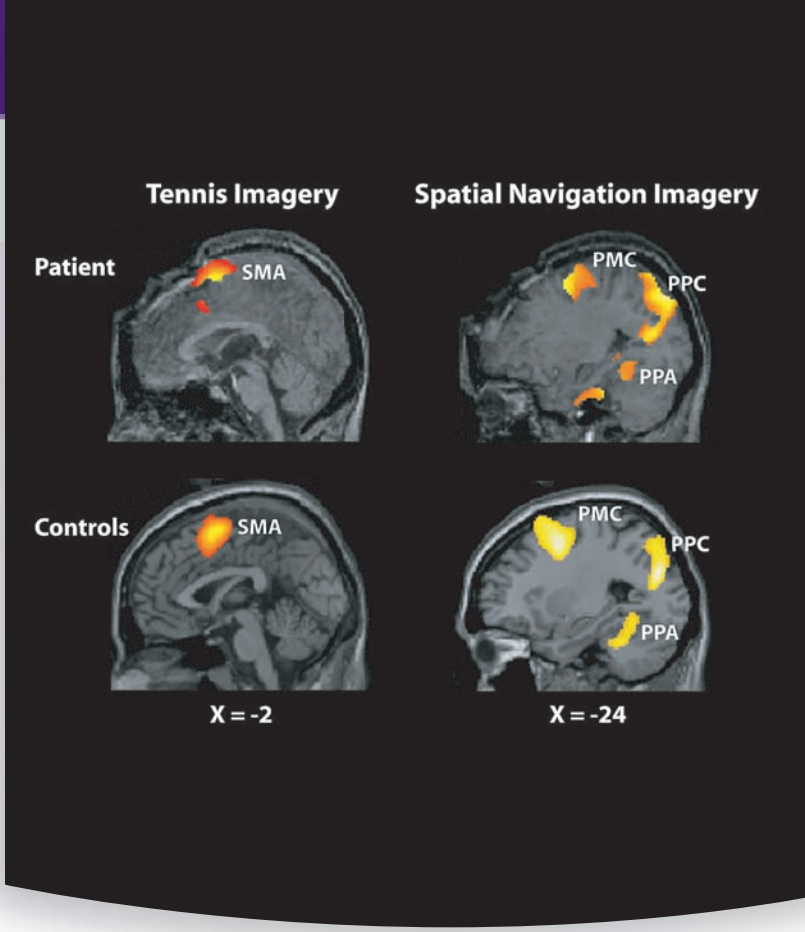
9 Nervous System



A woman who had suffered brain injury in a traffic accident and was in a persistent vegetative state was asked to imagine herself playing tennis and walking through the rooms of her home, while undergoing neuroimaging with functional MRI. The patterns in which her brain lit up matched those of 12 healthy individuals as they completed the same tasks.

"ISLANDS OF AWARENESS" IN THE VEGETATIVE BRAIN. The 23-year-old had been in a persistent vegetative state for five months after sustaining traumatic brain injury in a car accident. She was awake, but apparently not aware, and unable to communicate in any way. To an observer, she had no sense of her own existence and did not react to sight or sound. But British researchers decided to take a different type of look at the young woman—from her point of view.

The investigators used functional MRI (fMRI), a form of neuroimaging that measures regional blood flow. If a patient in a persistent vegetative state is given a particular stimulus, and the appropriate part of the brain lights up, then perhaps she is responding—just not in a way that can be directly observed. This is exactly what happened with the young accident victim. In a preliminary experiment, fMRI tracked her response to speech. First she heard a sentence that made sense, and then a sentence that had the same cadence as the first but was all nonsense words. Her brain lit up, in the speech-processing centers, only when the sentence had meaning. When she heard a sentence that included a homonym—a word that could have either of two meanings—an additional brain region lit up, presumably because she had to choose the correct meaning. Then the researchers asked her to imagine herself in two settings: playing tennis and walking through all of the rooms of her house. Healthy individuals asked the same questions served as controls. Both the young woman's brain and the control brains lit up in exactly the same areas.

The researchers had identified what they called "islands of awareness" in the brain of this supposedly completely unaware young woman. Although she did not have the most severe degree of brain injury, and her brain may not be able to coordinate those islands of awareness, the study suggests that neuroimaging may be a valuable tool in assessing consciousness in people who cannot communicate their self-awareness.

Learning Outcomes

After studying this chapter, you should be able to do the following:

9.1 Introduction

1. Distinguish between the two types of cells that comprise nervous tissue. (p. 212)
2. Name the two major groups of nervous system organs. (p. 212)

9.2 General Functions of the Nervous System

3. Explain the general functions of the nervous system. (p. 213)

9.3 Neuroglial Cells

4. State the functions of neuroglial cells in the central nervous system. (p. 214)
5. Distinguish among the types of neuroglial cells in the central nervous system. (p. 214)
6. Describe the Schwann cells of the peripheral nervous system. (p. 214)

9.4 Neurons

7. Describe the general structure of a neuron. (p. 214)
8. Explain how differences in structure and function are used to classify neurons. (p. 218)

9.5 The Synapse

9. Explain how information passes from one neuron to another. (p. 220)

9.6 Cell Membrane Potential

10. Explain how a membrane becomes polarized. (p. 221)
11. Describe the events that lead to the conduction of a nerve impulse. (p. 224)

9.7 Nerve Impulses

12. Compare nerve impulse conduction in myelinated and unmyelinated neurons in terms of the all-or-none response. (p. 225)

9.8 Synaptic Transmission

13. Identify the changes in membrane potential associated with excitatory and inhibitory neurotransmitters. (p. 225)

9.9 Impulse Processing

14. Describe the general ways in which the nervous system processes information. (p. 227)

9.10 Types of Nerves

15. Describe how nerve fibers in peripheral nerves are classified. (p. 228)

9.11 Nerve Pathways

16. Describe the function of each part of a reflex arc, and name two reflex examples. (p. 228)

9.12 Meninges

17. Describe the coverings of the brain and spinal cord. (p. 230)

9.13 Spinal Cord

18. Describe the structure of the spinal cord and its major functions. (p. 232)

9.14 Brain

19. Name the major parts and functions of the brain. (pp. 234–242)
20. Distinguish among motor, sensory, and association areas of the cerebral cortex. (p. 237)
21. Describe the location, formation, and function of cerebrospinal fluid. (p. 238)

9.15 Peripheral Nervous System

22. List the major parts of the peripheral nervous system. (p. 242)
23. Name the cranial nerves, and list their major functions. (p. 243)
24. Describe the structure of a spinal nerve. (p. 248)

9.16 Autonomic Nervous System

25. Describe the functions of the autonomic nervous system. (p. 248)
26. Distinguish between the sympathetic and parasympathetic divisions of the autonomic nervous system. (p. 249)
27. Describe a sympathetic and a parasympathetic nerve pathway. (p. 249)

Aids to Understanding Words

(Appendix A on page 567 has a complete list of Aids to Understanding Words.)

ax- [axis] *ax*on: Cylindrical nerve fiber that carries impulses away from a neuron cell body.

dendr- [tree] *dendr*ite: Branched nerve cell process that serves as a receptor surface of a neuron.

funi- [small cord or fiber] *funi*culus: Major nerve tract or bundle of myelinated nerve cell axons within the spinal cord.

gangli- [a swelling] *gangli*on: Mass of neuron cell bodies.

-lemm [rind or peel] neuri*lemm*a: Sheath that surrounds the myelin of a nerve cell axon.

mening- [membrane] *mening*es: Membranous coverings of the brain and spinal cord.

moto- [moving] *moto*r neuron: Neuron that stimulates a muscle to contract or a gland to secrete.

peri- [around] *peri*pheral nervous system: Portion of the nervous system that consists of nerves branching from the brain and spinal cord.

plex- [interweaving] choroid *plex*us: Mass of specialized capillaries associated with spaces in the brain.

sens- [feeling] *sens*ory neuron: Neuron that conducts impulses into the brain or spinal cord.

syn- [together] *syn*apse: Junction between two neurons.

ventr- [belly or stomach] *ventr*icle: Fluid-filled space within the brain.

9.1 INTRODUCTION

Feeling, thinking, remembering, moving, and being aware of the world require activity from the nervous system. This vast collection of cells also helps coordinate all other body functions to maintain homeostasis and to enable the body to respond to changing conditions. Information from within and outside the body is brought to the brain and spinal cord, which then stimulates responses from muscles and glands.

Recall from chapter 5 (p. 111) that nervous tissue consists of masses of nerve cells, or **neurons.** These cells are the structural and functional units of the nervous system and are specialized to react to physical and chemical changes in their surroundings (fig. 9.1). Neurons transmit information in the form of electrochemical changes, called **nerve impulses,** to other neurons and to cells outside the nervous system.

Neurons typically have a rounded area called the **cell body,** and two types of extensions: dendrites and axons. **Dendrites,** which may be numerous, receive electrochemical messages. **Axons** are extensions that send information in the form of nerve impulses. Usually a neuron has only one axon. Figure 9.1 depicts these major parts of a neuron.

Nerves are bundles of axons. Nervous tissue also includes **neuroglial cells** that provide physical support, insulation, and nutrients for neurons. During development before birth, neuroglial cells release and relay signals that guide the differentiation of neurons from progenitor cells (see chapter 3, p. 70).

The organs of the nervous system can be divided into two groups. One group, consisting of the brain and spinal cord, forms the **central nervous system (CNS).** The other, composed of the nerves (peripheral nerves) that connect the central nervous system to other body parts, is called the **peripheral nervous system (PNS)** (fig. 9.2). Together, these systems provide three general functions: sensory, integrative, and motor.

Check Your Recall

1. What are the two major types of cells that form nervous tissue?
2. What are the two major subdivisions of the nervous system?

9.2 GENERAL FUNCTIONS OF THE NERVOUS SYSTEM

The *sensory function* of the nervous system derives from **sensory receptors** (sen′so-re re-sep′torz) at the ends of peripheral neurons (see chapter 10, p. 261). These receptors gather information by detecting changes inside and outside the body. Sensory receptors monitor external environmental factors, such as light and sound intensities, and conditions of the body's internal environment, such as temperature and oxygen level.

Sensory receptors convert environmental information into nerve impulses, which are then transmitted over peripheral nerves to the central nervous system. There, the signals are integrated; that is, they are brought together, creating sensations, adding to memory, or helping produce thoughts that translate sensations into

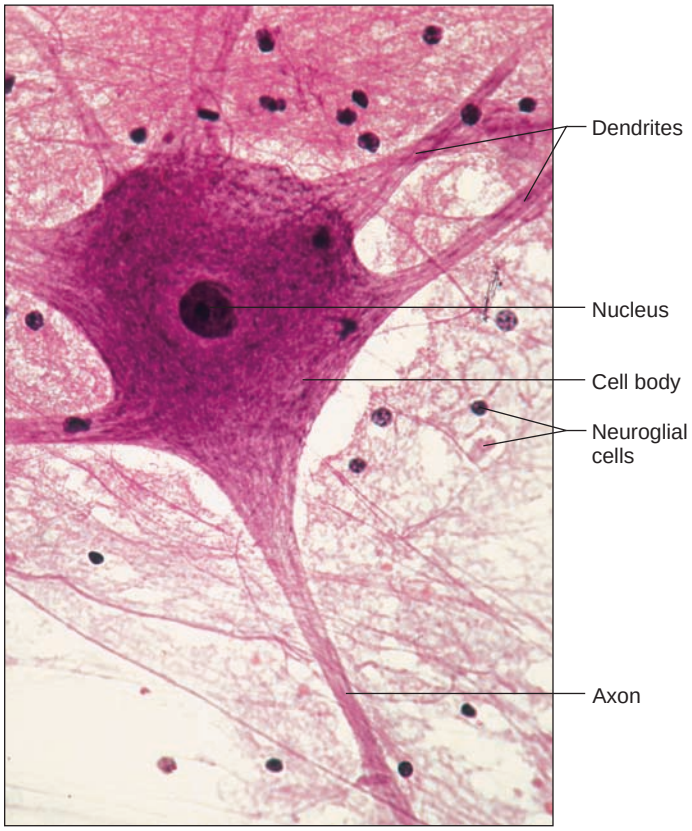


Figure 9.1
Neurons are the structural and functional units of the nervous system (600×). The dark spots in the area surrounding the neuron are neuroglial cells. Note the dendrites and the single axon of the neuron.

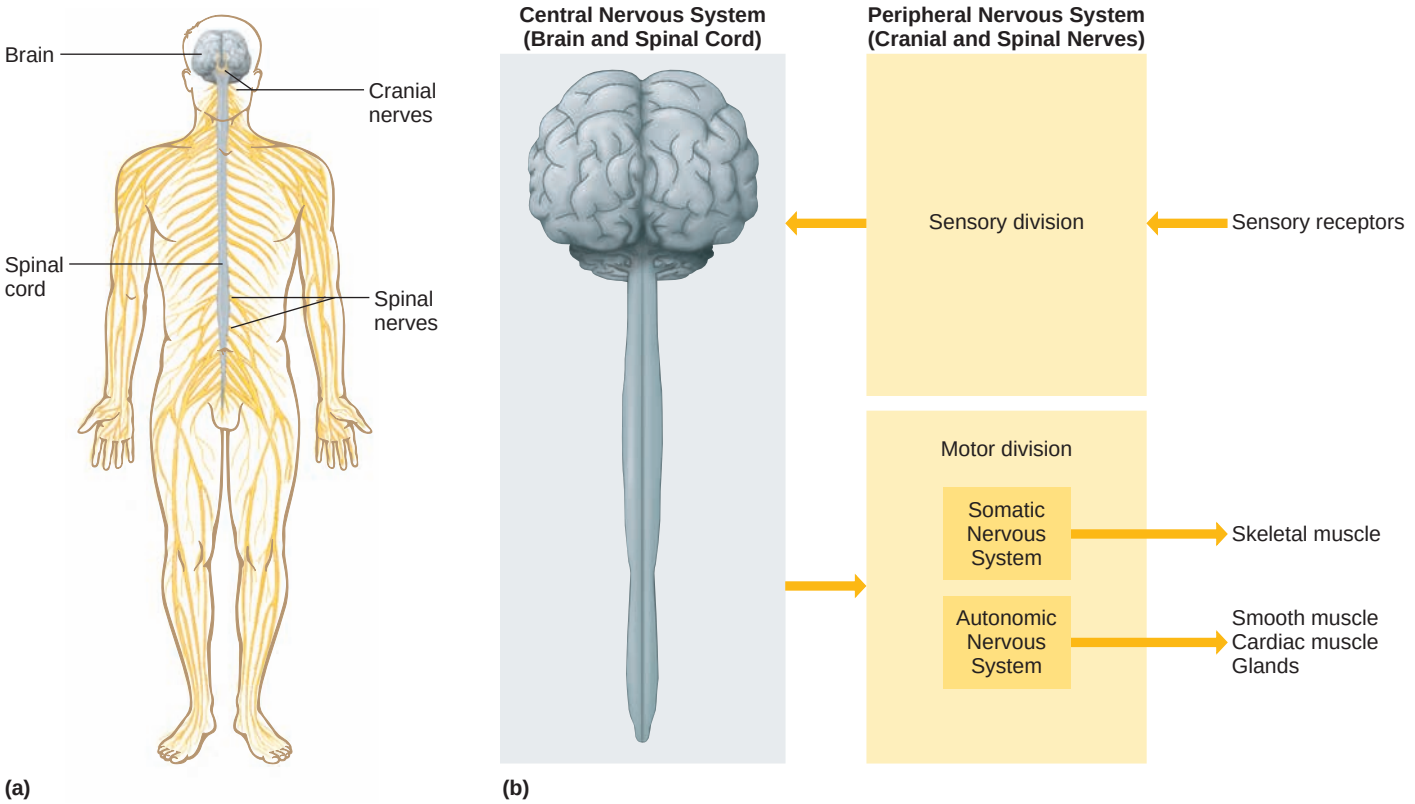


Figure 9.2
Nervous system. (*a*) The nervous system includes the central nervous system (brain and spinal cord) and the peripheral nervous system (cranial nerves and spinal nerves). (*b*) The nervous system receives information from sensory receptors and initiates responses through effector organs (muscles and glands).

perceptions. As a result of this *integrative function,* we make conscious or subconscious decisions, and then we use *motor functions* to act on them.

The motor functions of the nervous system employ peripheral neurons, which carry impulses from the central nervous system to responsive structures called **effectors** (e-fek′torz). Effectors, which are outside the nervous system, include muscles that contract and glands that secrete when stimulated by nerve impulses.

The motor functions of the peripheral nervous system can be divided into two categories. Those that are consciously controlled comprise the **somatic nervous system,** which controls skeletal muscle. In contrast, the **autonomic nervous system** controls effectors that are involuntary, such as the heart, smooth muscle in blood vessels, and various glands.

The nervous system can detect changes outside and within the body, make decisions based on the information received, and stimulate muscles or glands to respond. Typically, these responses counteract the effects of the changes detected, and in this way, the nervous system helps maintain homeostasis.

Check Your Recall

3. How do sensory receptors collect information?
4. How does the central nervous system integrate incoming information?
5. What are the two types of motor functions of the nervous system?

9.3 NEUROGLIAL CELLS

Neurons cannot exist without neuroglial cells (neuroglia), which fill spaces, provide structural frameworks, produce the components of the electrical insulator **myelin** (mi′ĕ-lin), and carry on phagocytosis. In the central nervous system, neuroglial cells greatly outnumber neurons, and can divide, whereas neurons do not normally divide. Neuroglia are of the following types (fig. 9.3):

1. **Microglial cells** are scattered throughout the central nervous system. They support neurons and phagocytize bacterial cells and cellular debris.
2. **Oligodendrocytes** align along nerve fibers. They provide insulating layers of myelin, called a *myelin sheath,* around axons within the brain and spinal cord.
3. **Astrocytes,** commonly found between neurons and blood vessels, provide structural support, join parts by their abundant cellular processes, and help regulate the concentrations of nutrients and ions within the tissue. Astrocytes also form scar tissue that fills spaces following injury to the CNS.
4. **Ependymal cells** form an epithelia-like membrane that covers specialized brain parts (choroid plexuses) and forms the inner linings that enclose spaces within the brain (ventricles) and spinal cord (central canal).

The peripheral nervous system includes neuroglial cells called **Schwann cells** that form a myelin sheath around axons.

Excess neuroglial cells can harm health. Fast-growing gliomas are brain tumors consisting of rapidly-dividing neuroglia (neurons do not divide). Immediately after a spinal cord injury, destruction of neuroglia strips axons of myelin. Subsequent overgrowth of neuroglia forms scars, which impede recovery of function.

In most of the body, capillaries (the smallest blood vessels) are "leaky," allowing small molecules to enter or leave the bloodstream. The cells that form capillaries in the brain, in contrast, are much more tightly connected, thanks partly to astrocytes. This specialized architecture creates a "blood–brain barrier" that shields delicate brain tissue from chemical fluctuations, blocking entry to many substances. The barrier can allow for selective drug delivery, such as preventing some antihistamines from entering the brain so they do not cause drowsiness. But this presents a trade-off—many drugs needed to treat the brain cannot get there.

Check Your Recall

6. List the functions of the cells that support neurons.
7. Distinguish among the types of neuroglial cells in the central nervous system.
8. What is the function of Schwann cells in the peripheral nervous system?

9.4 NEURONS

Neuron Structure

Neurons vary considerably in size and shape, but they all have common features. These include a cell body; the tubular, cytoplasm-filled dendrites, which conduct nerve impulses to the neuron cell body; and an axon, which conducts impulses away.

The neuron cell body consists of granular cytoplasm, a cell membrane, and organelles such as mitochondria, lysosomes, a Golgi apparatus, and a network of fine threads called **neurofibrils** (nu″ro-fi′brilz), which extends into the axon. Scattered throughout the cytoplasm are many membranous sacs called **chromatophilic substance**

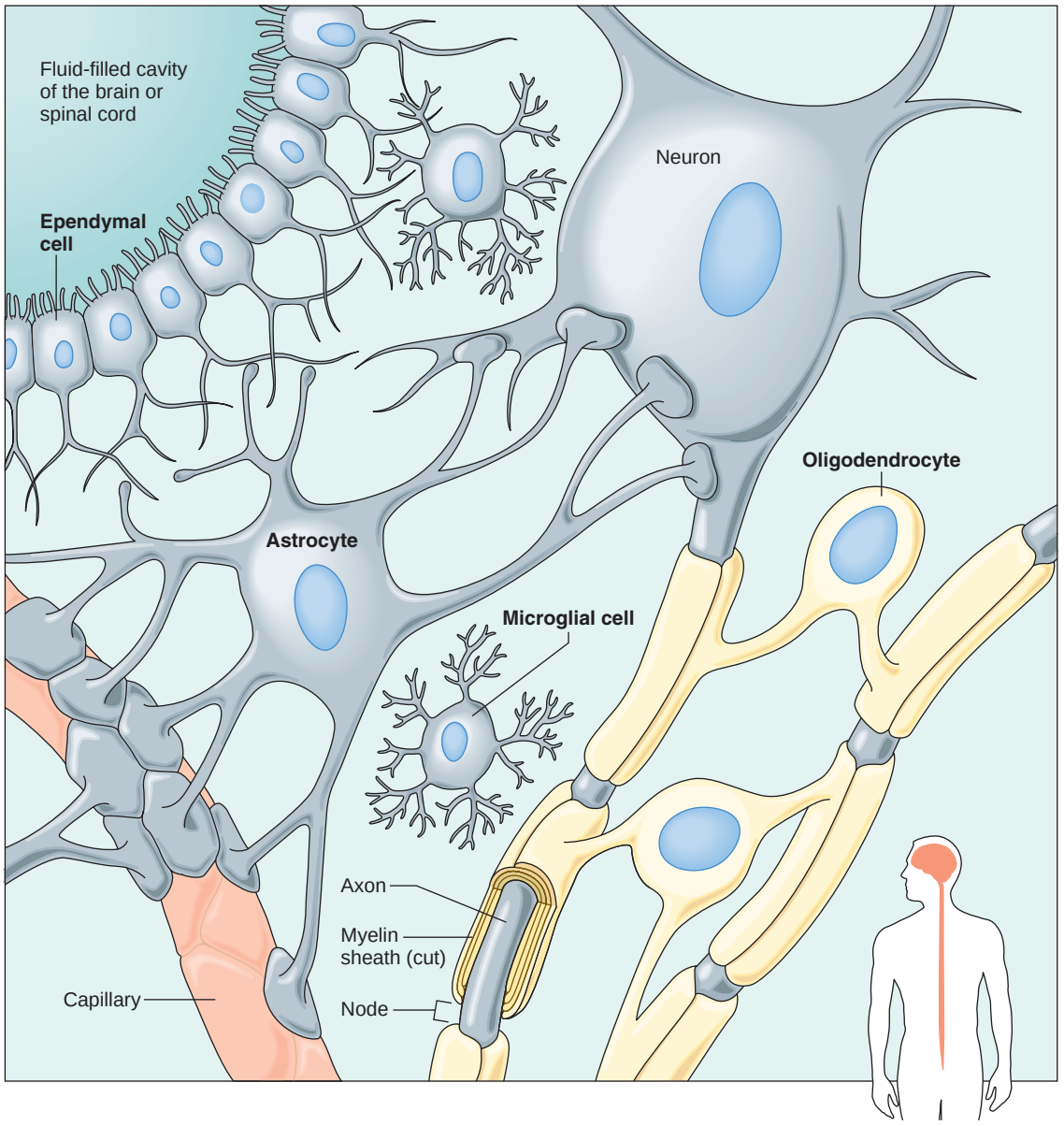


Figure 9.3

Types of neuroglial cells in the central nervous system include the microglial cell, oligodendrocyte, astrocyte, and ependymal cell. (Ependymal cells have cilia into early childhood. In adults, cilia remain only on ependymal cells in the ventricles of the brain.)

