease symptoms (Muenter & Tyce, 1971; Schapira et al., 2009).


RON SACHS/CNP/MEDIAPUNCH INC/ ALAMY STOCK PHOTO

Muhammad Ali and Michael J. Fox have increased public awareness of Parkinson's disease and spurred greater efforts toward finding a cure.

Another antagonist, *amphetamine,* stimulates the release of norepinephrine and dopamine and also blocks their reuptake. Norepinephrine and dopamine play a critical role in mood control, such that an increase in either neurotransmitter results in euphoria, wakefulness, and a burst of energy. However, norepinephrine also increases heart rate. An overdose of amphetamine can cause the heart to contract so rapidly that heartbeats do not last long enough to pump blood effectively, leading to fainting and sometimes death.

Opioids are a class of drugs either derived naturally from the opium poppy (such as morphine and heroin) or made synthetically (such as oxycodone and fentanyl). Most opioids work in part by acting as agonists for endorphins, which creates powerful feelings of calm and euphoria. Opioids have been widely prescribed for pain relief because they are also highly effective at decreasing the perception of pain. At the same time, opioids also diminish the brainstem's sensitivity to rising levels of carbon dioxide in the blood, which depresses breathing. Opioid overdose can lead to asphyxiation and death. Opioids are also highly addictive. In 2017, the Centers for Disease Control estimated that 115 people in the United States die from an opioid overdose every day.

These are just a few examples of the many drugs, natural and synthetic, legally prescribed and illegally used, that mimic neurotransmitters. You'll meet more of these later, in the Treatment of Psychological Disorders chapter.

The Organization of the Nervous System

Learning Outcomes

WHAT YOU NEED TO KNOW

- Differentiate the functions of the central and peripheral nervous systems.
- Understand the nature of the spinal reflex.

We've seen how individual neurons communicate with each other. What's the bigger picture? Neurons are the building blocks that form *nerves*, or bundles of axons and the glial cells that support them. The **nervous system** is *an interacting network of neurons that conveys electrochemical information throughout the body.* There are two major divisions of the nervous system: the central nervous system and the peripheral nervous system (see **FIGURE 3.6**). The **central nervous system (CNS)** is *the part of the nervous system composed of the brain and spinal cord.* It receives sensory information from the external world, processes and coordinates this information, and sends commands to the skeletal and muscular systems for action. The **peripheral nervous system (PNS)** is *the part of the nervous system that connects the central nervous system to the body's organs and muscles.* Let's examine each more closely.

nervous system An interacting network of neurons that conveys electrochemical information throughout the body.

central nervous system (CNS) The part of the nervous system composed of the brain and spinal cord.

peripheral nervous system (PNS) The part of the nervous system that connects the central nervous system to the body's organs and muscles.

somatic nervous system A part of the PNS that conveys information between skeletal muscles and the central nervous system.

autonomic nervous system (ANS) A part of the PNS that carries involuntary and automatic commands that control blood vessels, body organs, and glands.

The Peripheral Nervous System

The peripheral nervous system is composed of two major subdivisions, the somatic nervous system and the autonomic nervous system. The **somatic nervous system** is *a set of nerves that conveys information between skeletal muscles and the central nervous system*. Humans have conscious control over this system and use it to perceive, think, and coordinate their behaviors. For example, reaching for your morning cup of coffee involves the elegantly orchestrated activities of the somatic nervous system: Information from the receptors in your eyes travels to your brain, registering that a cup is on the table; signals from your brain travel to the muscles in your arm and hand; feedback from those muscles tells your brain that the cup has been grasped, and so on.

In contrast, the **autonomic nervous system (ANS)** is *a set of nerves that carries involuntary and automatic commands that control blood vessels, body organs, and glands*. As suggested by its name, this system works on its own ("autonomously") to regulate bodily systems, largely outside of conscious control. The ANS has two major subdivisions, the sympathetic nervous system and the parasympathetic nervous system. Each exerts a different type of control on the body.