(Nissl bodies). These are similar to rough endoplasmic reticulum in other cells (fig. 9.4). Ribosomes attached to chromatophilic substance function in protein synthesis, as they do elsewhere. Near the center of the cell body is a large, spherical nucleus with a conspicuous nucleolus.

Dendrites are usually short and highly branched. These processes, together with the membrane of the cell body, are the neuron's main receptive surfaces with which axons from other neurons communicate.

In most neurons the axon arises from a slight elevation of the cell body called the *axonal hillock*. The axon conducts nerve impulses away from the cell body. Many mitochondria, microtubules, and neurofibrils are in the axon cytoplasm. An axon originates as a single structure but may give off side branches (collaterals). Its end may branch into many fine extensions that contact the receptive surfaces of other cells.

Larger axons of peripheral neurons are enclosed in **myelin sheaths** (mi′ĕ-lin shēthz) produced by Schwann cells (figs. 9.4 and 9.5). These cells wind tightly around axons, somewhat like a bandage wrapped around a finger, coating them with many layers of cell membrane that have little or no cytoplasm between them. The portions of the Schwann cells that contain most of the cytoplasm and the nuclei remain outside the myelin sheath and comprise a **neurilemma** (nu″rĭ-lem′ah),

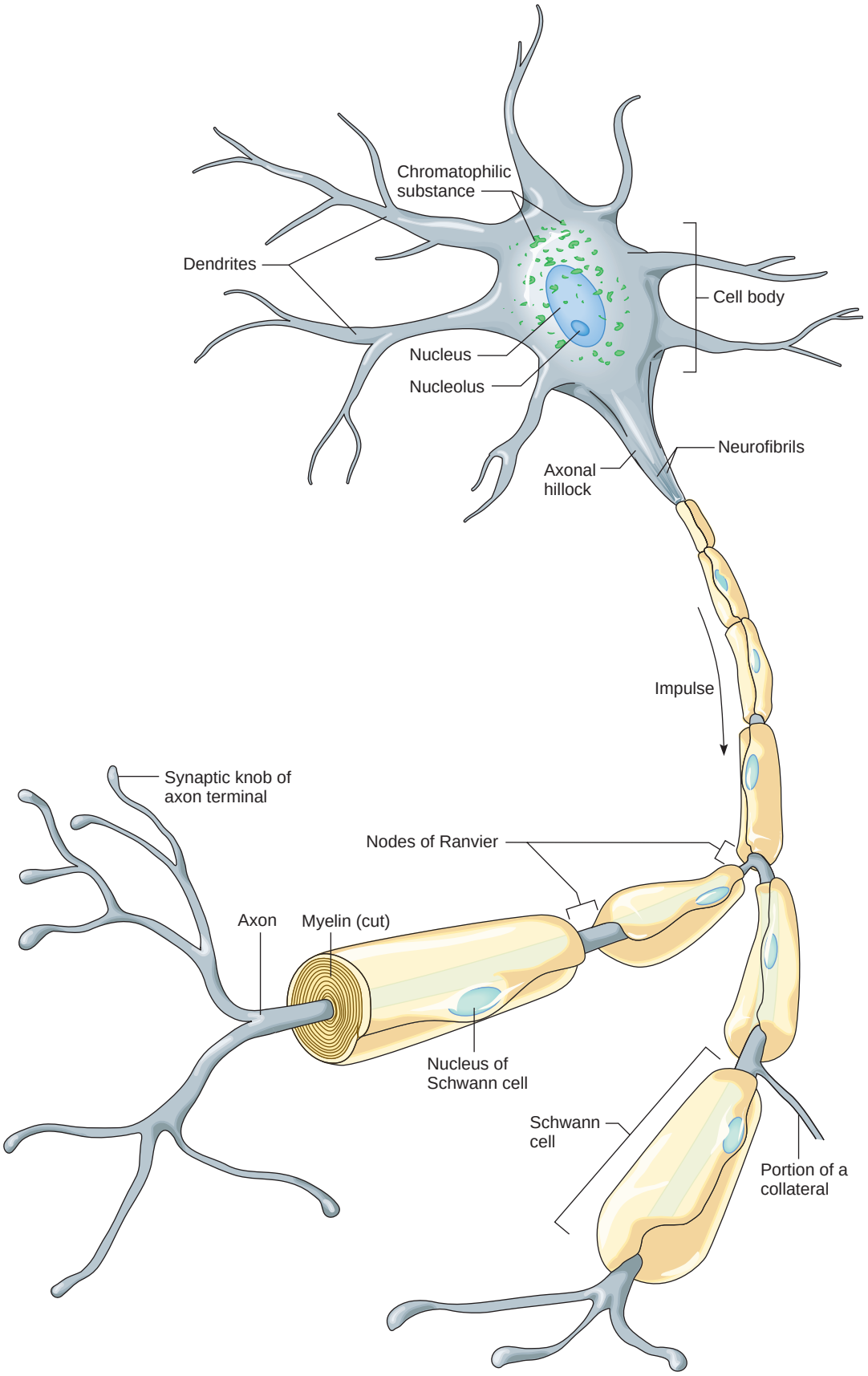


Figure 9.4
A common neuron.

or neurilemmal sheath, which surrounds the myelin sheath. Narrow gaps between Schwann cells are called **nodes of Ranvier** (nō-dz uv ron′vee-ay) (fig. 9.5).

Axons with myelin sheaths are called *myelinated,* and those that lack sheaths are *unmyelinated.* Myelin is also found in the CNS, where groups of myelinated axons appear white, and masses of such axons form the *white matter.* Unmyelinated axons and neuron cell bodies form *gray matter* within the CNS.

Myelin begins to form on axons during the fourteenth week of prenatal development. Yet many of the axons in newborns are not completely myelinated. As a result, an infant's nervous system cannot function as effectively as that of an older child or adult. Infants' responses to stimuli are coarse and undifferentiated, and may involve the whole body. All myelinated axons begin to develop sheaths by the time a child starts to walk, and myelination continues into adolescence. Deficiencies of essential nutrients during the developmental years may limit myelin formation, which may impair nervous system function later in life.

When peripheral nerves are damaged, their axons can regenerate. The neurilemma plays an important role in this process. In contrast, CNS axons are myelinated by oligodendrocytes, which do not provide a neurilemma. Damaged CNS neurons usually do not regenerate.

The brain harbors small collections of neural stem cells that can divide to give rise to new neurons or neuroglial cells, depending upon their chemical surroundings. Neural stem cells are found in the hippocampus and near the brain's ventricles.

To picture the relative sizes of a typical neuron's parts, imagine that the cell body is the size of a tennis ball. The axon would then be a mile long and half an inch thick. The dendrites would fill a large bedroom.

Classification of Neurons

Neurons differ in the structure, size, and shape of their cell bodies. They also vary in the length and size of their axons and dendrites and in the number of connections they make with other neurons.

On the basis of structural differences, neurons are classified into three major groups (fig. 9.6). Each type of neuron is specialized to send a nerve impulse in one direction.

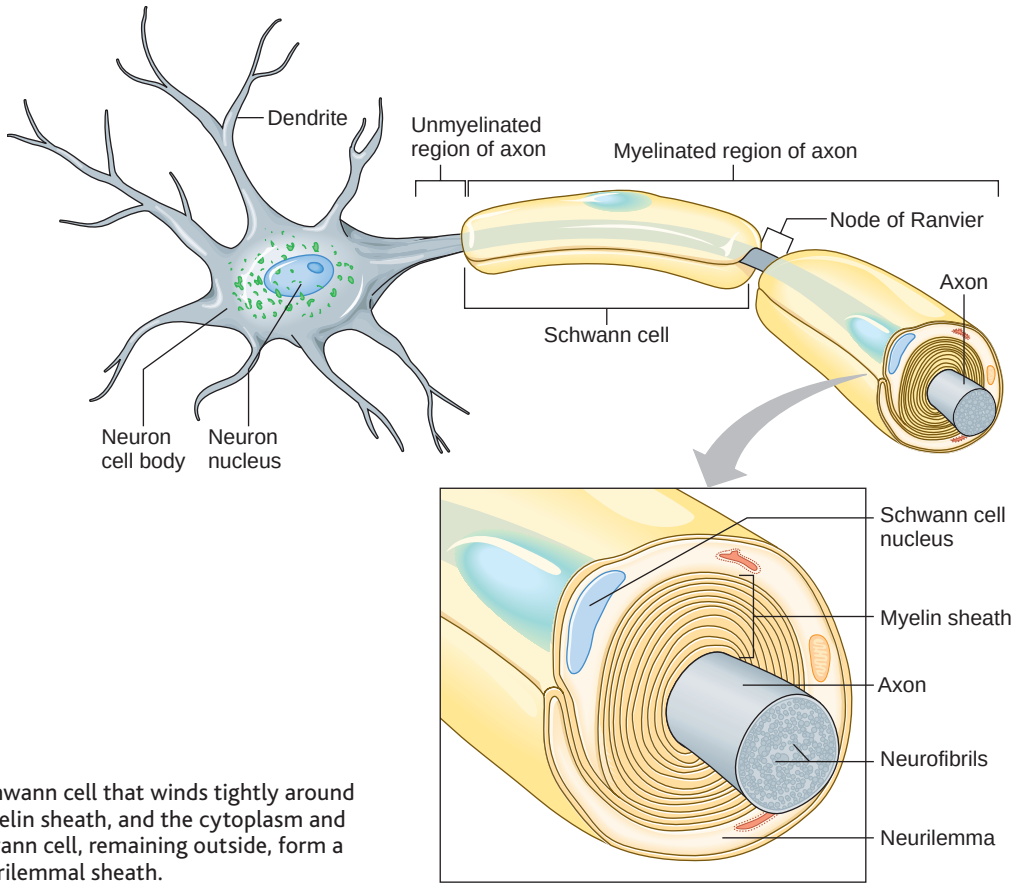


Figure 9.5
The portion of a Schwann cell that winds tightly around an axon forms a myelin sheath, and the cytoplasm and nucleus of the Schwann cell, remaining outside, form a neurilemma, or neurilemmal sheath.

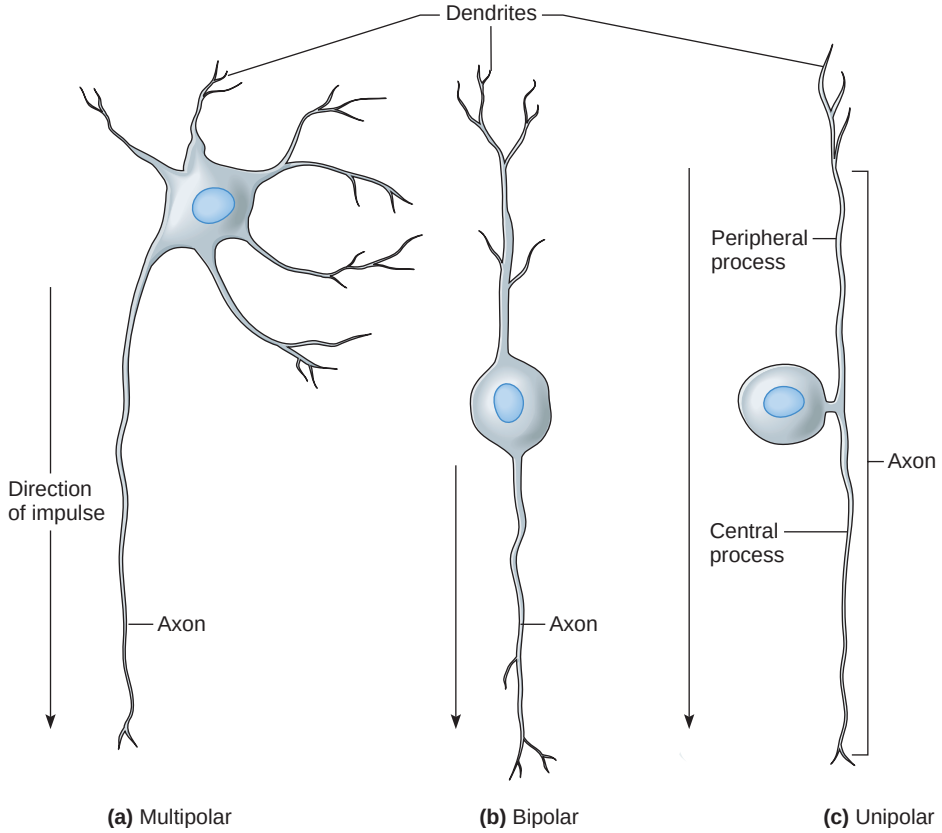


Figure 9.6
Structural types of neurons include (*a*) the multipolar neuron, (*b*) the bipolar neuron, and (*c*) the unipolar neuron.

1. **Multipolar neurons** have many processes arising from their cell bodies. Only one process of each neuron is an axon; the rest are dendrites. Most neurons whose cell bodies lie within the brain or spinal cord are multipolar.
2. **Bipolar neurons** have only two processes, one arising from each end of the cell body. These processes are structurally similar, but one is an axon and the other a dendrite. Neurons in specialized parts of the eyes, nose, and ears are bipolar.
3. **Unipolar neurons** have a single process extending from the cell body. A short distance from the cell body, this process divides into two branches, which really function as a single axon. One branch (the peripheral process) is associated with dendrites near a peripheral body part. The other branch (the central process) enters the brain or spinal cord. The cell bodies of some unipolar neurons aggregate in specialized masses of nervous tissue called **ganglia** (gang′gle-ah) (singular, *ganglion*), which are located outside the brain and spinal cord.

Neurons also vary in function. They may carry impulses into the brain or spinal cord, conduct impulses from neuron to neuron within the brain or spinal cord, or transmit impulses out of the brain or spinal cord.

On the basis of functional differences, neurons are grouped as follows (fig. 9.7):

1. **Sensory neurons** (afferent neurons) carry nerve impulses from peripheral body parts into the brain or spinal cord. Sensory neurons either have specialized *receptor ends* at the tips of their dendrites, or they have dendrites that are closely associated with *receptor cells* in the skin or in sensory organs.

   Changes that occur inside or outside the body stimulate receptor ends or receptor cells, triggering sensory nerve impulses. The impulses travel along the sensory neuron axons, which lead to the brain or spinal cord, where other neurons process the impulses. Most sensory neurons are unipolar; some are bipolar.
2. **Interneurons** (also called *association* or *internuncial neurons*) lie entirely within the brain or spinal cord. They are multipolar and link other neurons. Interneurons transmit impulses from one part of the brain or spinal cord to another. That is, they may direct incoming sensory impulses to appropriate parts for processing and interpreting. Other incoming impulses are transferred to motor neurons. The cell bodies of some interneurons aggregate in specialized masses of nervous tissue called **nuclei** (singular,

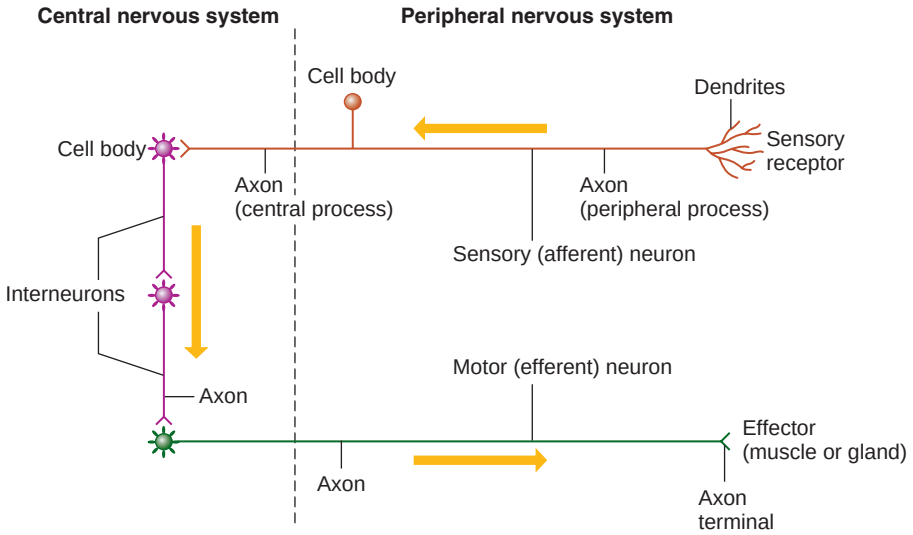


Figure 9.7

Neurons are classified by function as well as structure. Sensory (afferent) neurons carry information into the central nervous system (CNS), interneurons are completely within the CNS, and motor (efferent) neurons carry instructions to the peripheral nervous system (PNS).

nucleus). Nuclei are similar to ganglia, but are located within the central nervous system.

3. **Motor neurons** (efferent neurons) are multipolar and carry nerve impulses out of the brain or spinal cord to effectors. Motor impulses stimulate muscles to contract and glands to release secretions.

Neurons deprived of oxygen change shape as their nuclei shrink, and they eventually disintegrate. Oxygen deficiency can result from lack of blood flow (ischemia) through nerve tissue, an abnormally low blood oxygen concentration (hypoxemia), or toxins that prevent neurons from using oxygen by blocking aerobic respiration.

Check Your Recall

9. Distinguish between a dendrite and an axon.
10. Describe the components of a neuron.
11. Describe how a myelin sheath forms.
12. Explain why axons of peripheral nerves can regenerate, but axons of central nervous system nerves cannot.
13. Name three groups of neurons based on structure and three groups based on function.

9.5 THE SYNAPSE

Nerve impulses travel along complex **nerve pathways.** The junction between any two communicating neurons is called a **synapse** (sin′aps). The neurons at a synapse are not in direct physical contact, but are separated by a gap called a *synaptic cleft.* Communication along a nerve pathway must cross these gaps (fig. 9.8).

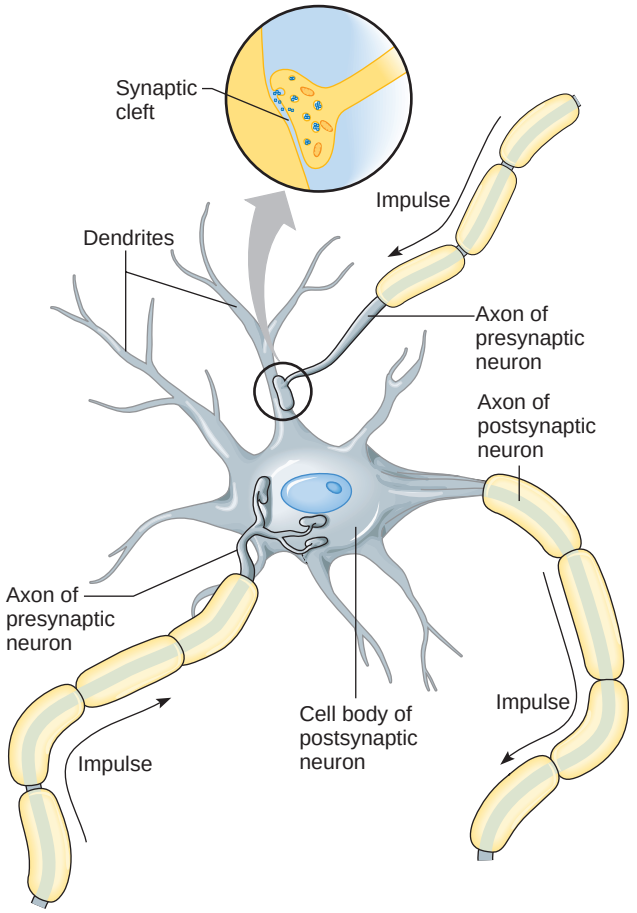


Figure 9.8

Synapses separate neurons. For an impulse to continue from one neuron to another, it must cross the synaptic cleft at a synapse. A synapse is usually between an axon and a dendrite or between an axon and a cell body.

When you receive a text message, the person writing the message is the sender and you are the receiver. Similarly, the neuron carrying the impulse into the synapse is the sender, or *presynaptic neuron.* The neuron that receives this input at the synapse is the receiver, or *postsynaptic neuron.* The process of crossing the synaptic cleft with this message is called *synaptic transmission.* The Topic of Interest box on page 221 discusses some factors that affect synaptic transmission.

Synaptic transmission is a one-way process carried out by biochemicals called **neurotransmitters.** The distal ends of axons have one or more extensions called *synaptic knobs,* absent in dendrites, which contain many membranous sacs, called *synaptic vesicles.* When a nerve impulse reaches a synaptic knob, some of the synaptic vesicles release neurotransmitter (figs. 9.9 and 9.10). The neurotransmitter diffuses across the synaptic cleft and reacts with specific receptors on the postsynaptic neuron membrane.

The action of neurotransmitter on a postsynaptic cell is either excitatory (turning a process on) or inhibitory (turning a process off). The net effect on the postsynaptic cell depends on the combined effect of the excitatory and inhibitory inputs from as few as 1 and as many as 10,000 presynaptic neurons.

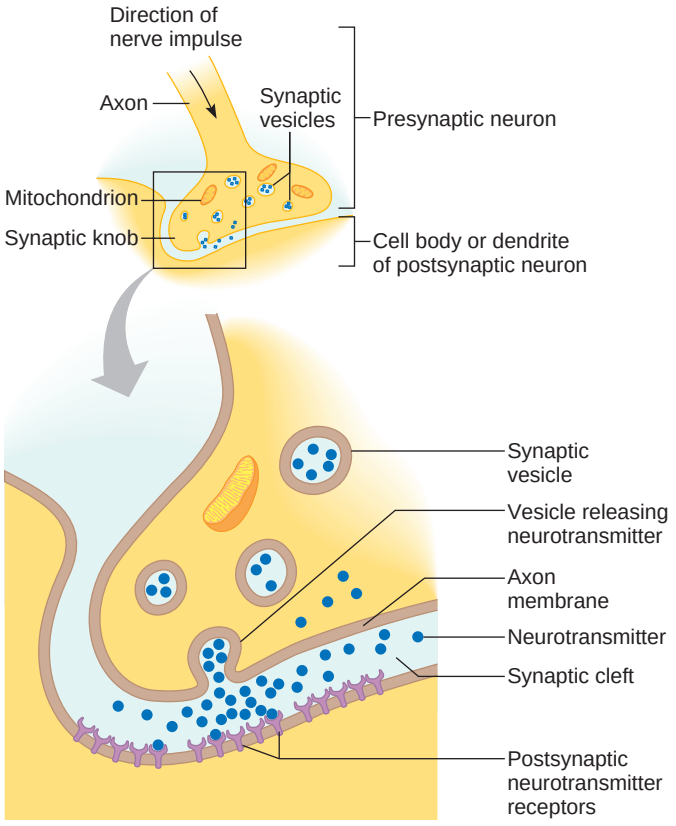


Figure 9.9

Action across a synapse. When a nerve impulse reaches the synaptic knob at the end of an axon, synaptic vesicles release a neurotransmitter that diffuses across the synaptic cleft and binds to specific receptors on the postsynaptic membrane.

9.6 CELL MEMBRANE POTENTIAL

The surface of a cell membrane (including a nonstimulated or *resting* neuron) is usually electrically charged, or *polarized,* with respect to the inside. This polarization arises from an unequal distribution of positive and negative ions between sides of the membrane, and it is particularly important in the conduction of muscle and nerve impulses. A characteristic change in neuron membrane polarization and return to the resting state, called an *action potential,* forms a nerve impulse that is propagated along an axon.

Distribution of Ions

Because of the active transport of sodium and potassium ions, cells throughout the body have a greater concentration of sodium ions (Na^+) outside and a greater concentration of potassium ions (K^+) inside (see chapter 3, p. 64). The cytoplasm of these cells has many large, negatively charged particles, including phosphate ions (PO_4^{-3}), sulfate ions (SO_4^{-2}), and proteins, that cannot diffuse across the cell membranes.

Chapter 3 (p. 53) introduced cell membranes as selectively permeable phospholipid bilayers. The distribution of ions inside and outside cells is determined in part by channels in the cell membranes (see chapter 3, pp. 54–55). Some channels are always open, and others can be opened or closed. Furthermore, channels can be selective; that is, a channel may allow one kind of ion to pass through and exclude other kinds (fig. 9.11).

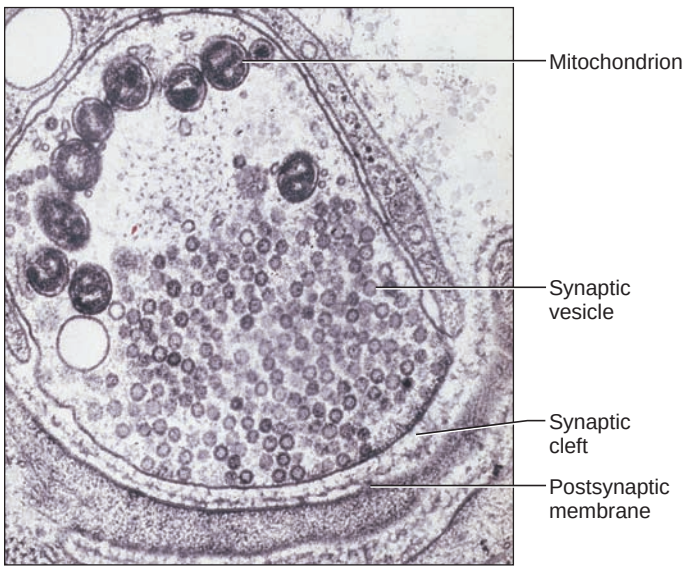


Figure 9.10

This transmission electron micrograph of a synaptic knob shows abundant synaptic vesicles, which are filled with neurotransmitter molecules.

Topic of Interest

Factors Affecting Synaptic Transmission

Nerve impulses reaching synaptic knobs too rapidly can exhaust neurotransmitter supplies, and impulse conduction ceases until more neurotransmitters are synthesized. This happens during an epileptic seizure. Abnormal and too rapid impulses originate from certain brain cells and reach skeletal muscle fibers, stimulating violent contractions. In time, the synaptic knobs run out of neurotransmitters, and the seizure subsides.

A drug called Dilantin (diphenylhydantoin) treats seizure disorders by increasing the effectiveness of the sodium active transport mechanism. More sodium ions transported from inside the neurons stabilize membrane thresholds against too rapid stimulation.

Many other drugs affect synaptic transmission. For example, caffeine in coffee, tea, and cola drinks stimulates nervous system activity by lowering the thresholds at synapses so that neurons are more easily excited. Antidepressants called "selective serotonin reuptake inhibitors" keep the neurotransmitter serotonin in synapses longer, compensating for a still little-understood deficit that presumably causes depression.

Potassium ions pass through cell membranes much more easily than sodium ions. This makes potassium ions a major contributor to membrane polarization. Calcium ions are less able to cross the resting cell membrane than either sodium ions or potassium ions, and have a special role in nerve function, described later.

Resting Potential

Sodium and potassium ions follow the laws of diffusion discussed in chapter 3 (p. 61) and show a net movement from high concentration to low concentration as permeabilities permit. Because a resting cell membrane is more permeable to potassium ions than to sodium ions, potassium ions diffuse out of the cell more rapidly than sodium ions can diffuse in (fig. 9.12*a*). Every millisecond, more positive charges leave the cell by diffusion than enter it. As a result, the outside of the cell membrane gains a slight surplus of positive charges, and the inside is left with a slight surplus of impermeant negative charges (fig. 9.12*b*).

The difference in electrical charge between two regions is called a *potential difference.* In a resting nerve cell, the potential difference between the region inside the membrane and the region outside the membrane is called a **resting potential.** As long as a nerve cell membrane is undisturbed, the membrane remains in this polarized state. At the same time, the cell continues to expend energy to drive the Na^+/K^+ "pumps" that actively transport sodium and potassium ions in opposite directions. The pump maintains the concentration gradients responsible for diffusion of these ions in the first place (fig. 9.12*c*).

Potential Changes

Nerve cells are excitable; that is, they can respond to changes in their surroundings. Some nerve cells, for example, are specialized to detect changes in temper-

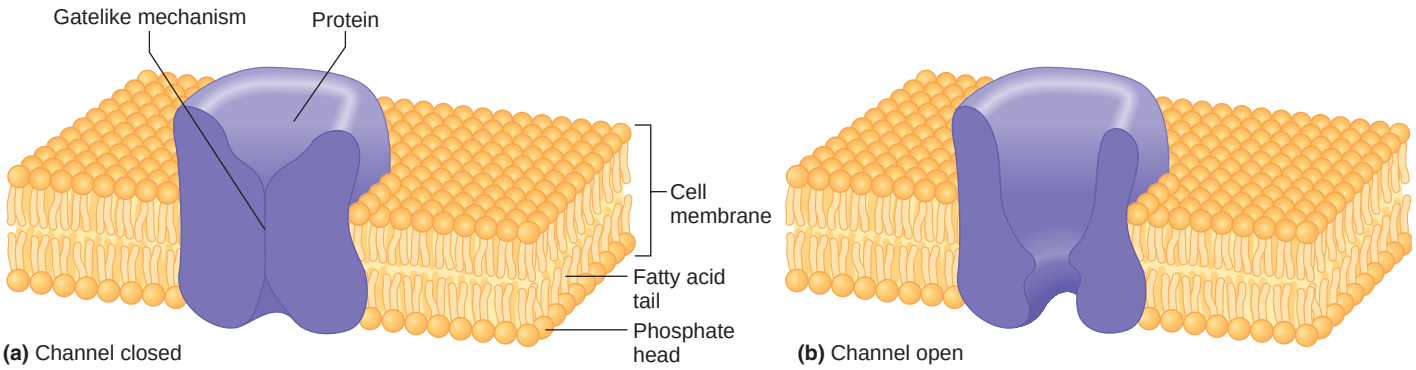


Figure 9.11

Cell membrane polarization is necessary for nerve transmission, and depends upon the movements of ions through channels. A gatelike mechanism can (*a*) close or (*b*) open some of the channels in cell membranes through which ions pass.

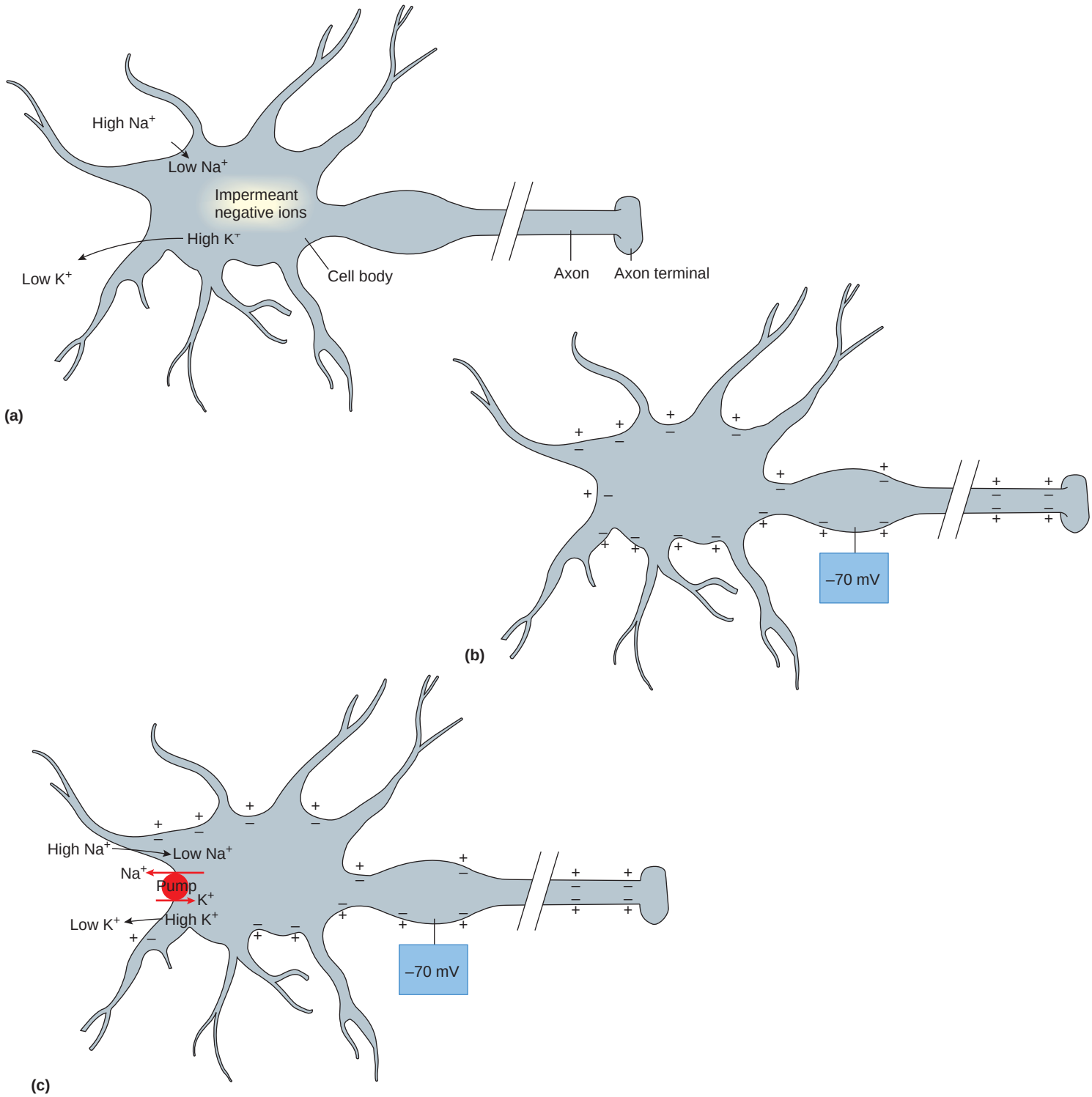


Figure 9.12

The resting potential. (*a*) Conditions that lead to the resting potential. (*b*) In the resting neuron, the inside of the membrane is negative relative to the outside. (*c*) The Na^+/K^+ pump maintains the concentration gradients for Na^+ and K^+ ions.

ature, light, or pressure from outside the body. Many neurons respond to neurotransmitters from other neurons. Such changes (or stimuli) usually affect the resting potential in a particular region of a nerve cell membrane. If the membrane's resting potential decreases (as the inside of the membrane becomes less negative when compared to the outside), the membrane is said to be *depolarized* (fig. 9.13*a*).

Local potential changes are graded. This means that the magnitude of change in the resting potential is directly

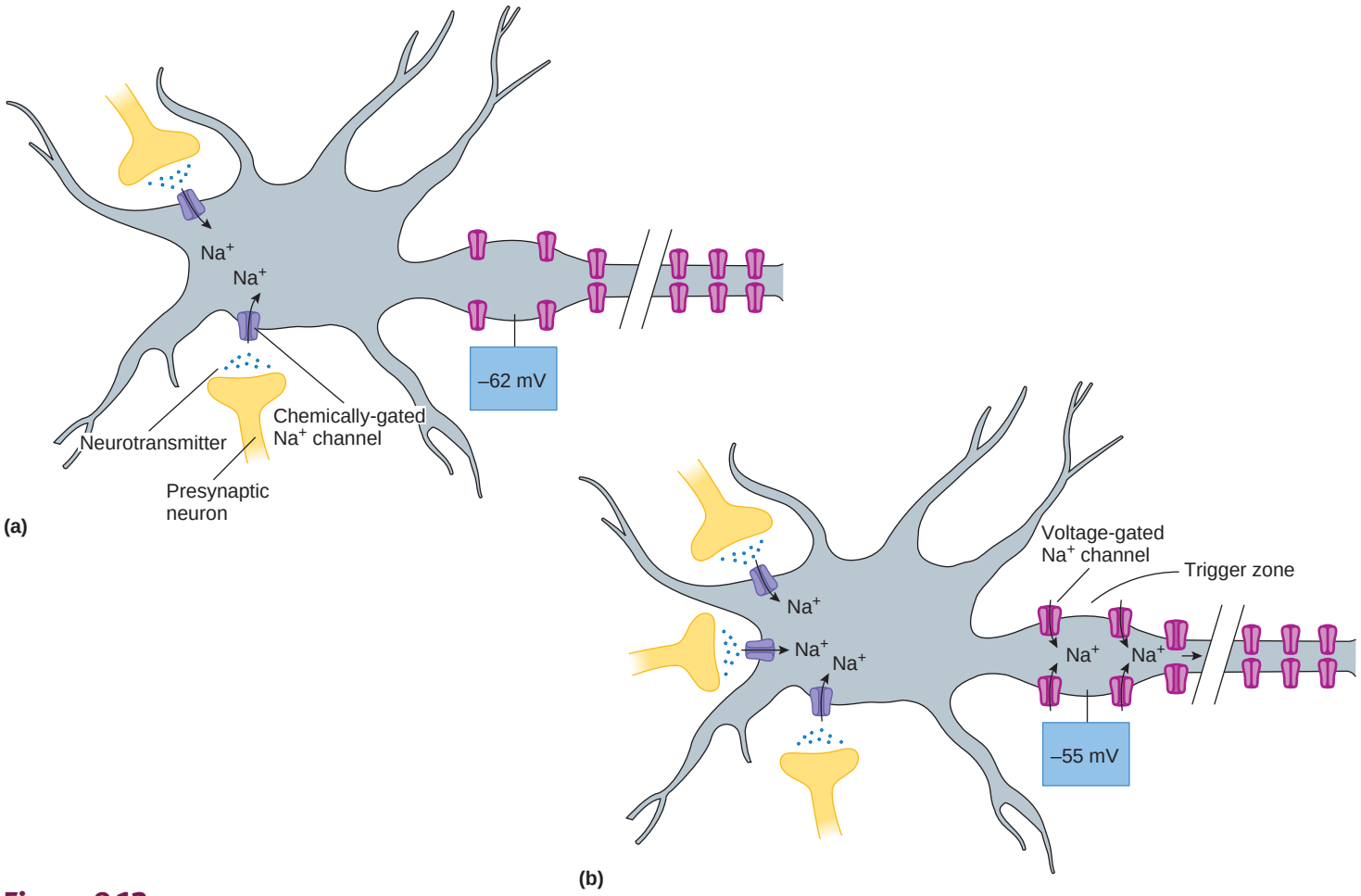


Figure 9.13

Action potentials. (*a*) A subthreshold depolarization will not result in an action potential. (*b*) Stimulation from multiple presynaptic neurons may cause the postsynaptic neuron to reach threshold, opening voltage-gated channels at the trigger zone.

proportional to the intensity of the stimulus. That is, if the membrane is being depolarized, the greater the stimulus, the greater the depolarization. If neurons are depolarized sufficiently, the membrane potential reaches a level called the **threshold potential,** which is approximately –55 millivolts. If threshold is reached, an **action potential** results, which is the basis for the nerve impulse.

Action Potential

At the threshold potential, permeability suddenly changes at the trigger zone of the neuron being stimulated. Channels highly selective for sodium ions open and allow sodium to diffuse freely inward (figs. 9.13*b* and 9.14*b*). This movement is aided by the negative electrical condition on the inside of the membrane, which attracts the positively charged sodium ions.

As sodium ions diffuse inward, the membrane loses its negative electrical charge and becomes depolarized. At almost the same time, however, membrane channels open that allow potassium ions to pass through, and as these positive ions diffuse outward, the inside of the membrane becomes negatively charged once more (fig. 9.14*c*). The membrane potential may briefly become overly negative (*hyperpolarization*), but the membrane quickly returns to the resting potential (*repolarization*), and it remains in this state until stimulated again.

This rapid sequence of depolarization and repolarization, which takes about one-thousandth of a second, is the action potential. Because only a small fraction of the sodium and potassium ions move through the membrane during an action potential, many action potentials can occur, and resting potentials be reestablished, before the original concentrations of these ions change significantly. Also, active transport within the membrane maintains the original concentrations of sodium and potassium ions on either side.

Check Your Recall

14. Describe the events that occur at a synapse.
15. Summarize how a nerve fiber becomes polarized.
16. List the major events of an action potential.

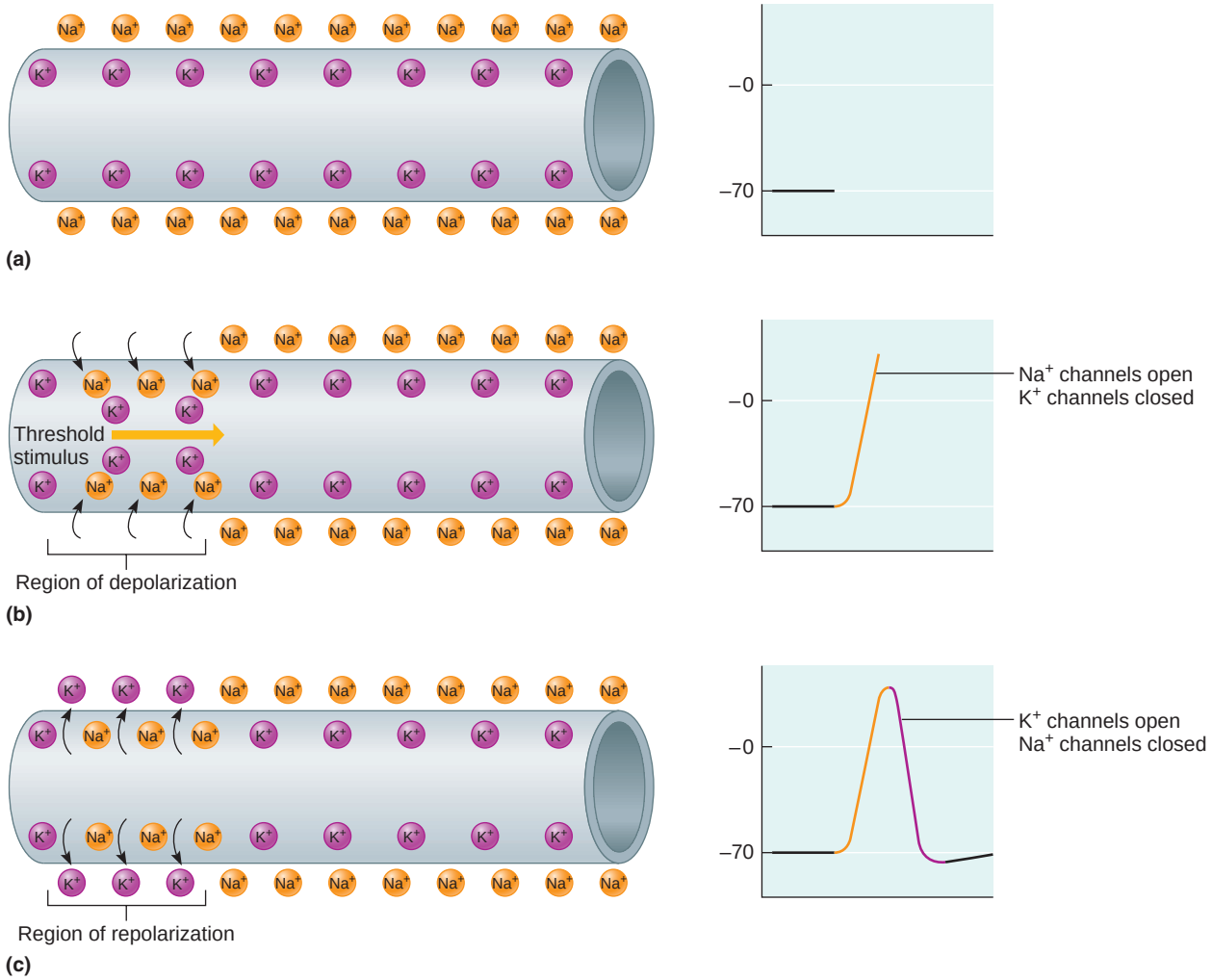


Figure 9.14

Action potential. (*a*) At rest, the membrane potential is negative. (*b*) When the membrane reaches threshold, sodium channels open, some sodium (Na^+) diffuses in, and the membrane is depolarized. (*c*) Soon afterward, potassium channels open, potassium (K^+) diffuses out, and the membrane is repolarized. (For simplicity, negative ions are not shown.)

9.7 NERVE IMPULSES

When an action potential occurs in one region of a nerve cell membrane, it causes a bioelectric current to flow to adjacent portions of the membrane. This *local current* stimulates the adjacent membrane to its threshold level and triggers another action potential. This, in turn, stimulates the next adjacent region. A wave of action potentials moves down the axon to the end. This propagation of action potentials along a nerve axon constitutes the nerve impulse (fig. 9.15). Table 9.1 summarizes the events leading to the conduction of a nerve impulse.

Certain local anesthetic drugs, such as those used in dentistry, decrease membrane permeability to sodium ions. Such a drug in the fluids surrounding an axon interrupts impulses from passing through the affected region and reaching the brain, preventing sensations of touch and pain.

Table 9.1 Events Leading to the Conduction of a Nerve Impulse

1. Neuron membrane maintains resting potential.
2. Threshold stimulus is received.
3. Sodium channels in the trigger zone of the neuron open.
4. Sodium ions diffuse inward, depolarizing the membrane.
5. Potassium channels in the membrane open.
6. Potassium ions diffuse outward, repolarizing the membrane.
7. The resulting action potential causes a local bioelectric current that stimulates adjacent portions of the membrane.
8. A wave of action potentials travels the length of the axon as a nerve impulse.

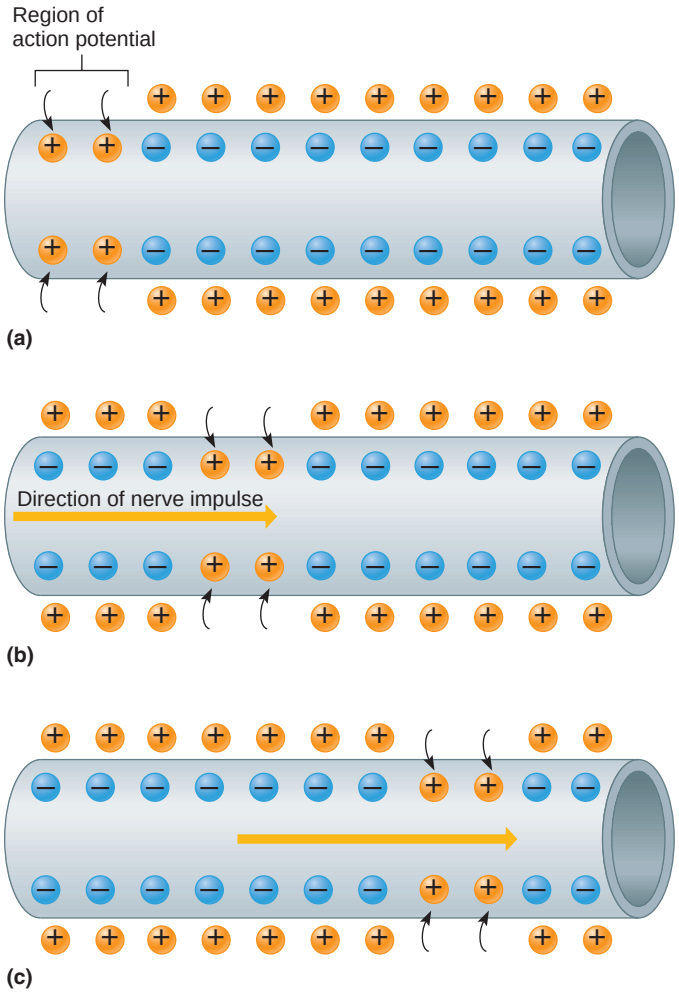


Figure 9.15

A nerve impulse. (*a*) An action potential in one region stimulates the adjacent region, and (*b*) and (*c*) a wave of action potentials (a nerve impulse) moves along the axon.

Impulse Conduction

An unmyelinated axon conducts an impulse over its entire surface. A myelinated axon functions differently because myelin insulates and prevents almost all ion flow through the membrane it encloses. The myelin sheath would prevent the conduction of a nerve impulse altogether if the sheath was continuous. However, nodes of Ranvier between Schwann cells interrupt the sheath (see fig. 9.4). Action potentials occur at these nodes, where the exposed axon membrane has sodium and potassium channels. A nerve impulse traveling along a myelinated axon appears to jump from node to node. This type of impulse conduction, termed saltatory, is many times faster than conduction on an unmyelinated axon.

The speed of nerve impulse conduction is proportional to the diameter of the axon—the greater the diameter, the faster the impulse. For example, an impulse on a relatively thick, myelinated axon, such as that of a motor neuron associated with a skeletal muscle, might travel 120 meters per second. An impulse on a thin, unmyelinated axon, such as that of a sensory neuron associated with the skin, might move only 0.5 meter per second.

All-or-None Response

Nerve impulse conduction is an *all-or-none response.* That is, if a neuron responds at all, it responds completely. Thus, a nerve impulse is conducted whenever a stimulus of threshold intensity or above is applied to an axon, and all impulses carried on that axon are of the same strength. A greater intensity of stimulation does not produce a stronger impulse, but rather, more impulses per second.

For a very short time following a nerve impulse, a threshold stimulus will not trigger another impulse on an axon. This brief period, called the *refractory period,* limits the frequency of impulses in a neuron. It also ensures that the impulse proceeds in only one direction—down the axon. Although a frequency of 700 impulses per second is possible, 100 impulses per second is more common.

Check Your Recall

17. What is the relationship between action potentials and nerve impulses?
18. Explain how impulse conduction differs in myelinated and unmyelinated nerve fibers.
19. Define *all-or-none response* as it relates to nerve impulse conduction.

9.8 SYNAPTIC TRANSMISSION

Neurotransmitters have various effects when they diffuse across the synaptic cleft and react with specific receptor molecules in the postsynaptic neuron membrane.

Excitatory and Inhibitory Actions

Neurotransmitters that increase postsynaptic membrane permeability to sodium ions will bring the postsynaptic membrane closer to threshold and may trigger nerve impulses. Such neurotransmitters are **excitatory.** Neurotransmitters that make it less likely that threshold will be reached are called **inhibitory,** because they decrease the chance that a nerve impulse will occur.

The synaptic knobs of a thousand or more neurons may communicate with the dendrites and cell body of a single postsynaptic neuron. Neurotransmitters released by some of these knobs have an excitatory action, but those from other knobs have an inhibitory action. The effect on the postsynaptic neuron depends on which presynaptic

knobs are activated from moment to moment. In other words, if more excitatory than inhibitory neurotransmitters are released, the postsynaptic neuron's threshold may be reached, and a nerve impulse will be triggered. Conversely, if most of the neurotransmitters released are inhibitory, threshold may not be reached.

Neurotransmitters

About fifty types of neurotransmitters have been identified in the nervous system. Some neurons release only one type, while others produce two or three kinds. The neurotransmitters include *acetylcholine,* which stimulates skeletal muscle contractions (see chapter 8, p. 181); a group of compounds called *monoamines* (such as epinephrine, norepinephrine, dopamine, and serotonin), which form from modified amino acids; several *amino acids* (such as glycine, glutamic acid, aspartic acid, and gamma-aminobutyric acid—GABA); and a large group of *neuropeptides,* which are short chains of amino acids. Acetylcholine and norepinephrine are excitatory. Dopamine, GABA, and glycine are inhibitory. Neurotransmitters are usually synthesized in the cytoplasm of the synaptic knobs and stored in the synaptic vesicles. Some neurotransmitters and their actions are listed in table 9.2.

When an action potential reaches the membrane of a synaptic knob, it increases the membrane's permeability to calcium ions by opening calcium ion channels in the membrane. Consequently, calcium ions diffuse inward, and in response, some synaptic vesicles fuse with the membrane and release their contents into the synaptic cleft. A vesicle that has released its neurotransmitter eventually breaks away from the membrane and reenters the cytoplasm, where it can pick up more neurotransmitter.

After being released, some neurotransmitters are decomposed by enzymes. For example, the enzyme *acetylcholinesterase* decomposes acetylcholine and is present in the synapse and on the postsynaptic membrane of neuromuscular junctions, which control skeletal muscle contraction. Other neurotransmitters are transported back into the synaptic knob that released them (reuptake) or into nearby neurons or neuroglial cells. Decomposition or removal of neurotransmitters prevents continuous stimulation of postsynaptic neurons. Table 9.3 summarizes the events leading to the release of a neurotransmitter.

Check Your Recall

20. Distinguish between the actions of excitatory and inhibitory neurotransmitters.
21. What types of chemicals function as neurotransmitters?
22. What are possible fates of neurotransmitters?

Table 9.2 Some Neurotransmitters and Representative Actions

Neurotransmitter	Location	Major Actions
Acetylcholine	CNS	Controls skeletal muscle actions
	PNS	Stimulates skeletal muscle contraction at neuromuscular junctions. May excite or inhibit at autonomic nervous system synapses
Monoamines		
Norepinephrine	CNS	Creates a sense of feeling good; low levels may lead to depression
	PNS	May excite or inhibit autonomic nervous system actions, depending on receptors
Dopamine	CNS	Creates a sense of feeling good; deficiency in some brain areas is associated with Parkinson disease
	PNS	Limited actions in autonomic nervous system; may excite or inhibit, depending on receptors
Serotonin	CNS	Primarily inhibitory; leads to sleepiness; action is blocked by LSD, enhanced by selective serotonin reuptake inhibitor drugs
Histamine	CNS	Release in hypothalamus promotes alertness
Amino acids		
GABA	CNS	Generally inhibitory
Glutamic acid	CNS	Generally excitatory
Neuropeptides		
Substance P	PNS	Excitatory; pain perception
Endorphins, enkephalins	CNS	Generally inhibitory; reduce pain by inhibiting substance P release
Gases		
Nitric oxide	PNS	Vasodilation
	CNS	May play a role in memory

Table 9.3 Events Leading to the Release of a Neurotransmitter

1. Action potential passes along an axon and over the surface of its synaptic knob.
2. Synaptic knob membrane becomes more permeable to calcium ions, and they diffuse inward.
3. In the presence of calcium ions, synaptic vesicles fuse to synaptic knob membrane.
4. Synaptic vesicles release their neurotransmitter into synaptic cleft.
5. Synaptic vesicles reenter cytoplasm of axon and pick up more neurotransmitter.

9.9 IMPULSE PROCESSING

The way the nervous system processes and responds to nerve impulses reflects, in part, the organization of neurons and their axons within the brain and spinal cord.

Neuronal Pools

Neurons within the CNS are organized into **neuronal pools.** These are groups of neurons that make hundreds of synaptic connections with each other and work together to perform a common function. Each pool receives input from neurons (which may be part of other pools), and each pool generates output. Neuronal pools may have excitatory or inhibitory effects on other pools or on peripheral effectors.

Facilitation

As a result of incoming impulses and neurotransmitter release, a particular neuron of a neuronal pool may receive excitatory and inhibitory input. If the net effect of the input is excitatory, threshold may be reached, and an outgoing impulse triggered. If the net effect is excitatory but subthreshold, an impulse is not triggered, but the neuron is more excitable to incoming stimulation than before, a state called **facilitation** (fah-sil″ĭ-ta′shun).

Convergence

Any single neuron in a neuronal pool may receive impulses from two or more incoming axons. Axons originating from different parts of the nervous system and leading to the same neuron exhibit **convergence** (kon-ver′jens) (fig. 9.16*a*).

Convergence makes it possible for impulses arriving from different sources to have an additive effect on a neuron. For example, if a neuron is facilitated by receiving subthreshold stimulation from one input neuron, it may reach threshold if it receives additional stimulation from a second input neuron. As a result, a nerve impulse may travel to a particular effector and evoke a response.

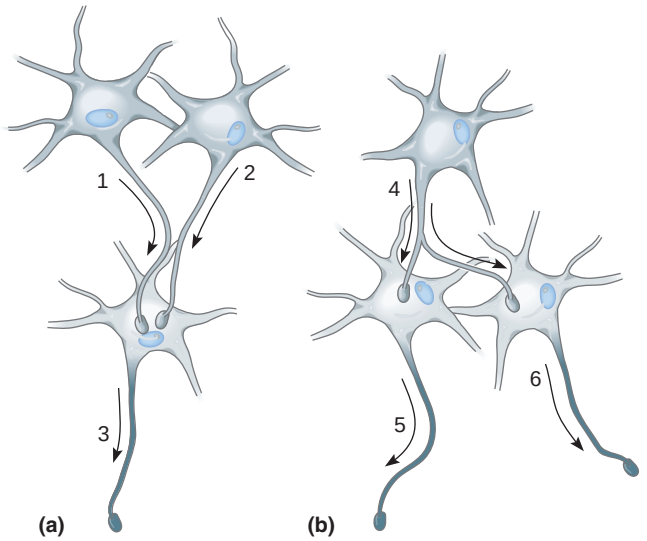


Figure 9.16
Impulse processing in neuronal pools. (*a*) Axons of neurons 1 and 2 converge to the cell body of neuron 3. (*b*) The axon of neuron 4 diverges to the cell bodies of neurons 5 and 6.

Incoming impulses often bring information from several sensory receptors that detect changes. Convergence allows the nervous system to collect a variety of kinds of information, process it, and respond to it in a special way.

Divergence

Impulses leaving a neuron of a neuronal pool often exhibit **divergence** (di-ver′jens) by passing into several other output neurons (fig. 9.16*b*). For example, an impulse from one neuron may stimulate two others; each of these, in turn, may stimulate several others, and so forth. Divergence can amplify an impulse—that is, spread it to more neurons within the pool. As a result of divergence, an impulse originating from a single neuron in the CNS may be amplified so that impulses reach enough motor units within a skeletal muscle to cause forceful contraction (see chapter 8, p. 188). Similarly, an impulse originating from a sensory receptor may diverge and reach several different regions of the CNS, where the resulting impulses are processed and acted upon.

Check Your Recall

23. Define *neuronal pool*.
24. Distinguish between convergence and divergence.

9.10 TYPES OF NERVES

Recall from section 9.1 that nerves are bundles of axons. An axon is often referred to as a nerve fiber. Because of this, we will refer to the neuron processes that bring sensory information into the CNS as **sensory fibers,** or **afferent fibers.** In contrast, **motor fibers** or **efferent fibers** carry impulses from the CNS to effectors (muscles or glands). A nerve is a cordlike bundle (or group of bundles) of nerve fibers within layers of connective tissue (fig. 9.17).

The terminology used to describe muscle and nerve fibers is somewhat inconsistent. "Muscle fiber" refers to a muscle cell, whereas "nerve fiber" refers to an axon, which is part of a cell. However, names for the associated connective tissues are similar. Both muscle and nerve fibers are bundled into fascicles. Recall from figure 8.1 that epimysium and perimysium connective tissue separates muscle tissue into compartments. Similarly, a nerve is defined by an outer *epineurium,* with *perineurium* surrounding a nerve fascicle within the nerve, and *endoneurium* surrounding an individual nerve fiber.

Like neurons, nerves that conduct impulses to the brain or spinal cord are called **sensory nerves,** and those that carry impulses to muscles or glands are termed **motor nerves.** Most nerves include both sensory and motor fibers and are called **mixed nerves.**

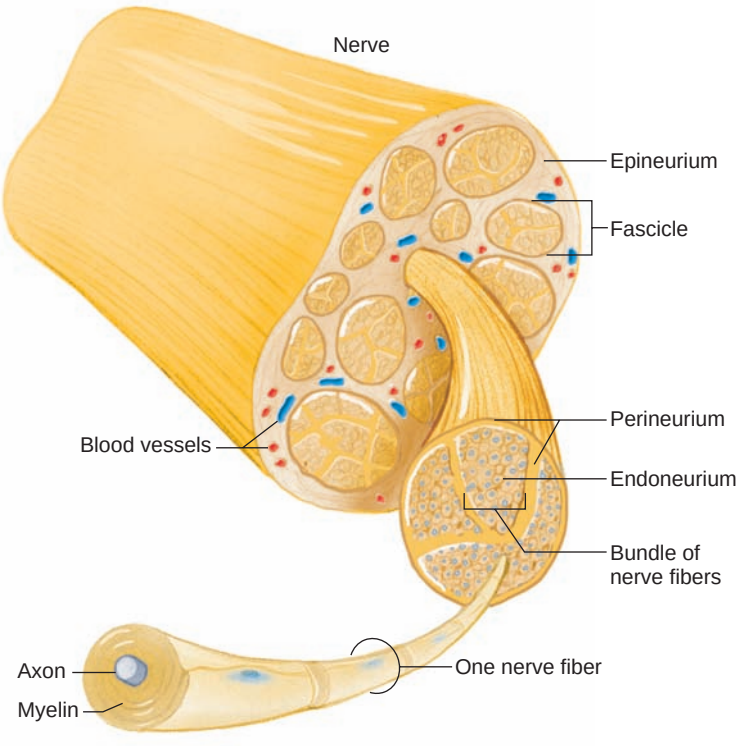


Figure 9.17
Connective tissue binds a bundle of nerve fibers, forming a fascicle. Many fascicles form a nerve.

Check Your Recall

25. What is a nerve?
26. How does a mixed nerve differ from a sensory nerve? From a motor nerve?

9.11 NERVE PATHWAYS

Recall from section 9.5 that the routes nerve impulses follow as they travel through the nervous system are called *nerve pathways.* The simplest of these pathways includes only a few neurons and is called a **reflex** (re′fleks) **arc.** It constitutes the structural and functional basis for involuntary actions called **reflexes.**

Reflex Arcs

A reflex arc begins with a receptor at the end of a sensory (or afferent) neuron. This neuron usually leads to several interneurons within the CNS, which serve as a processing center, or *reflex center.* These interneurons can connect with interneurons in other parts of the nervous system. They also communicate with motor (or efferent) neurons, whose axons pass outward from the CNS to effectors, usually muscles or glands (fig. 9.18).

Reflex Behavior

Reflexes are automatic responses to changes (stimuli) within or outside the body. They help maintain homeostasis by controlling many involuntary processes, such as heart rate, breathing rate, blood pressure, and digestion. Reflexes also carry out the automatic actions of swallowing, sneezing, coughing, and vomiting.

The *patellar reflex* (knee-jerk reflex) is an example of a simple reflex involving a pathway of only two neurons—a sensory neuron communicating directly with a motor neuron. Striking the patellar ligament just below

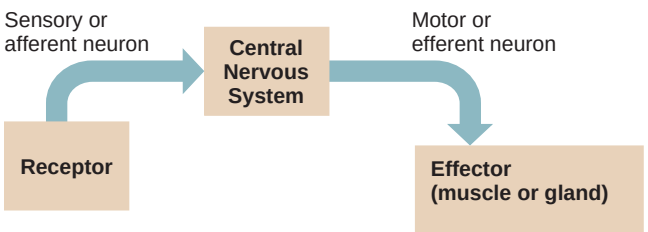


Figure 9.18
A reflex arc is the simplest nerve pathway. It involves a sensory neuron that sends a message to the CNS, and a motor neuron that sends the message from the CNS to a muscle or gland.

the patella initiates this reflex. The quadriceps femoris muscle group, which is attached to the patella by a tendon, is pulled slightly, stimulating stretch receptors in these muscles. These receptors, in turn, trigger impulses that pass along the axon of a sensory neuron into the spinal cord. Within the spinal cord, the sensory axon makes a synapse with a motor neuron. An impulse is then triggered along the axon of the motor neuron and travels back to the quadriceps femoris group. The muscle group contracts in response, and the reflex is completed as the leg extends (fig. 9.19).

The patellar reflex helps maintain upright posture. If the knee begins to bend from the force of gravity when a person is standing still, the quadriceps femoris group is stretched, the reflex is triggered, and the leg straightens again.

Another type of reflex, called a *withdrawal reflex,* occurs when a person unexpectedly touches a body part to something painful, such as stepping on a tack. This activates skin receptors and sends sensory impulses to the spinal cord. There, the impulses pass to the interneurons of a reflex center and are directed to motor neurons. The motor neurons transmit signals to flexor muscles in the injured part, and the muscles contract in response. At the same time, the antagonistic extensor muscles are inhibited, and the foot is rapidly and unconsciously withdrawn from the painful stimulus. Concurrent with the withdrawal reflex, other interneurons carry sensory impulses to the brain and the person becomes aware of the experience and may feel pain (fig. 9.20). A withdrawal reflex is protective because it may limit tissue damage caused by touching something harmful. Table 9.4 summarizes the parts of a reflex arc.

Because normal reflexes depend on normal neuron functions, reflexes provide information about the condition of the nervous system. For instance, an anesthesiologist may try to initiate a reflex in a patient being anesthetized to determine how well the anesthetic drug is affecting nerve functions. A neurologist may test reflexes when nervous system injury has occurred to determine the location and extent of damage.

Check Your Recall

27. What is a nerve pathway?
28. List the parts of a reflex arc.
29. Define *reflex*.
30. List the actions that occur during a withdrawal reflex.

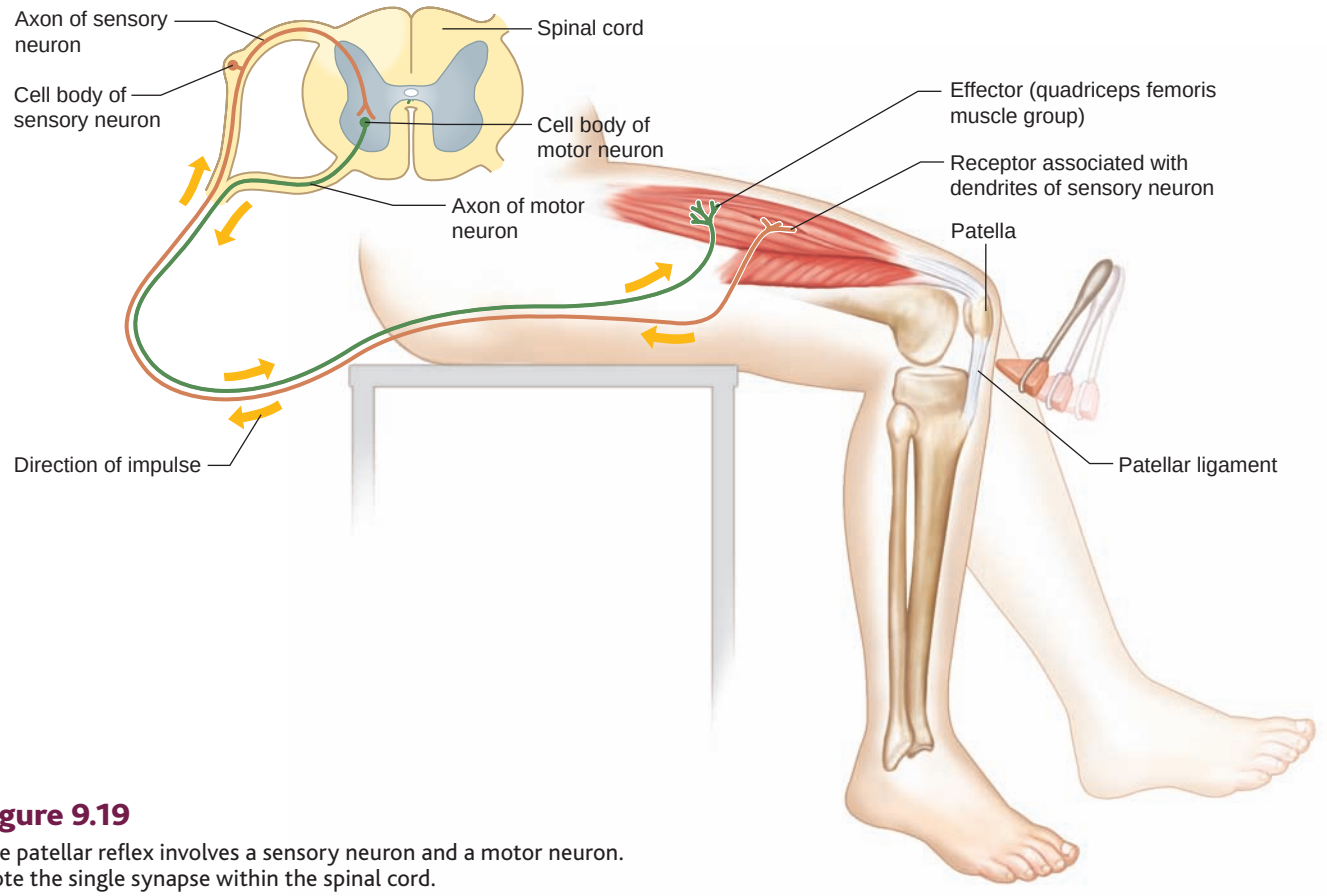


Figure 9.19
The patellar reflex involves a sensory neuron and a motor neuron. Note the single synapse within the spinal cord.

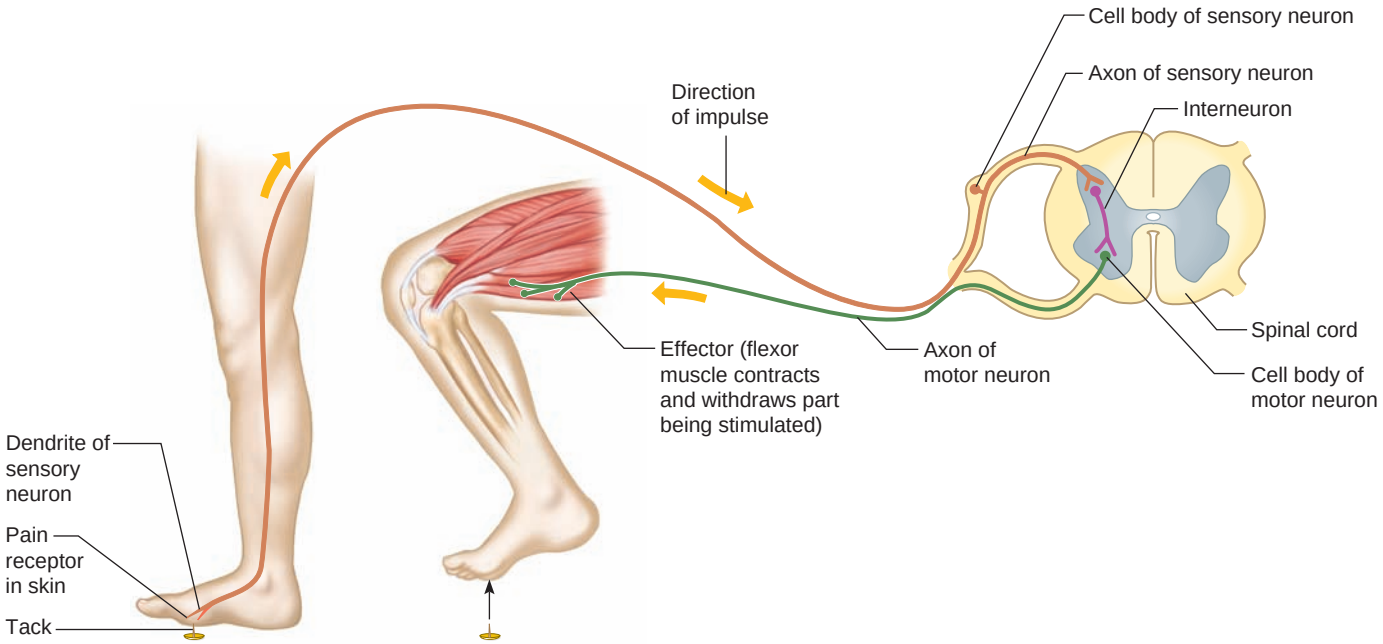


Figure 9.20
A withdrawal reflex involves a sensory neuron, an interneuron, and a motor neuron.

Table 9.4 Parts of a Reflex Arc

Part	Description	Function
Receptor	Receptor end of a dendrite or a specialized receptor cell in a sensory organ	Senses specific type of internal or external change
Sensory neuron	Dendrite, cell body, and axon of a sensory neuron	Transmits nerve impulse from receptor into brain or spinal cord
Interneuron	Dendrite, cell body, and axon of a neuron within the brain or spinal cord	Conducts nerve impulse from sensory neuron to motor neuron
Motor neuron	Dendrite, cell body, and axon of a motor neuron	Transmits nerve impulse from brain or spinal cord out to effector
Effector	Muscle or gland	Responds to stimulation by motor neuron and produces reflex or behavioral action

9.12 MENINGES

Bones, membranes, and fluid surround the organs of the CNS. The brain lies within the cranial cavity of the skull, and the spinal cord occupies the vertebral canal within the vertebral column. Layered membranes called **meninges** (mĕ-nin′jēz) (singular, *meninx*) lie between these bony coverings and the soft tissues of the CNS, protecting the brain and spinal cord (fig. 9.21*a*).

The meninges have three layers—dura mater, arachnoid mater, and pia mater (fig. 9.21*b*). The **dura mater** (du′rah ma′ter) is the outermost layer of the meninges. It is composed primarily of tough, white, fibrous connective tissue and contains many blood vessels and nerves. It attaches to the inside of the cranial cavity and forms the internal periosteum of the surrounding skull bones. In some regions, the dura mater extends inward between lobes of the brain and forms partitions that support and protect these parts.

The dura mater continues into the vertebral canal as a strong, tubular sheath that surrounds the spinal cord. It terminates as a blind sac below the end of the cord. The membrane around the spinal cord is not attached directly to the vertebrae but is separated by an *epidural space,* which lies between the dural sheath and the bony walls (fig. 9.22). This space contains loose connective and adipose tissues, which pad the spinal cord.

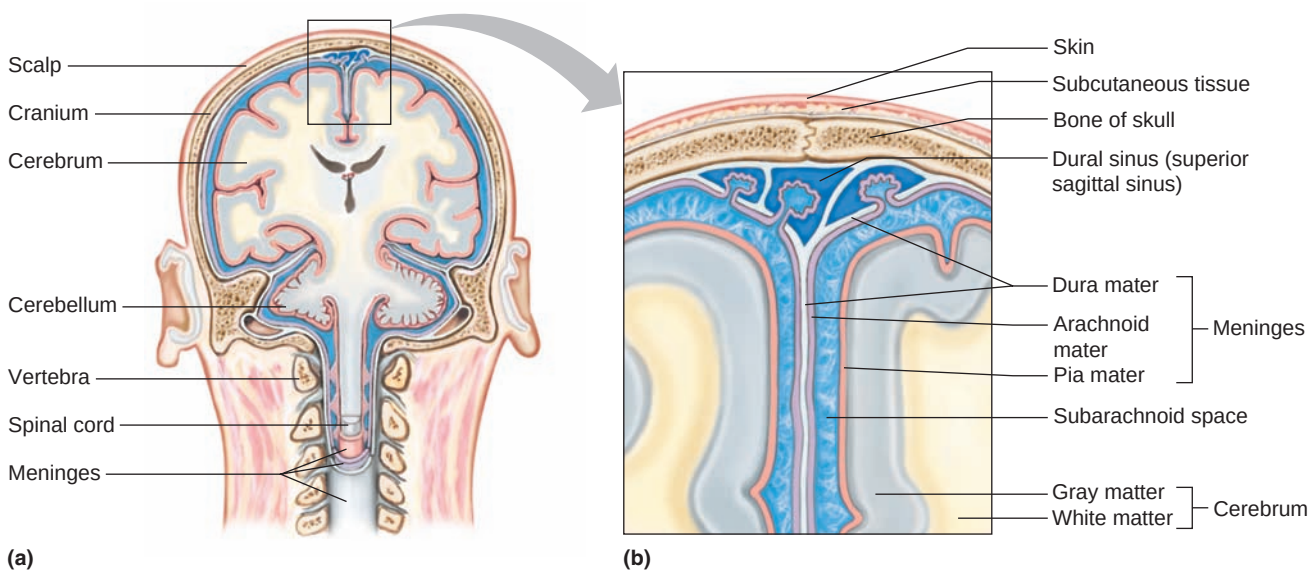


Figure 9.21

Meninges. (*a*) Membranes called meninges enclose the brain and spinal cord. (*b*) The meninges include three layers: dura mater, arachnoid mater, and pia mater.

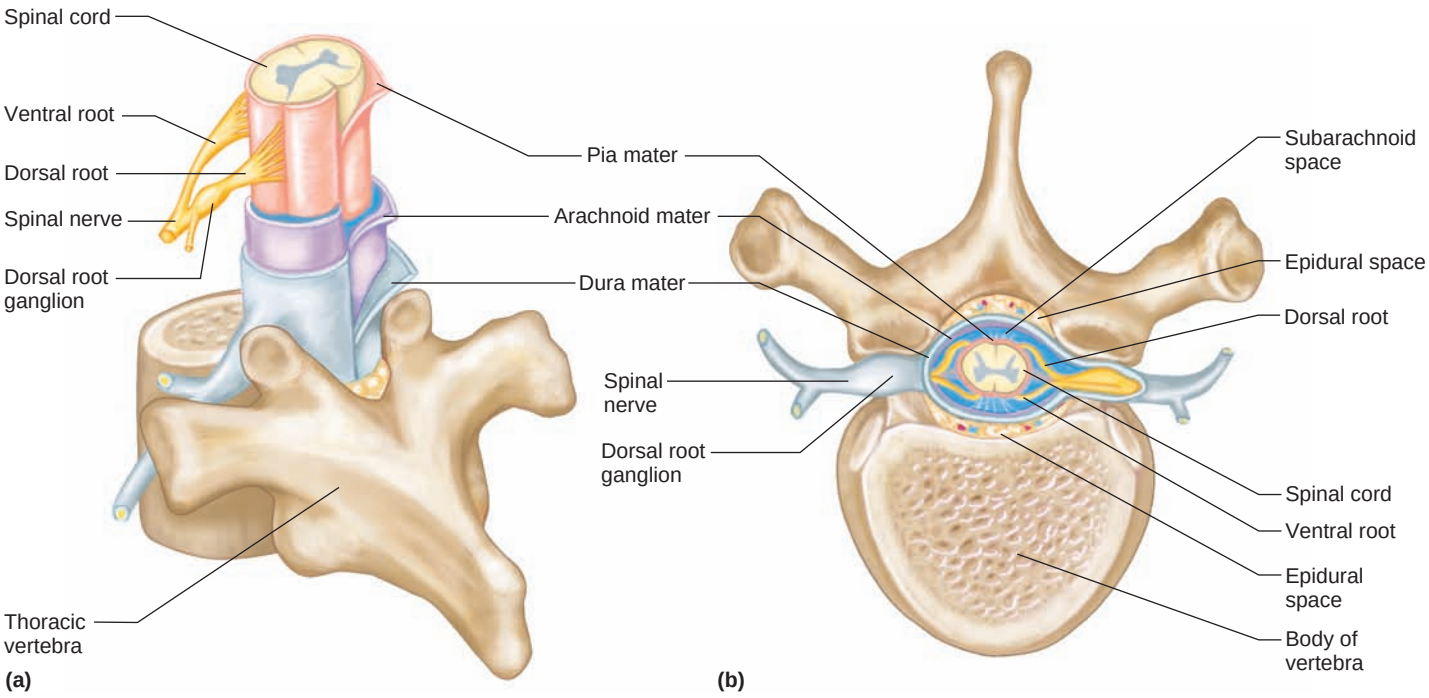


Figure 9.22

Meninges of the spinal cord. (*a*) The dura mater ensheaths the spinal cord. (*b*) Tissues forming a protective pad around the cord fill the epidural space between the dural sheath and the bone of the vertebra.

The **arachnoid mater** is a thin, weblike membrane without blood vessels that lies between the dura and pia maters. Between the arachnoid and pia maters is a *subarachnoid space* that contains the clear, watery **cerebrospinal fluid (CSF).** The **pia mater** (pi′ah ma′ter) is very thin and contains many nerves and blood vessels that nourish underlying cells of the brain and spinal cord. This layer hugs the surfaces of these organs and follows their irregular contours, passing over high areas and dipping into depressions.

A blow to the head may break some blood vessels associated with the brain, and escaping blood may collect beneath the dura mater. Such a *subdural hematoma* increases pressure between the rigid bones of the skull and the soft tissues of the brain. Unless the accumulating blood is evacuated, compression of the brain may lead to functional losses or even death.

Check Your Recall

31. Describe the meninges.
32. State the location of cerebrospinal fluid.

9.13 SPINAL CORD

The **spinal cord** is a slender nerve column that passes downward from the brain into the vertebral canal. Although continuous with the brain, the spinal cord begins where nervous tissue leaves the cranial cavity at the level of the foramen magnum. The spinal cord tapers to a point and terminates near the intervertebral disc that separates the first and second lumbar vertebrae (fig. 9.23).

Structure of the Spinal Cord

The spinal cord consists of thirty-one segments, each of which gives rise to a pair of **spinal nerves.** These nerves branch to various body parts and connect them with the CNS (see fig. 9.35).

In the neck region, a thickening in the spinal cord, called the *cervical enlargement,* supplies nerves to the upper limbs. A similar thickening in the lower back, the *lumbar enlargement,* gives off nerves to the lower limbs (fig. 9.23).

Two grooves, a deep *anterior median fissure* and a shallow *posterior median sulcus,* extend the length of the spinal cord, dividing it into right and left halves (fig. 9.24). A cross section of the cord reveals a core of gray matter within white matter. The pattern of gray matter roughly resembles a butterfly with its wings spread. The upper and lower wings of gray matter are called the *posterior horns* and *anterior horns,* respectively. Between them on either side in the thoracic and upper lumbar segments is a protrusion of gray matter called the *lateral horn.*

Neurons with large cell bodies located in the anterior horns give rise to motor fibers that pass out through spinal nerves to skeletal muscles. However, the majority of neurons in the gray matter of the spinal cord are interneurons.

Gray matter divides the white matter of the spinal cord into three regions on each side—the *anterior, lateral,* and *posterior funiculi* (fig. 9.24*a*). Each funiculus consists of longitudinal bundles of myelinated nerve fibers that comprise major nerve pathways called **nerve tracts.**

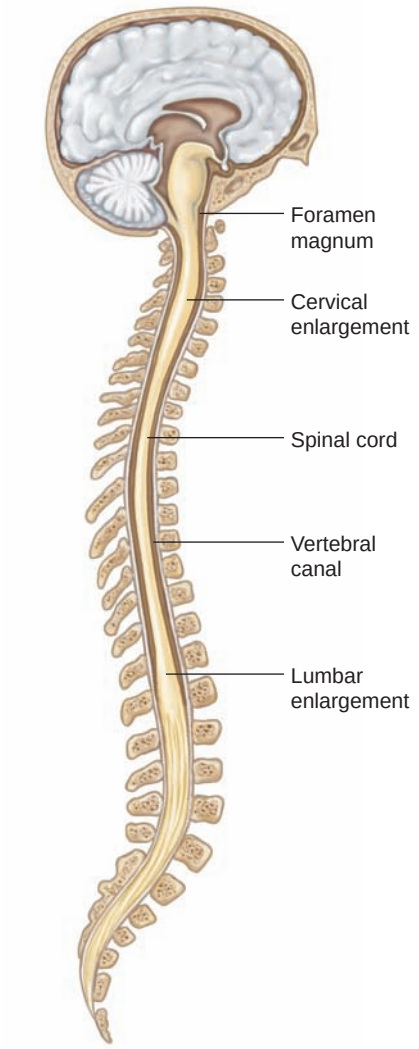
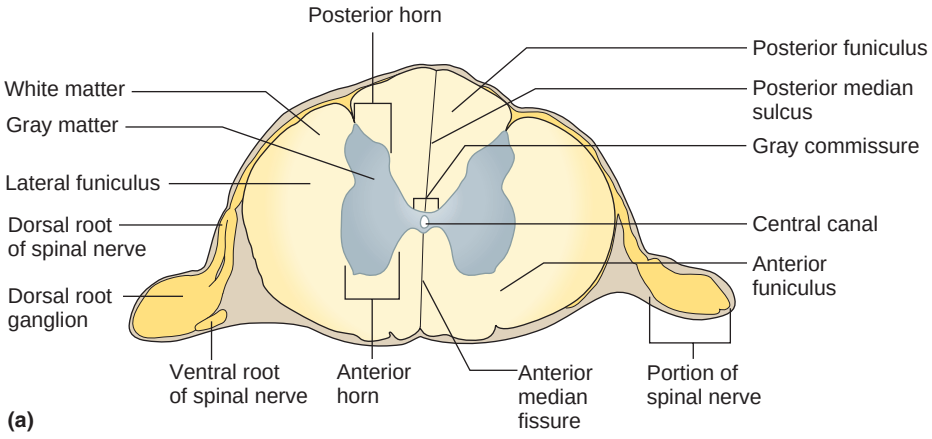


Figure 9.23
The spinal cord begins at the level of the foramen magnum and ends near the intervertebral disc between the first and second lumbar vertebrae.

A horizontal bar of gray matter in the middle of the spinal cord, the *gray commissure,* connects the wings of the gray matter on the right and left sides. This bar surrounds the **central canal,** which contains cerebrospinal fluid.

Functions of the Spinal Cord

The spinal cord has two major functions—conducting nerve impulses and serving as a center for spinal reflexes. The nerve tracts of the spinal cord consist of axons that provide a two-way communication system between the brain and the body parts outside the nervous system. The tracts that carry sensory information to



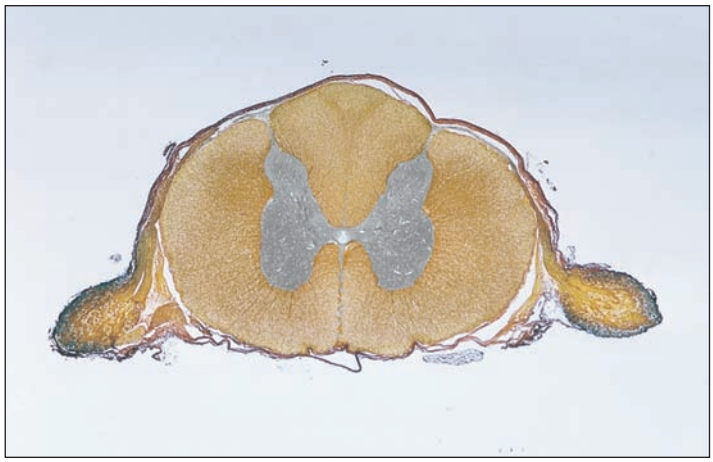


Figure 9.24

The spinal cord. (*a*) A cross section of the spinal cord. (*b*) Identify the parts of the spinal cord in this micrograph (7.5×).

the brain are called **ascending tracts** (fig. 9.25); those that conduct motor impulses from the brain to muscles and glands are called **descending tracts** (fig. 9.26).

Typically, all the axons within a given tract originate from neuron cell bodies located in the same part of the nervous system and terminate together in some other part. The names that identify nerve tracts often reflect these common origins and terminations. For example, a *spinothalamic tract* begins in the spinal cord and carries sensory impulses associated with the sensations of pain, touch, and temperature to the thalamus of the brain. A *corticospinal tract* originates in the cortex of the brain and carries motor impulses downward through the spinal cord and spinal nerves. These impulses control skeletal muscle movements.

Corticospinal tracts are also called *pyramidal tracts* after the pyramid-shaped areas in the medulla oblongata of the brain through which they pass. Other descending tracts, called *extrapyramidal tracts,* control motor activities associated with maintaining balance and posture.

In addition to providing a pathway for nerve tracts, the spinal cord functions in many reflexes, including the patellar and withdrawal reflexes described previously. These are called **spinal reflexes** because their reflex arcs pass through the spinal cord.

Some axons extend from the base of the spinal cord to the toes. If you stub your toe, a sensory message reaches the spinal cord in less than one-hundredth of a second.

Check Your Recall

33. Describe the structure of the spinal cord.
34. Describe the general functions of the spinal cord.
35. Distinguish between an ascending and a descending tract.

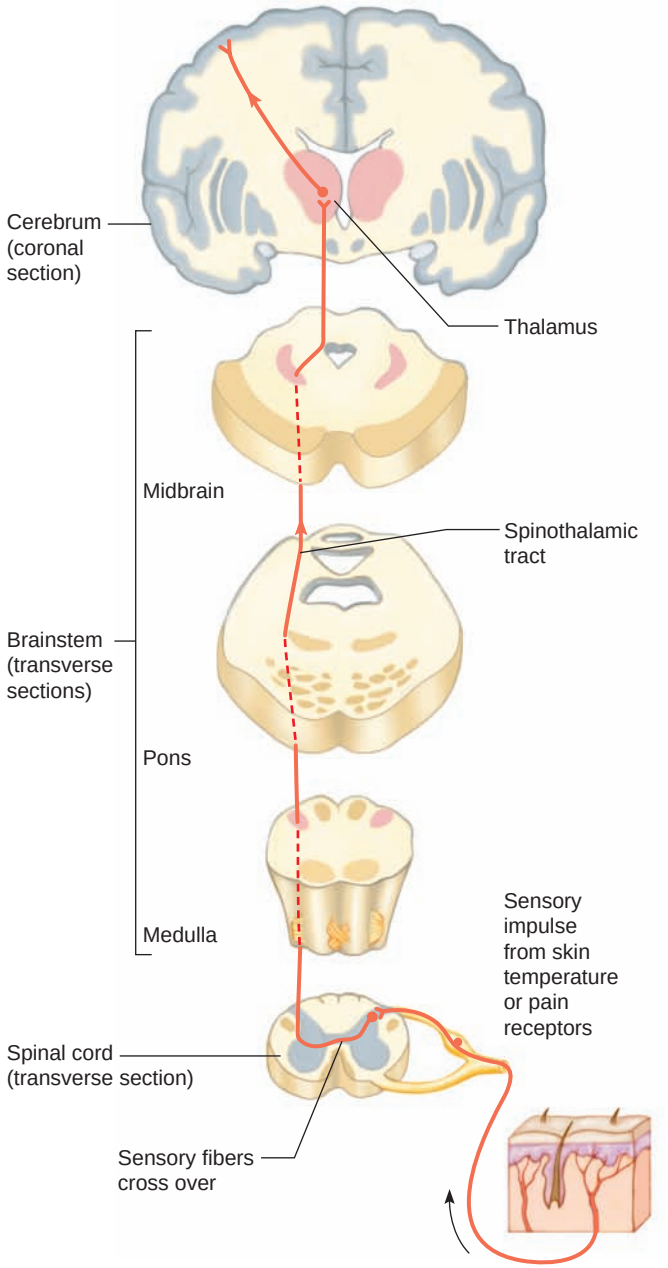


Figure 9.25
Ascending tracts. Sensory impulses originating in skin receptors cross over in the spinal cord and ascend to the brain. Other sensory tracts cross over in the medulla oblongata.

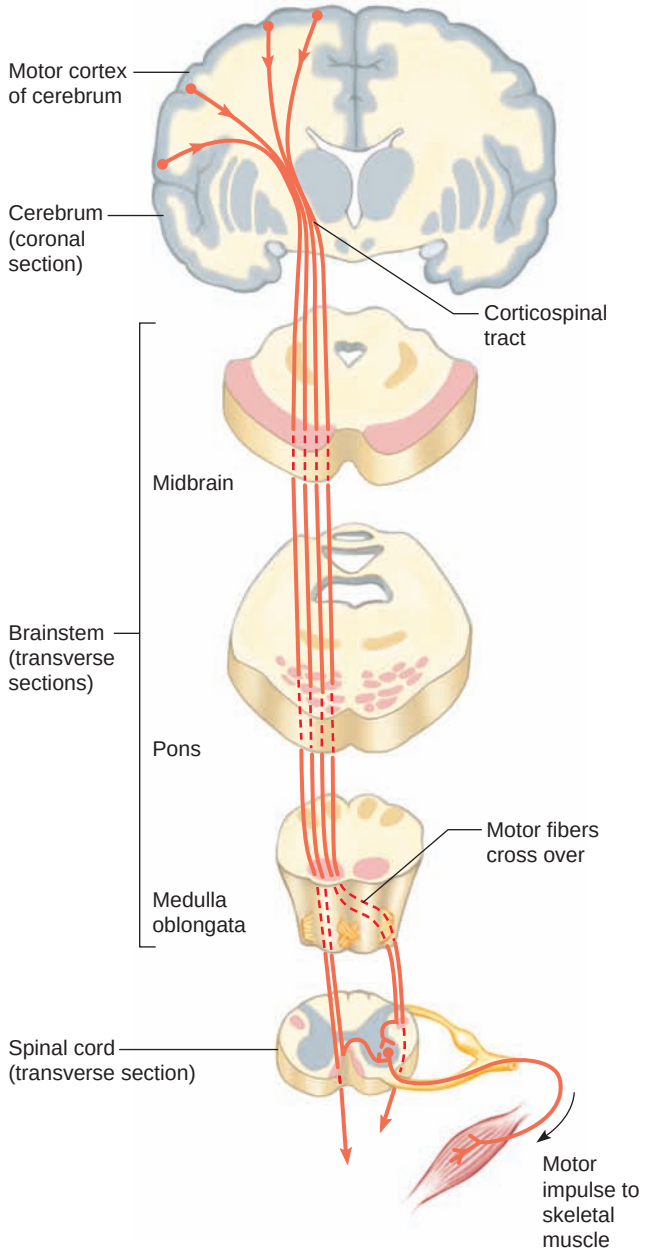
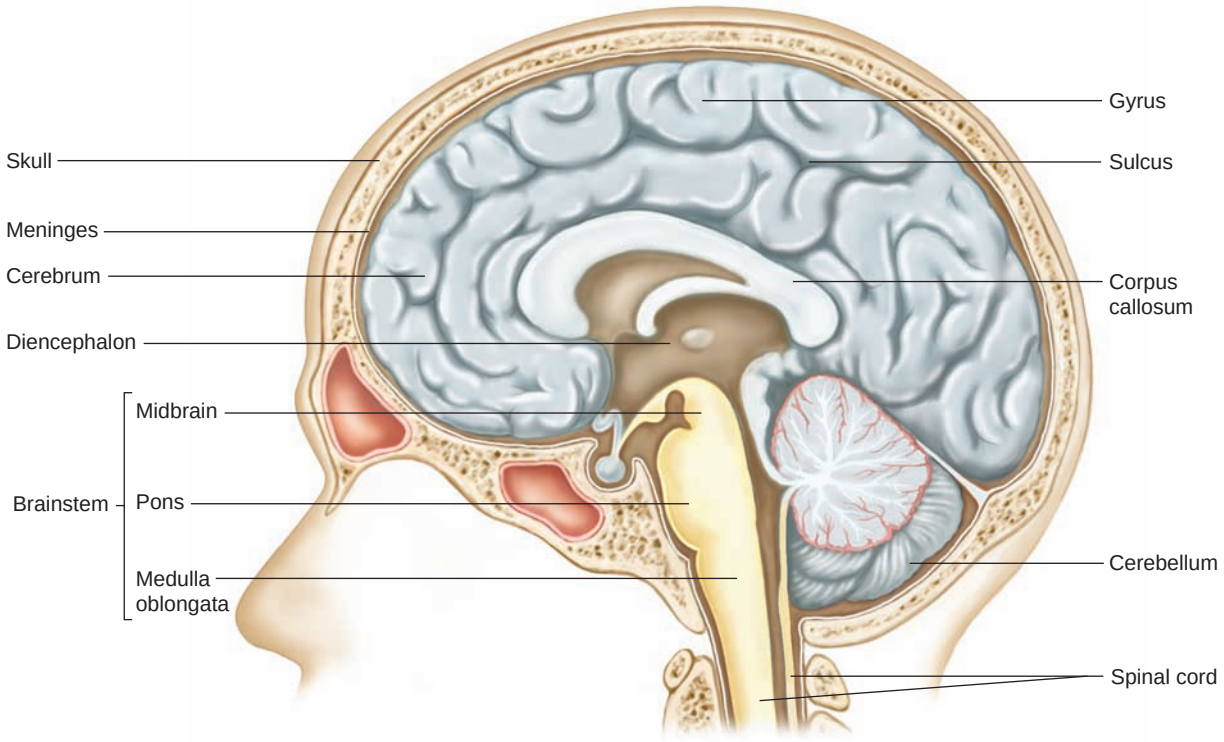


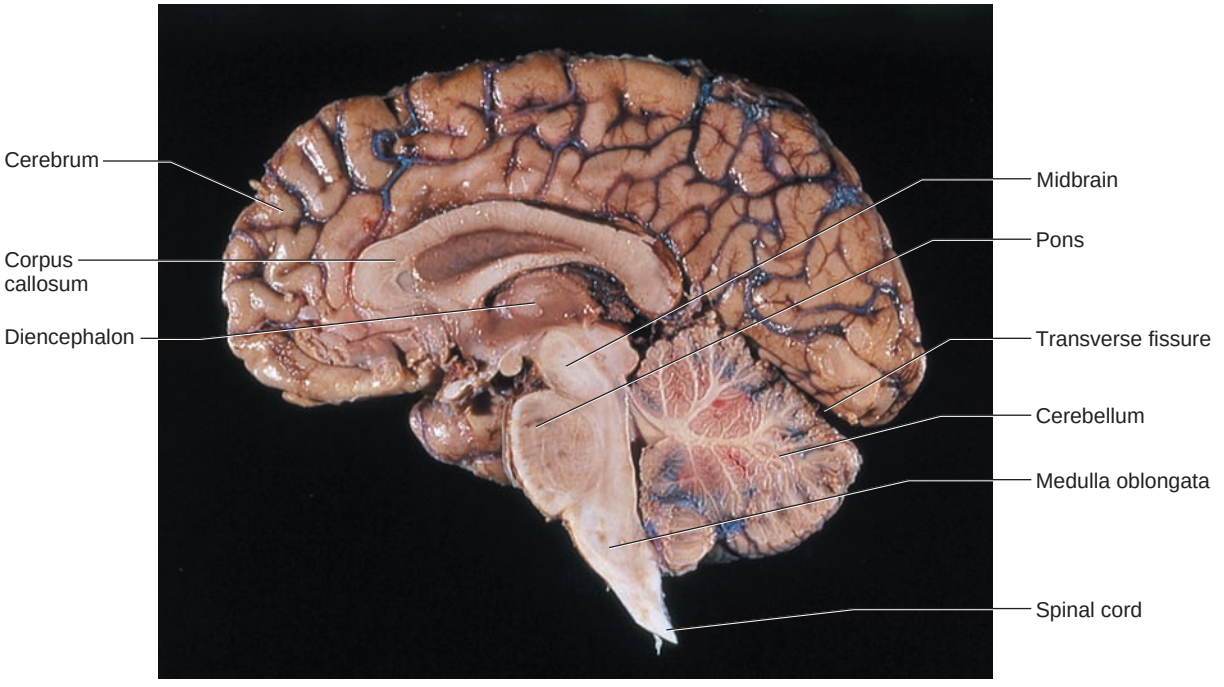
Figure 9.26
Descending tracts. Motor fibers of the corticospinal tract begin in the cerebral cortex, cross over in the medulla oblongata, and descend in the spinal cord. There, they synapse with neurons whose fibers lead to the spinal nerves that supply skeletal muscles.

9.14 BRAIN

The **brain** is composed of about 100 billion (10^{11}) multipolar neurons which communicate with one another and with neurons in other parts of the nervous system. As figure 9.27 shows, the brain can be divided into four major portions—the cerebrum, the diencephalon, the brainstem, and the cerebellum. The *cerebrum,* the largest part, includes nerve centers associated with sensory and motor functions and provides higher mental functions, including memory and reasoning. The *diencephalon* also processes sensory information. Nerve pathways in the *brainstem* connect various parts of the nervous system and regulate certain visceral activities. The *cerebellum* includes centers that coordinate voluntary muscular movements.



(a)



(b)

Figure 9.27

The major portions of the brain are the cerebrum, the diencephalon, the brainstem, and the cerebellum.

Structure of the Cerebrum

The **cerebrum** (ser′ĕ-brum) consists of two large masses called the left and right **cerebral hemispheres** (ser″ĕ-bral hem′ĭ-sfērz), which are essentially mirror images of each other. A deep bridge of nerve fibers called the **corpus callosum** (kor′pus kah-lo′sum) connects the cerebral hemispheres. A layer of dura mater (falx cerebri) separates them.

The surface of the cerebrum has many ridges (convolutions) or **gyri** (ji′ri), singular *gyrus*, separated by

grooves. A shallow groove is called a **sulcus** (sul′kus), and a deep groove is called a **fissure.** Although the structural organization of these elevations and depressions is complex, they form distinct patterns in all normal brains. For example, a *longitudinal fissure* separates the right and left cerebral hemispheres, a *transverse fissure* separates the cerebrum from the cerebellum, and several sulci divide each hemisphere into lobes.

The lobes of the cerebral hemispheres are named after the skull bones they underlie (fig. 9.28). They include:

1. **Frontal lobe** The frontal lobe forms the anterior portion of each cerebral hemisphere. It is bordered posteriorly by a *central sulcus,* which extends from the longitudinal fissure at a right angle, and inferiorly by a *lateral sulcus,* which extends from the undersurface of the brain along its sides.
2. **Parietal lobe** The parietal lobe is posterior to the frontal lobe and separated from it by the central sulcus.
3. **Temporal lobe** The temporal lobe lies below the frontal and parietal lobes and is separated from them by the lateral sulcus.
4. **Occipital lobe** The occipital lobe forms the posterior portion of each cerebral hemisphere and is separated from the cerebellum by a shelflike extension of dura mater (tentorium cerebelli). The boundary between the occipital lobe and the parietal and temporal lobes is not distinct.
5. **Insula** (in′su-lah) The insula is located deep within the lateral sulcus and is covered by parts of the frontal, parietal, and temporal lobes. A *circular sulcus* separates the insula from the other lobes.

A thin layer of gray matter called the **cerebral cortex** (ser″ĕ-bral kor′teks) is the outermost portion of the cerebrum. This layer covers the gyri and dips into the sulci and fissures. It contains nearly 75% of all the neuron cell bodies in the nervous system.

Just beneath the cerebral cortex is a mass of white matter that makes up the bulk of the cerebrum. This mass contains bundles of myelinated axons that connect neuron cell bodies of the cortex with other parts of the nervous system. Some of these fibers pass from one cerebral hemisphere to the other by way of the corpus callosum, and others carry sensory or motor impulses from portions of the cortex to nerve centers in the brain or spinal cord.

Functions of the Cerebrum

The cerebrum provides higher brain functions. It has centers for interpreting sensory impulses arriving from sense organs and centers for initiating voluntary muscular movements. The cerebrum stores the information that comprises memory and utilizes it to reason. Intelligence and personality also stem from cerebral activity.

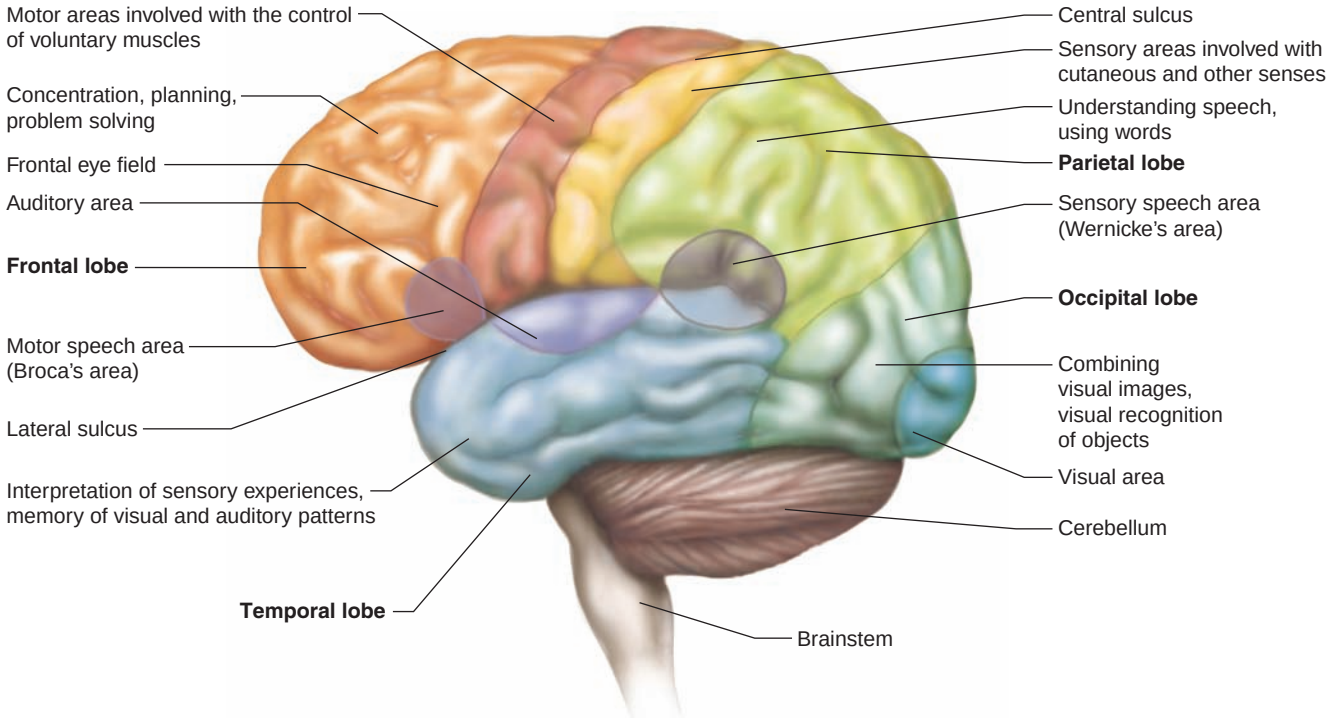


Figure 9.28

The cerebral cortex. Major portions of the cortex, called lobes, are named for the skull bones they lie beneath. The figure also depicts motor, sensory, and association areas of the left cerebral cortex.

Functional Regions of the Cerebral Cortex

Specific regions of the cerebral cortex perform specific functions. Although functions overlap among regions, the cortex can be divided into motor, sensory, and association areas.

The primary **motor areas** of the cerebral cortex lie in the frontal lobes, just in front of the central sulcus (fig. 9.28). The nervous tissue in these regions contains many large *pyramidal cells,* named for their pyramid-shaped cell bodies. These cells are also termed *upper motor neurons,* because of their location.

Impulses from the pyramidal cells travel downward through the brainstem and into the spinal cord on the corticospinal tracts (see fig. 9.26). Here they form synapses with *lower motor neurons* whose axons leave the spinal cord and reach skeletal muscle fibers. Most of the axons in these tracts cross over from one side of the brain to the other within the brainstem. As a result, the motor area of the right cerebral hemisphere generally controls skeletal muscles on the left side of the body, and vice versa.

In addition to the primary motor areas, certain other regions of the frontal lobe affect motor functions. For example, anterior and lateral to the primary motor cortex is a region called the *frontal eye field.* The motor cortex in this area controls voluntary movements of the eyes and eyelids. Another region just in front of the primary motor area controls the muscular movements of the hands and fingers that make skills such as writing possible.

Sensory areas located in several lobes of the cerebrum interpret impulses that arrive from sensory receptors, producing feelings or sensations. For example, sensations from all parts of the skin (cutaneous senses) arise in the anterior portions of the parietal lobes along the central sulcus (fig. 9.28). The posterior parts of the occipital lobes affect vision (visual area), and the temporal lobes contain the centers for hearing (auditory area). The sensory areas for taste are located near the bases of the central sulci along the lateral sulci, and the sense of smell arises from centers deep within the cerebrum.

Like motor fibers, sensory fibers cross over either in the spinal cord or in the brainstem (see fig. 9.25). Thus, the centers in the right cerebral hemisphere interpret impulses originating from the left side of the body, and vice versa.

Association areas are neither primarily sensory nor primarily motor. They connect with one another and with other brain structures. These areas analyze and interpret sensory experiences and oversee memory, reasoning, verbalizing, judgment, and emotion. Association areas occupy the anterior portions of the frontal lobes and are widespread in the lateral portions of the parietal, temporal, and occipital lobes (fig. 9.28).

Association areas of the frontal lobes control a number of higher intellectual processes. These include concentrating, planning, complex problem solving, and judging the possible consequences of behavior. Association areas of the parietal lobes help in understanding speech and choosing words to express thoughts and feelings. Two connected areas that accomplish this are the *sensory speech area* or Wernicke's (ver′nĭ-kēz) area and the *motor speech area* or Broca's (bro′kahz) area. In most people these are found in the left hemisphere. The sensory speech area is located in the parietal lobe near the temporal lobe, just posterior to the lateral sulcus. This area receives input from both the visual cortex and auditory cortex, and is necessary for understanding written and spoken language. The motor speech area is in the frontal lobe, just anterior to the primary motor cortex and superior to the lateral sulcus. This area generates the movements of muscles necessary for speech (fig. 9.28).

These regions also provide memory of visual scenes, music, and other complex sensory patterns. Association areas of the occipital lobes that are adjacent to the visual centers are important in analyzing visual patterns and combining visual images with other sensory experiences, as when one recognizes another person or an object.

Check Your Recall

36. List the major divisions of the brain.
37. Describe the cerebral cortex.
38. Describe the major functions of the cerebrum.
39. Locate the major functional regions of the cerebral cortex.

The effects of injuries to the cerebral cortex depend on the location and extent of the damage. The abilities that become impaired can indicate the site of damage. For example, injury to the motor areas of one frontal lobe causes partial or complete paralysis on the opposite side of the body.

A person with damage to the association areas of the frontal lobe may have difficulty concentrating on complex mental tasks and may appear disorganized and easily distracted. A person who suffers damage to association areas of the temporal lobes may have trouble recognizing printed words or arranging words into meaningful thoughts.

Hemisphere Dominance

Both cerebral hemispheres participate in basic functions, such as receiving and analyzing sensory impulses, controlling skeletal muscles, and storing memory. However, in most persons, one side of the cerebrum is the **dominant hemisphere,** controlling the ability to use and understand language.

In most people the left hemisphere is dominant for the language-related activities of speech, writing, and reading, and for complex intellectual functions requiring verbal, analytical, and computational skills. In other persons, the right hemisphere is dominant for language-related abilities, or the hemispheres are equally dominant. Broca's area in the dominant hemisphere controls the muscles that function in speaking.

In addition to carrying on basic functions, the nondominant hemisphere specializes in nonverbal functions, such as motor tasks that require orientation of the body in space, understanding and interpreting musical patterns, and nonverbal visual experiences. The nondominant hemisphere also controls emotional and intuitive thinking.

Nerve fibers of the corpus callosum, which connect the cerebral hemispheres, allow the dominant hemisphere to control the motor cortex of the nondominant hemisphere (see fig. 9.27). These fibers also transfer sensory information reaching the nondominant hemisphere to the dominant one, where the information can be used in decision making.

Deep within each cerebral hemisphere are several masses of gray matter called **basal nuclei** (basal ganglia) (fig. 9.29). They are the *caudate nucleus,* the *putamen,* and the *globus pallidus.* Their neuron cell bodies serve as relay stations for motor impulses originating in the cerebral cortex and passing into the brainstem and spinal cord. The basal nuclei modify the pattern of these motor impulses and thereby help control various skeletal muscle activities. Neurons of the basal nuclei respond to the inhibitory neurotransmitter dopamine released from nearby cells.

The signs of Parkinson disease and Huntington disease result from altered activity of basal nuclei neurons. In Parkinson disease, nearby neurons release less dopamine, and the basal nuclei become overactive, inhibiting movement. In Huntington disease, basal nuclei neurons gradually deteriorate, resulting in unrestrained movement.

Ventricles and Cerebrospinal Fluid

Within the cerebral hemispheres and brainstem is a series of interconnected cavities called **ventricles** (fig. 9.30). These spaces are continuous with the central canal of the spinal cord, and like it, they contain cerebrospinal fluid.

The largest ventricles are the *lateral ventricles* (first and second ventricles), which extend into the cerebral hemispheres and occupy portions of the frontal, temporal, and occipital lobes. A narrow space that constitutes the *third ventricle* is in the midline of the brain, beneath the corpus callosum. This ventricle communicates with the lateral ventricles through openings (interventricular foramina) in its anterior end. The *fourth ventricle* is in the brainstem just anterior to the cerebellum. A narrow canal, the *cerebral aqueduct,* connects it to the third ventricle and passes lengthwise through the brainstem. The fourth ventricle is continuous with

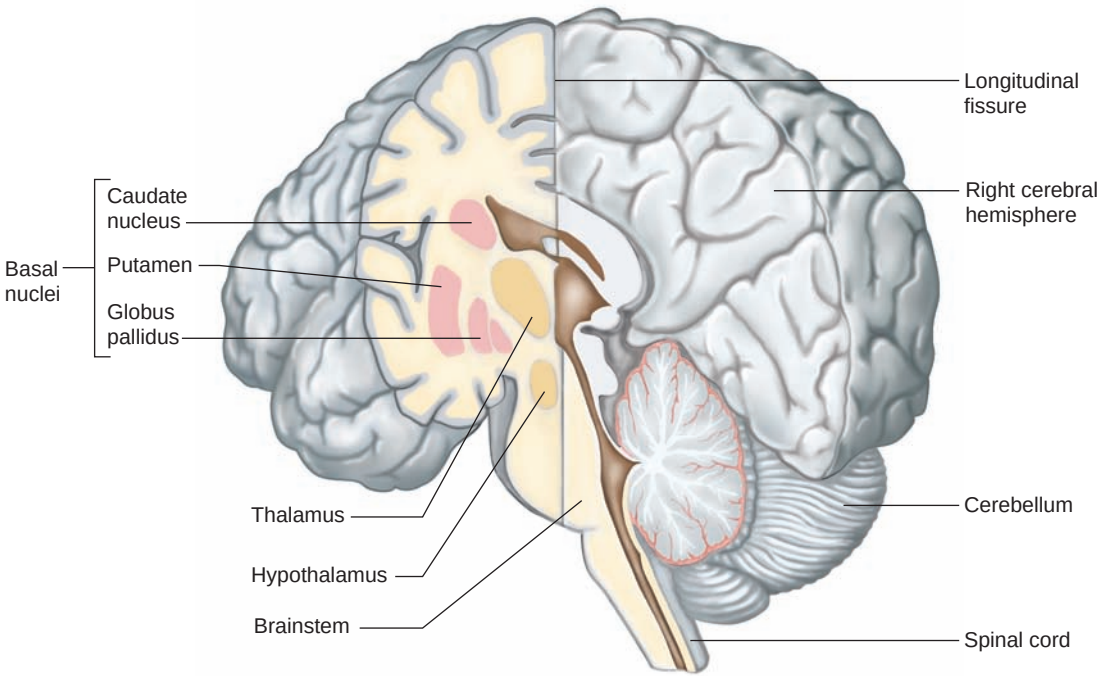


Figure 9.29
A coronal section of the left cerebral hemisphere reveals some of the basal nuclei.

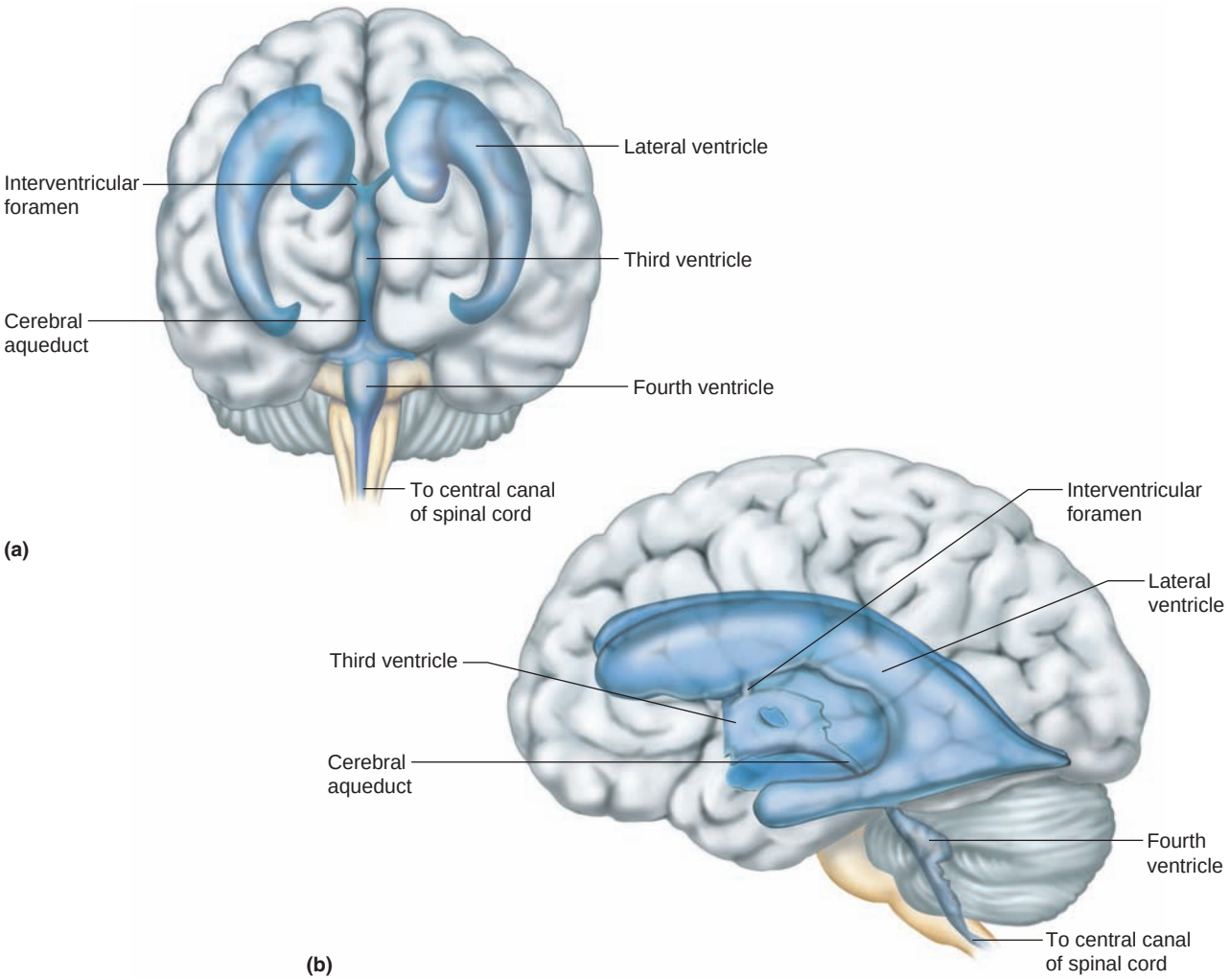


Figure 9.30

Ventricles in the brain. (*a*) Anterior view of the ventricles within the cerebral hemispheres and brainstem. (*b*) Lateral view.

the central canal of the spinal cord and has openings in its roof that lead into the subarachnoid space of the meninges.

Tiny, reddish, cauliflower-like masses of specialized capillaries from the pia mater, called **choroid plexuses** (plek′sus-ez), secrete cerebrospinal fluid (fig. 9.31). These structures project into the ventricles. Most of the cerebrospinal fluid is formed in the lateral ventricles. From there, it circulates slowly into the third and fourth ventricles and into the central canal of the spinal cord. Cerebrospinal fluid also enters the subarachnoid space of the meninges through the wall of the fourth ventricle near the cerebellum and completes its circuit by being reabsorbed into the blood.

Cerebrospinal fluid completely surrounds the brain and spinal cord because it occupies the subarachnoid space of the meninges. In effect, these organs float in the fluid, which supports and protects them by absorbing forces that might otherwise jar and damage them. Cerebrospinal fluid also maintains a stable ionic concentration in the CNS and provides a pathway to the blood for wastes.

Because cerebrospinal fluid is secreted and reabsorbed continuously, the fluid pressure in the ventricles normally remains relatively constant. An infection, a tumor, or a blood clot can interfere with fluid circulation, increasing pressure within the ventricles and thus in the cranial cavity (intracranial pressure). This can injure the brain by forcing it against the rigid skull.

A *lumbar puncture* (spinal tap) is used to measure the pressure of cerebrospinal fluid. In this procedure, a fine, hollow needle is inserted into the subarachnoid space between the third and fourth or between the fourth and fifth lumbar vertebrae. An instrument called a *manometer* then measures the pressure.

Check Your Recall

40. What is hemisphere dominance?
41. What are the major functions of the dominant hemisphere? The nondominant one?
42. Where are the ventricles of the brain?
43. Describe the circulation of cerebrospinal fluid.

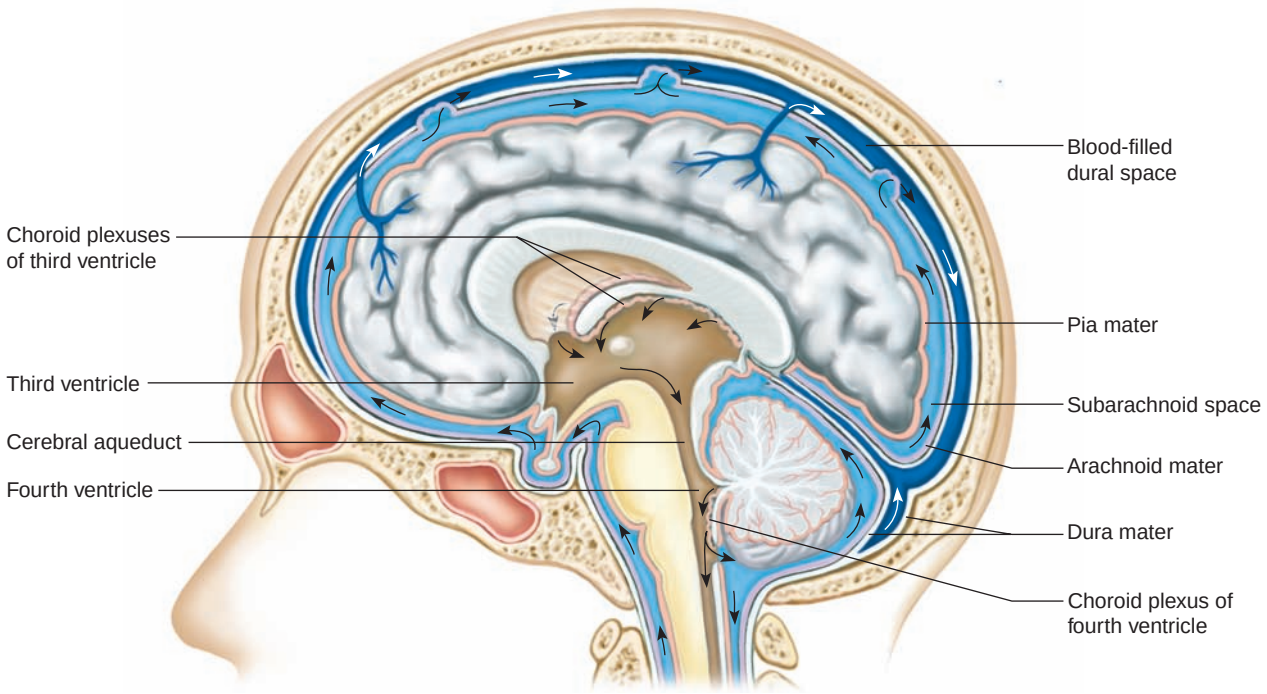


Figure 9.31

The choroid plexuses in the walls of the ventricles secrete cerebrospinal fluid. The fluid circulates through the ventricles and central canal, enters the subarachnoid space, and is reabsorbed into the blood.

Diencephalon

The **diencephalon** (di″en-sef′ah-lon) is located between the cerebral hemispheres and above the midbrain. It surrounds the third ventricle and is composed largely of gray matter. Within the diencephalon, a dense mass called the **thalamus** bulges into the third ventricle from each side (see figs. 9.29 and 9.32*b*). Another region of the diencephalon that includes many nuclei (masses of gray matter) is the **hypothalamus.** It lies below the thalamus and forms the lower walls and floor of the third ventricle.

Other parts of the diencephalon include: (1) the **optic tracts** and the **optic chiasma** that is formed by optic nerve fibers crossing over each other; (2) the **infundibulum,** a conical process behind the optic chiasma to which the pituitary gland attaches; (3) the **posterior pituitary gland,** which hangs from the floor of the hypothalamus; (4) the **mammillary bodies,** which appear as two rounded structures behind the infundibulum; and (5) the **pineal gland** (pin′e-al gland), a cone-shaped structure attached to the upper portion of the diencephalon (see chapter 11, p. 307).

The thalamus is a central relay station for sensory impulses ascending from other parts of the nervous system to the cerebral cortex. It receives all sensory impulses (except those associated with the sense of smell) and channels them to the appropriate regions of the cortex for interpretation. In addition, all regions of the cerebral cortex can communicate with the thalamus by means of descending fibers. The cerebral cortex pinpoints the origin of sensory stimulation, and the thalamus produces a general awareness of certain sensations, such as pain, touch, and temperature.

Nerve fibers connect the hypothalamus to the cerebral cortex, thalamus, and other parts of the brainstem. The hypothalamus maintains homeostasis by regulating a variety of visceral activities and by linking the nervous and endocrine systems. The hypothalamus regulates:

1. Heart rate and arterial blood pressure
2. Body temperature
3. Water and electrolyte balance
4. Control of hunger and body weight
5. Control of movements and glandular secretions of the stomach and intestines
6. Production of neurosecretory substances that stimulate the pituitary gland to secrete hormones
7. Sleep and wakefulness

Structures in the general region of the diencephalon also control emotional responses. For example, portions of the cerebral cortex in the medial parts of the frontal and temporal lobes interconnect with a number of deep masses of gray matter, including the hypothalamus, thalamus, and basal nuclei. Together, these structures comprise a complex called the **limbic system.**

The limbic system controls emotional experience and expression. It can modify the way a person acts by producing such feelings as fear, anger, pleasure, and sorrow. The limbic system recognizes upsets in a person's physical or psychological condition that might threaten

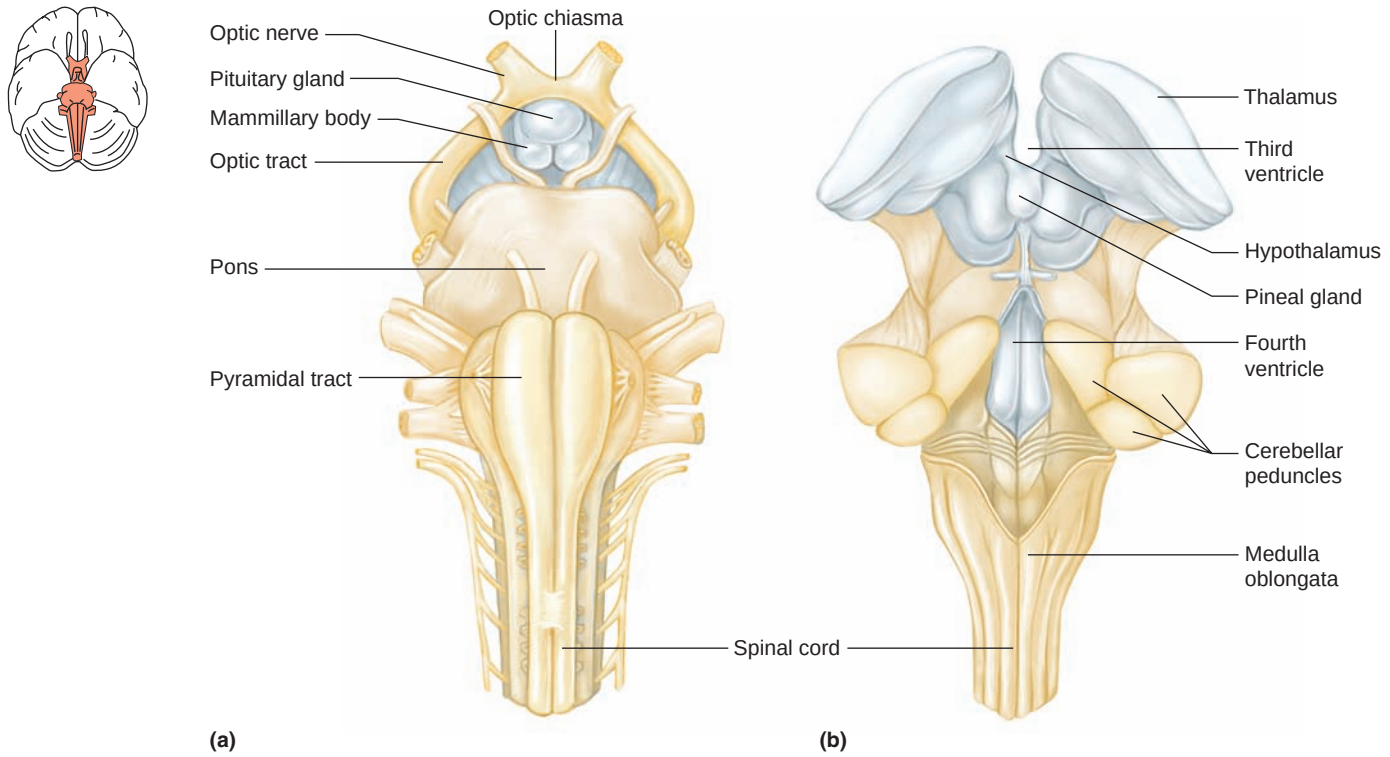


Figure 9.32

The brainstem. (*a*) Ventral view of the brainstem. (*b*) Dorsal view of the brainstem with the cerebellum removed, exposing the fourth ventricle.

life. By causing pleasant or unpleasant feelings about experiences, the limbic system guides a person into behavior that is likely to increase the chance of survival.

Brainstem

The **brainstem** is a bundle of nervous tissue that connects the cerebrum to the spinal cord. It consists of numerous tracts of nerve fibers and several nuclei. The parts of the brainstem include the midbrain, pons, and medulla oblongata (figs. 9.27 and 9.32).

Midbrain

The **midbrain** is a short section of the brainstem between the diencephalon and the pons (see fig. 9.27). It contains bundles of myelinated axons that join lower parts of the brainstem and spinal cord with higher parts of the brain. Two prominent bundles of axons on the underside of the midbrain are the corticospinal tracts and are the main motor pathways between the cerebrum and lower parts of the nervous system.

The midbrain includes several masses of gray matter that serve as reflex centers. For example, the midbrain contains the centers for certain visual reflexes, such as those responsible for moving the eyes to view something as the head turns. It also contains the auditory reflex centers that enable a person to move the head to hear sounds more distinctly.

Pons

The **pons** (ponz) is a rounded bulge on the underside of the brainstem, where it separates the midbrain from the medulla oblongata (see fig. 9.27). The dorsal portion of the pons consists largely of longitudinal nerve fibers, which relay impulses to and from the medulla oblongata and the cerebrum. The ventral portion of the pons has large bundles of transverse nerve fibers, which transmit impulses from the cerebrum to centers within the cerebellum.

Several nuclei of the pons relay sensory impulses from peripheral nerves to higher brain centers. Other nuclei function with centers of the medulla oblongata to maintain the basic rhythm of breathing (see chapter 16, pp. 457–458).

Medulla Oblongata

The **medulla oblongata** (mĕ-dul′ah ob″long-gah′tah) extends from the pons to the foramen magnum of the skull (see fig. 9.27). Its dorsal surface flattens to form the floor of the fourth ventricle, and its ventral surface is marked by the corticospinal tracts, most of whose fibers cross over at this level (see fig. 9.26).

All of the ascending and descending nerve fibers connecting the brain and spinal cord must pass through the medulla oblongata because of its location. As in the spinal cord, the white matter of the medulla oblongata surrounds a central mass of gray matter. Here, however,

nerve fibers separate the gray matter into nuclei, some of which relay ascending impulses to the other side of the brainstem and then on to higher brain centers. Other nuclei within the medulla oblongata control vital visceral activities. These centers include:

1. **Cardiac center** Impulses originating in the cardiac center are transmitted to the heart on peripheral nerves, altering heart rate.
2. **Vasomotor center** Certain cells of the vasomotor center initiate impulses that travel to smooth muscles in the walls of certain blood vessels and stimulate them to contract. This constricts the blood vessels (vasoconstriction), elevating blood pressure. Other cells of the vasomotor center produce the opposite effect—dilating blood vessels (vasodilation) and consequently dropping blood pressure.
3. **Respiratory center** The respiratory center adjusts the rate and depth of breathing and acts with the pons to maintain the basic rhythm of breathing.

Still other nuclei within the medulla oblongata are centers for the reflexes associated with coughing, sneezing, swallowing, and vomiting.

Reticular Formation

Scattered throughout the medulla oblongata, pons, and midbrain is a complex network of nerve fibers associated with tiny islands of gray matter. This network, the **reticular formation** (rĕ-tik′u-lar for-ma′shun) (reticular activating system), extends from the upper portion of the spinal cord into the diencephalon. Its nerve fibers join centers of the hypothalamus, basal nuclei, cerebellum, and cerebrum with fibers in all the major ascending and descending tracts.

When sensory impulses reach the reticular formation, it responds by activating the cerebral cortex into a state of wakefulness. Without this arousal, the cortex remains unaware of stimulation and cannot interpret sensory information or carry on thought processes. Thus, decreased activity in the reticular formation results in sleep. If the reticular formation is injured so that it cannot function, the person remains unconscious and cannot be aroused, even with strong stimulation. This is called a comatose state. Barbiturate drugs, which dampen CNS activity, affect the reticular formation (see the Topic of Interest on page 245).

Check Your Recall

44. What are the major functions of the thalamus? The hypothalamus?
45. How may the limbic system influence behavior?
46. List the structures of the brainstem.
47. What vital reflex centers are located in the brainstem?
48. What is the function of the reticular formation?

Cerebellum

The **cerebellum** (ser″ĕ-bel′um) is a large mass of tissue located below the occipital lobes of the cerebrum and posterior to the pons and medulla oblongata (see fig. 9.27). It consists of two lateral hemispheres partially separated by a layer of dura mater (falx cerebelli) and connected in the midline by a structure called the *vermis.* Like the cerebrum, the cerebellum is composed primarily of white matter, with a thin layer of gray matter, the **cerebellar cortex,** on its surface.

The cerebellum communicates with other parts of the CNS by means of three pairs of nerve tracts called *cerebellar peduncles* (figs. 9.32 and 9.33). One pair (the inferior peduncles) brings sensory information concerning the position of the limbs, joints, and other body parts to the cerebellum. Another pair (the middle peduncles) transmits signals from the cerebral cortex to the cerebellum concerning the desired positions of these parts. After integrating and analyzing this information, the cerebellum sends correcting impulses via a third pair (the superior peduncles) to the midbrain. These corrections are incorporated into motor impulses that travel downward through the pons, medulla oblongata, and spinal cord in the appropriate patterns to move the body in the desired way.

The cerebellum is a reflex center for integrating sensory information concerning the position of body parts and for coordinating complex skeletal muscle movements. It also helps maintain posture. Damage to the cerebellum is likely to result in tremors, inaccurate movements of voluntary muscles, loss of muscle tone, a reeling walk, and loss of equilibrium.

Check Your Recall

49. Where is the cerebellum located?
50. What are the major functions of the cerebellum?

9.15 PERIPHERAL NERVOUS SYSTEM

The peripheral nervous system (PNS) consists of nerves that branch out from the CNS and connect it to other body parts. The PNS includes the cranial nerves, which arise from the brain, and the spinal nerves, which arise from the spinal cord.

The PNS can also be subdivided into the somatic and autonomic nervous systems. Generally, the **somatic** (so-mat′ik) **nervous system** consists of the cranial and spinal nerve fibers that connect the CNS to the skin and skeletal muscles; it oversees conscious activities. The **autonomic** (aw″to-nom′ik) **nervous system** includes fibers that connect the CNS to viscera, such as the heart, stomach, intestines, and glands; it controls unconscious

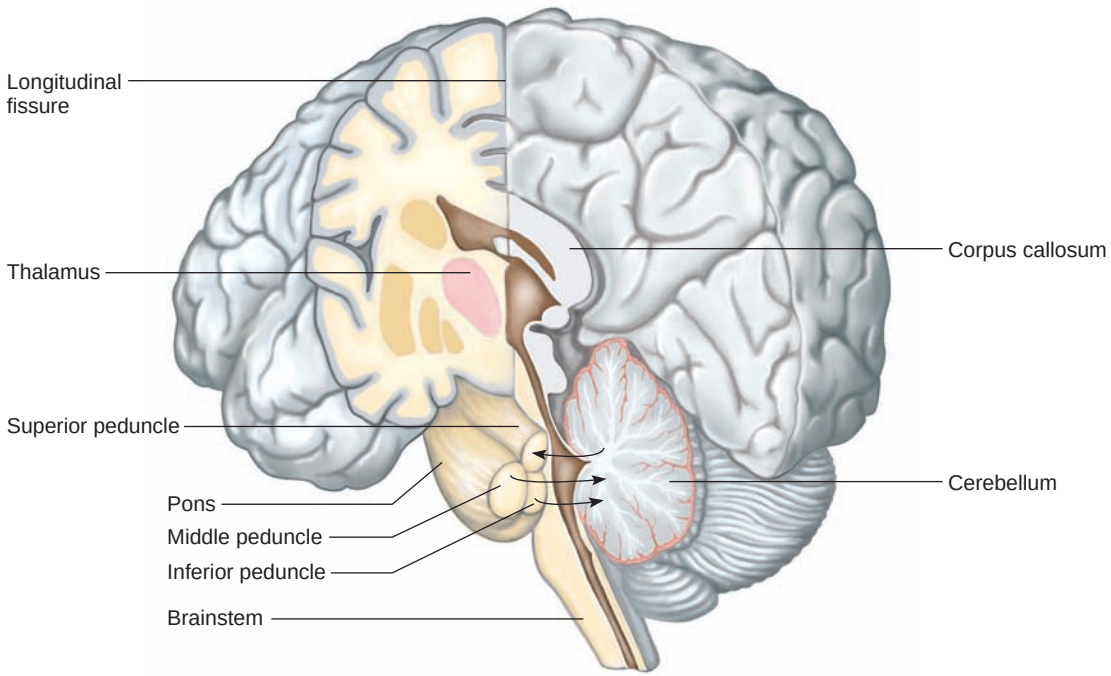


Figure 9.33

The cerebellum, which is located below the occipital lobes of the cerebrum, communicates with other parts of the nervous system by means of the cerebellar peduncles.

activities. Table 9.5 outlines the subdivisions of the nervous system (see fig. 9.2).

Cranial Nerves

Twelve pairs of **cranial nerves** arise from the underside of the brain (fig. 9.34). Except for the first pair, which begins in the cerebrum, these nerves originate from the brainstem. They pass from their sites of origin through foramina of the skull and lead to parts of the head, neck, and trunk.

Most of the cranial nerves are mixed nerves, but some of those associated with special senses, such as smell and vision, contain only sensory fibers. Other cranial nerves that affect muscles and glands are composed primarily of motor fibers.

Table 9.5 Subdivisions of the Nervous System

1. Central nervous system (CNS)
   a. Brain
   b. Spinal cord
2. Peripheral nervous system (PNS)
   a. Cranial nerves arising from the brain and brainstem
      (1) Somatic fibers connecting to skin and skeletal muscles
      (2) Autonomic fibers connecting to viscera
   b. Spinal nerves arising from the spinal cord
      (1) Somatic fibers connecting to skin and skeletal muscles
      (2) Autonomic fibers connecting to viscera

Sensory fibers present in the cranial nerves have neuron cell bodies that are outside the brain, usually in groups called *ganglia*. On the other hand, motor neuron cell bodies are typically located within the gray matter of the brain.

Numbers or names designate the cranial nerves. The numbers indicate the order in which the nerves arise from the front to the back of the brain, and the names describe their primary functions or the general distribution of their fibers (fig. 9.34).

The first pair of cranial nerves, the **olfactory nerves (I),** are associated with the sense of smell and contain axons only of sensory neurons. These bipolar neurons, located in the lining of the upper nasal cavity, serve as *olfactory receptor cells.* Axons from these receptors pass upward through the cribriform plates of the ethmoid bone, carrying impulses to the olfactory neurons in the *olfactory bulbs,* which are extensions of the cerebral cortex located just beneath the frontal lobes (see fig. 10.4, p. 266). Sensory impulses travel from the olfactory bulbs along *olfactory tracts* to cerebral centers where they are interpreted. The result of this interpretation is the sensation of smell.

The second pair of cranial nerves, the **optic nerves (II),** lead from the eyes to the brain and are associated with vision. The sensory nerve cell bodies of these nerve fibers are in ganglion cell layers within the eyes, and their axons pass through the *optic foramina* of the orbits and continue into the visual nerve pathways of the brain (see chapter 10, p. 284). Sensory impulses

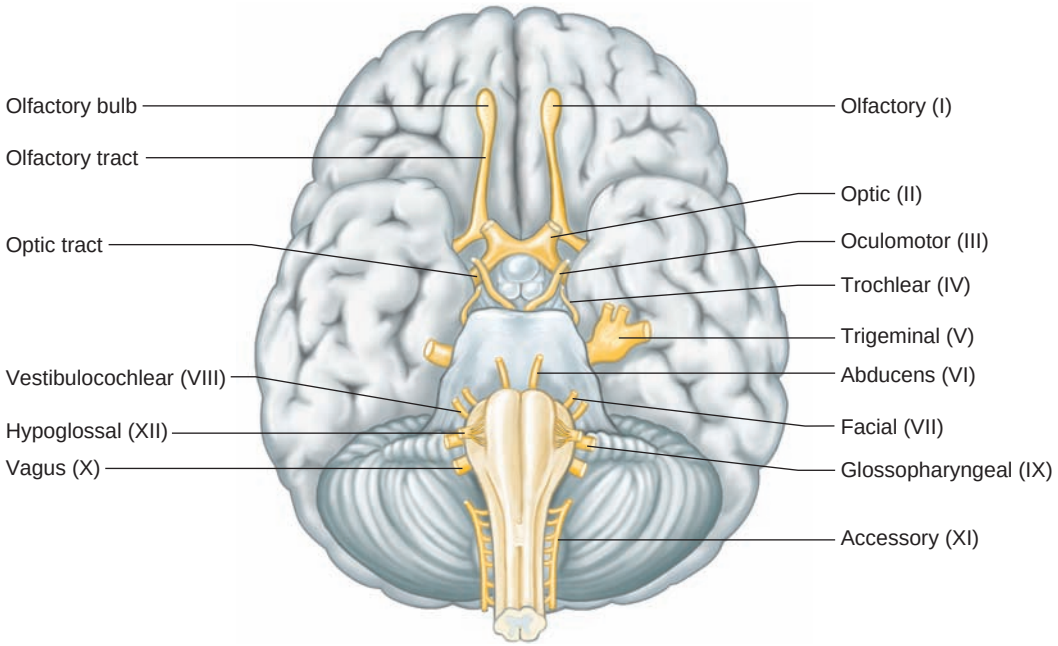


Figure 9.34

The cranial nerves, except for the first pair, arise from the brainstem. They are identified by numbers indicating their order, by their function, or by the general distribution of their fibers.

transmitted on the optic nerves are interpreted in the visual cortices of the occipital lobes.

The third pair of cranial nerves, the **oculomotor nerves (III),** arise from the midbrain and pass into the orbits of the eyes. One component of each nerve connects to the voluntary muscles that raise the eyelid and to four of the six muscles that move the eye. A second component of each oculomotor nerve is part of the autonomic nervous system and supplies involuntary muscles within the eyes. These muscles adjust the amount of light entering the eyes and focus the lenses.

The fourth pair of cranial nerves, the **trochlear nerves (IV),** arise from the midbrain and are the smallest cranial nerves. Each nerve carries motor impulses to a fifth voluntary muscle that moves the eye and is not innervated by the oculomotor nerve.

The fifth pair of cranial nerves, the **trigeminal nerves (V),** are the largest cranial nerves and arise from the pons. They are mixed nerves, with the sensory portions more extensive than the motor portions. Each sensory component includes three large branches, called the ophthalmic, maxillary, and mandibular divisions.

The *ophthalmic division* of the trigeminal nerves consists of sensory fibers that bring impulses to the brain from the surface of the eyes, the tear glands, and the skin of the anterior scalp, forehead, and upper eyelids. The fibers of the *maxillary division* carry sensory impulses from the upper teeth, upper gum, and upper lip, as well as from the mucous lining of the palate and the skin of the face. The *mandibular division* includes both motor and sensory fibers. The sensory branches transmit impulses from the scalp behind the ears, the skin of the jaw, the lower teeth, the lower gum, and the lower lip. The motor branches supply the muscles of mastication and certain muscles in the floor of the mouth.

The sixth pair of cranial nerves, the **abducens nerves (VI),** are quite small and originate from the pons near the medulla oblongata. Each nerve enters the orbit of the eye and supplies motor impulses to the remaining muscle that moves the eye.

The seventh pair of cranial nerves, the **facial nerves (VII),** arise from the lower part of the pons and emerge on the sides of the face. Their sensory branches are associated with taste receptors on the anterior two-thirds of the tongue, and some of their motor fibers transmit impulses to the muscles of facial expression. Still other motor fibers of these nerves function in the autonomic nervous system and stimulate secretions from tear glands and salivary glands.

The eighth pair of cranial nerves, the **vestibulocochlear nerves (VIII),** are sensory nerves that arise from the medulla oblongata. Each of these nerves has two distinct parts—a vestibular branch and a cochlear branch.

The neuron cell bodies of the *vestibular branch* fibers are located in ganglia associated with parts of the inner ear. These parts contain the receptors involved with reflexes that help maintain equilibrium. The neuron cell bodies of the *cochlear branch* fibers are located in the parts of the inner ear that house the hearing receptors. Impulses from these branches pass through the pons and medulla oblongata on their way to the temporal lobes, where they are interpreted.

Topic of Interest

Drug Abuse

Drug abuse is the chronic self-administration of a drug in doses high enough to cause *addiction*—a physical or psychological dependence in which the user is preoccupied with locating and taking the drug. Stopping drug use causes intense, unpleasant withdrawal symptoms. Prolonged and repeated abuse of a drug may also result in *drug tolerance,* in which the physiological response to a particular dose of the drug becomes less intense over time. Drug tolerance results as the drug increases synthesis of certain liver enzymes, which metabolize the drug more rapidly, so that the addict needs the next dose sooner. Drug tolerance also arises from physiological changes that lessen the drug's effect on its target cells.

The most commonly abused drugs are CNS depressants ("downers"), CNS stimulants ("uppers"), hallucinogens, and anabolic steroids (see Topic of Interest in chapter 8, p. 186).

CNS depressants include barbiturates, benzodiazepines, opiates, and cannabinoids. *Barbiturates* act uniformly throughout the brain, but the reticular formation is particularly sensitive to their effects. CNS depression occurs due to inhibited secretion of certain excitatory and inhibitory neurotransmitters. Effects range from mild calming of the nervous system (sedation) to sleep, loss of sensory sensations (anesthesia), respiratory distress, cardiovascular collapse, and death.

The *benzodiazepines,* such as diazepam, depress activity in the limbic system and the reticular formation. Low doses relieve anxiety, and higher doses cause sedation, sleep, or anesthesia. These drugs increase either the activity or release of the inhibitory neurotransmitter GABA. When benzodiazepines are metabolized, they may form other biochemicals that have depressing effects.

The *opiates* include heroin (which has no legal use in the United States), codeine, morphine, meperidine, and methadone. These drugs stimulate certain receptors (opioid receptors) in the CNS, and when taken in prescribed dosages, they sedate and relieve pain (analgesia). Opiates cause both physical and psychological dependence. Effects of overdose include a feeling of well-being (euphoria), respiratory distress, convulsions, coma, and possible death. On the other hand, these drugs are very important in treating chronic, severe pain. For example, cancer patients find pain relief with oxycodone, which is taken twice daily in a timed-release pill. Many people abuse this drug, and by breaking the pills, release high doses rapidly, which can be deadly.

The *cannabinoids* include marijuana and hashish, both derived from the hemp plant. Hashish is several times more potent than marijuana. These drugs depress higher brain centers and release lower brain centers from the normal inhibitory influence of the higher centers. This induces an anxiety-free state, characterized by euphoria and a distorted perception of time and space. *Hallucinations* (sensory perceptions that have no external stimuli), respiratory distress, and vasomotor depression may occur with higher doses.

CNS stimulants include amphetamines and cocaine (including "crack"). These drugs have great abuse potential and may quickly produce psychological dependence. Cocaine, especially when smoked or inhaled, produces euphoria but may also change personality, cause seizures, and constrict certain blood vessels, leading to sudden death from stroke or cardiac arrhythmia. Cocaine's very rapid effect, and perhaps its addictiveness, reflect its rapid entry and metabolism in the brain. Cocaine arrives at the basal nuclei in 4 to 6 minutes and is cleared mostly within 30 minutes. The drug inhibits transporter molecules that remove dopamine from synapses after it is released. "Ecstasy" is a type of amphetamine.

Hallucinogens alter perceptions. They cause *illusions,* which are distortions of vision, hearing, taste, touch, and smell; *synesthesia,* such as "hearing" colors or "feeling" sounds; and hallucinations. The most commonly abused and most potent hallucinogen is lysergic acid diethylamide (LSD). LSD may act as an excitatory neurotransmitter. A person under the influence of LSD may greatly overestimate physical capabilities, such as believing he or she can fly off the top of a high building. Phencyclidine (PCP) is another commonly abused hallucinogen. Its use can lead to prolonged psychosis that may provoke assault, murder, and suicide.

The ninth pair of cranial nerves, the **glossopharyngeal nerves (IX),** are associated with the tongue and pharynx. These mixed nerves arise from the medulla oblongata, with predominantly sensory fibers. These sensory fibers carry impulses from the linings of the pharynx, tonsils, and posterior third of the tongue to the brain. Fibers in the motor component innervate muscles of the pharynx that function in swallowing.

The tenth pair of cranial nerves, the **vagus nerves (X),** originate in the medulla oblongata and extend downward through the neck into the chest and abdomen. These nerves are mixed, containing both somatic and autonomic branches, with autonomic fibers predominant. Certain somatic motor fibers carry impulses to muscles of the larynx that are associated with speech and swallowing. Autonomic motor fibers of the vagus

nerves supply the heart and many smooth muscles and glands in the thorax and abdomen.

The eleventh pair of cranial nerves, the **accessory nerves (XI),** originate in the medulla oblongata and the spinal cord; thus, they have both cranial and spinal branches. Each *cranial branch* joins a vagus nerve and carries impulses to muscles of the soft palate, pharynx, and larynx. The *spinal branch* descends into the neck and supplies motor fibers to the trapezius and sternocleidomastoid muscles.

The twelfth pair of cranial nerves, the **hypoglossal nerves (XII),** arise from the medulla oblongata and pass into the tongue. They include motor fibers that carry impulses to muscles that move the tongue in speaking, chewing, and swallowing. Table 9.6 summarizes the functions of the cranial nerves.

Check Your Recall

51. Define *peripheral nervous system.*
52. Distinguish between somatic and autonomic nerve fibers.
53. Name the cranial nerves, and list the major functions of each.

The consequences of a cranial nerve injury depend on the injury's location and extent. Damage to one member of a nerve pair limits loss of function to the affected side, but injury to both nerves affects both sides. If a nerve is severed completely, functional loss is total; if the cut is incomplete, loss may be partial.

Table 9.6 Functions of Cranial Nerves

Nerve		Type	Function
I	Olfactory	Sensory	Sensory fibers transmit impulses associated with the sense of smell.
II	Optic	Sensory	Sensory fibers transmit impulses associated with the sense of vision.
III	Oculomotor	Primarily motor	Motor fibers transmit impulses to muscles that raise eyelids, move eyes, adjust the amount of light entering the eyes, and focus lenses.
			Some sensory fibers transmit impulses associated with the condition of muscles.
IV	Trochlear	Primarily motor	Motor fibers transmit impulses to muscles that move the eyes.
			Some sensory fibers transmit impulses associated with the condition of muscles.
V	Trigeminal	Mixed	
	Ophthalmic division		Sensory fibers transmit impulses from the surface of the eyes, tear glands, scalp, forehead, and upper eyelids.
	Maxillary division		Sensory fibers transmit impulses from the upper teeth, upper gum, upper lip, lining of the palate, and skin of the face.
	Mandibular division		Sensory fibers transmit impulses from the skin of the jaw, lower teeth, lower gum, and lower lip.
			Motor fibers transmit impulses to muscles of mastication and to muscles in the floor of the mouth.
VI	Abducens	Primarily motor	Motor fibers transmit impulses to muscles that move the eyes.
			Some sensory fibers transmit impulses associated with the condition of muscles.
VII	Facial	Mixed	Sensory fibers transmit impulses associated with taste receptors of the anterior tongue. Motor fibers transmit impulses to muscles of facial expression, tear glands, and salivary glands.
VIII	Vestibulocochlear	Sensory	
	Vestibular branch		Sensory fibers transmit impulses associated with the sense of equilibrium.
	Cochlear branch		Sensory fibers transmit impulses associated with the sense of hearing.
IX	Glossopharyngeal	Mixed	Sensory fibers transmit impulses from the pharynx, tonsils, posterior tongue, and carotid arteries.
			Motor fibers transmit impulses to muscles of the pharynx used in swallowing and to salivary glands.
X	Vagus	Mixed	Somatic motor fibers transmit impulses to muscles associated with speech and swallowing; autonomic motor fibers transmit impulses to the heart, smooth muscles, and glands in the thorax and abdomen.
			Sensory fibers transmit impulses from the pharynx, larynx, esophagus, and viscera of the thorax and abdomen.
XI	Accessory	Primarily motor	
	Cranial branch		Motor fibers transmit impulses to muscles of the soft palate, pharynx, and larynx.
	Spinal branch		Motor fibers transmit impulses to muscles of the neck and back.
XII	Hypoglossal	Primarily motor	Motor fibers transmit impulses to muscles that move the tongue.

Spinal Nerves

Thirty-one pairs of **spinal nerves** originate from the spinal cord (fig. 9.35). They are mixed nerves that provide two-way communication between the spinal cord and parts of the upper and lower limbs, neck, and trunk.

Spinal nerves are not named individually, but are grouped according to the level from which they arise. Each nerve is numbered in sequence. On each vertebra the vertebral notches, the major parts of the intervertebral foramina, are associated with the inferior portion of their respective vertebrae. For this reason, each spinal nerve, as it passes through the intervertebral foramen, is associated with the vertebra above it. The cervical spinal nerves are an exception, because spinal nerve C1 passes superior to the vertebra C1. Thus, although there are seven cervical vertebrae, there are eight pairs of *cervical nerves* (numbered C1 to C8), twelve pairs of *thoracic nerves* (numbered T1 to T12), five pairs of *lumbar nerves* (numbered L1 to L5), five

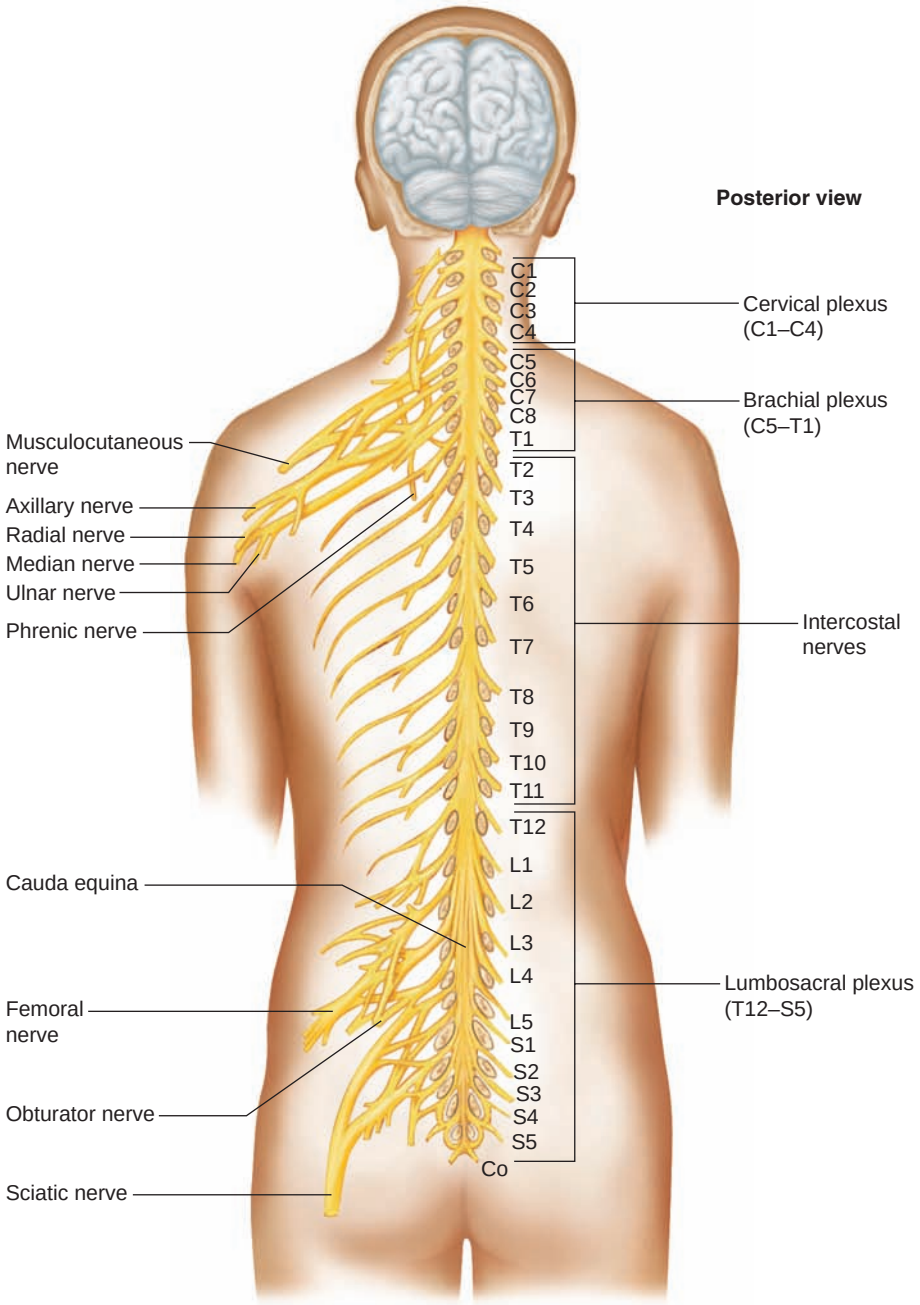


Figure 9.35

The anterior branches of the spinal nerves in the thoracic region give rise to intercostal nerves. Those in other regions combine to form complex networks called plexuses. (Note that there are eight pairs of cervical nerves, one pair originating above the first cervical vertebra and the eighth pair originating below the seventh cervical vertebra.)

pairs of *sacral nerves* (numbered S1 to S5), and one pair of *coccygeal nerves* (Co).

The adult spinal cord ends at the level between the first and second lumbar vertebrae. The lumbar, sacral, and coccygeal nerves descend beyond the end of the cord, forming a structure called the *cauda equina* (horse's tail).

Each spinal nerve emerges from the cord by two short branches, or *roots,* which lie within the vertebral column. The **dorsal root** (posterior or sensory root) can be identified by an enlargement called the *dorsal root ganglion* (see fig. 9.22*a*). This ganglion contains the cell bodies of the sensory neurons whose axons (peripheral process) conduct impulses inward from the peripheral body parts. The axons of these neurons extend through the dorsal root and into the spinal cord (central process), where they form synapses with dendrites of other neurons (see fig. 9.6). The **ventral root** (anterior or motor root) of each spinal nerve consists of axons from the motor neurons whose cell bodies are within the gray matter of the cord.

A ventral root and a dorsal root unite to form a spinal nerve, which extends outward from the vertebral canal through an *intervertebral foramen* (see fig. 7.17, p. 149). Just beyond its foramen, each spinal nerve divides into several parts.

Except in the thoracic region, the main portions of the spinal nerves combine to form complex networks called **plexuses** instead of continuing directly to peripheral body parts (fig. 9.35). In a plexus, spinal nerve fibers are sorted and recombined so that fibers that innervate a particular peripheral body part reach it in the same nerve, even though the fibers originate from different spinal nerves.

Cervical Plexuses

The **cervical plexuses** lie deep in the neck on either side and form from the branches of the first four cervical nerves. Fibers from these plexuses supply the muscles and skin of the neck. In addition, fibers from the third, fourth, and fifth cervical nerves pass into the right and left **phrenic nerves,** which conduct motor impulses to the muscle fibers of the diaphragm.

Brachial Plexuses

Branches of the lower four cervical nerves and the first thoracic nerve give rise to the **brachial plexuses.** These networks of nerve fibers are located deep within the shoulders between the neck and axillae (armpits). The major branches emerging from the brachial plexuses supply the muscles and skin of the arm, forearm, and hand, and include the **musculocutaneous, ulnar, median, radial,** and **axillary nerves.**

Lumbosacral Plexuses

The **lumbosacral plexuses** are formed on either side by the last thoracic nerve and the lumbar, sacral, and coccygeal nerves. These networks of nerve fibers extend from the lumbar region of the back into the pelvic cavity, giving rise to a number of motor and sensory fibers associated with the muscles and skin of the lower abdominal wall, external genitalia, buttocks, thighs, legs, and feet. The major branches of these plexuses include the **obturator, femoral,** and **sciatic nerves.**

The anterior branches of the thoracic spinal nerves do not enter a plexus. Instead, they enter spaces between the ribs and become **intercostal nerves.** These nerves supply motor impulses to the intercostal muscles and the upper abdominal wall muscles. They also receive sensory impulses from the skin of the thorax and abdomen.

Check Your Recall

54. How are spinal nerves grouped?
55. Describe how a spinal nerve joins the spinal cord.
56. Name and locate the major nerve plexuses.

Spinal nerves may be injured in a variety of ways, including stabs, gunshot wounds, birth injuries, dislocations and fractures of the vertebrae, and pressure from tumors in surrounding tissues. The nerves of the cervical plexuses, for example, are sometimes compressed by a sudden bending of the neck called *whiplash,* which may occur during rear-end automobile collisions. Whiplash may cause continuing headaches and pain in the neck and skin, which are supplied by the cervical nerves.

9.16 AUTONOMIC NERVOUS SYSTEM

The **autonomic nervous system** is the portion of the PNS that functions independently (autonomously) and continuously without conscious effort. This system controls visceral functions by regulating the actions of smooth muscles, cardiac muscles, and glands. It regulates heart rate, blood pressure, breathing rate, body temperature, and other visceral activities that maintain homeostasis. Portions of the autonomic nervous system respond to emotional stress and prepare the body to meet the demands of strenuous physical activity.

General Characteristics

Reflexes in which sensory signals originate from receptors within the viscera and the skin regulate autonomic activities. Nerve fibers transmit these signals to nerve centers within the brain or spinal cord. In response, motor impulses travel out from these centers on peripheral nerve fibers within cranial and spinal nerves.

Typically, peripheral nerve fibers lead to ganglia outside the CNS. The impulses they carry are integrated within these ganglia and relayed to viscera (muscles and

glands) that respond by contracting, releasing secretions, or being inhibited. The integrative function of the ganglia provides the autonomic system with a degree of independence from the brain and spinal cord.

The autonomic nervous system includes two divisions—the **sympathetic** (sim″pah-thet′ik) and **parasympathetic** (par″ah-sim″pah-thet′ik) **divisions.** Some viscera have nerve fibers from each division. In such cases, impulses on one set of fibers may activate an organ, while impulses on the other set inhibit it. Thus, the divisions may act antagonistically, alternately activating or inhibiting the actions of some viscera.

The functions of the autonomic divisions are mixed; that is, each activates some organs and inhibits others. However, the divisions have important functional differences. The sympathetic division prepares the body for energy-expending, stressful, or emergency situations, as part of the *fight or flight* response. Conversely, the parasympathetic division is most active under ordinary, restful conditions. It also counterbalances the effects of the sympathetic division and restores the body to a resting state following a stressful experience. For example, during an emergency, the sympathetic division increases heart and breathing rates; following the emergency, the parasympathetic division decreases these activities.

Autonomic Nerve Fibers

The neurons of the autonomic nervous system are motor neurons. However, unlike the motor pathways of the somatic nervous system, which usually include a single neuron between the brain or spinal cord and a skeletal muscle, those of the autonomic system include two neurons (fig. 9.36). The cell body of one neuron is located in the brain or spinal cord. Its axon, the **preganglionic fiber** (pre″gang-gle-on′ik fi′ber), leaves the CNS and synapses with one or more neurons whose cell bodies are housed within an autonomic ganglion. The axon of such a second neuron is called a **postganglionic fiber** (pōst″gang-gle-on′ik fi′ber), and it extends to a visceral effector.

Sympathetic Division

In the sympathetic division, the preganglionic fibers originate from neurons in the gray matter of the spinal cord (fig. 9.37). Their axons leave the cord through

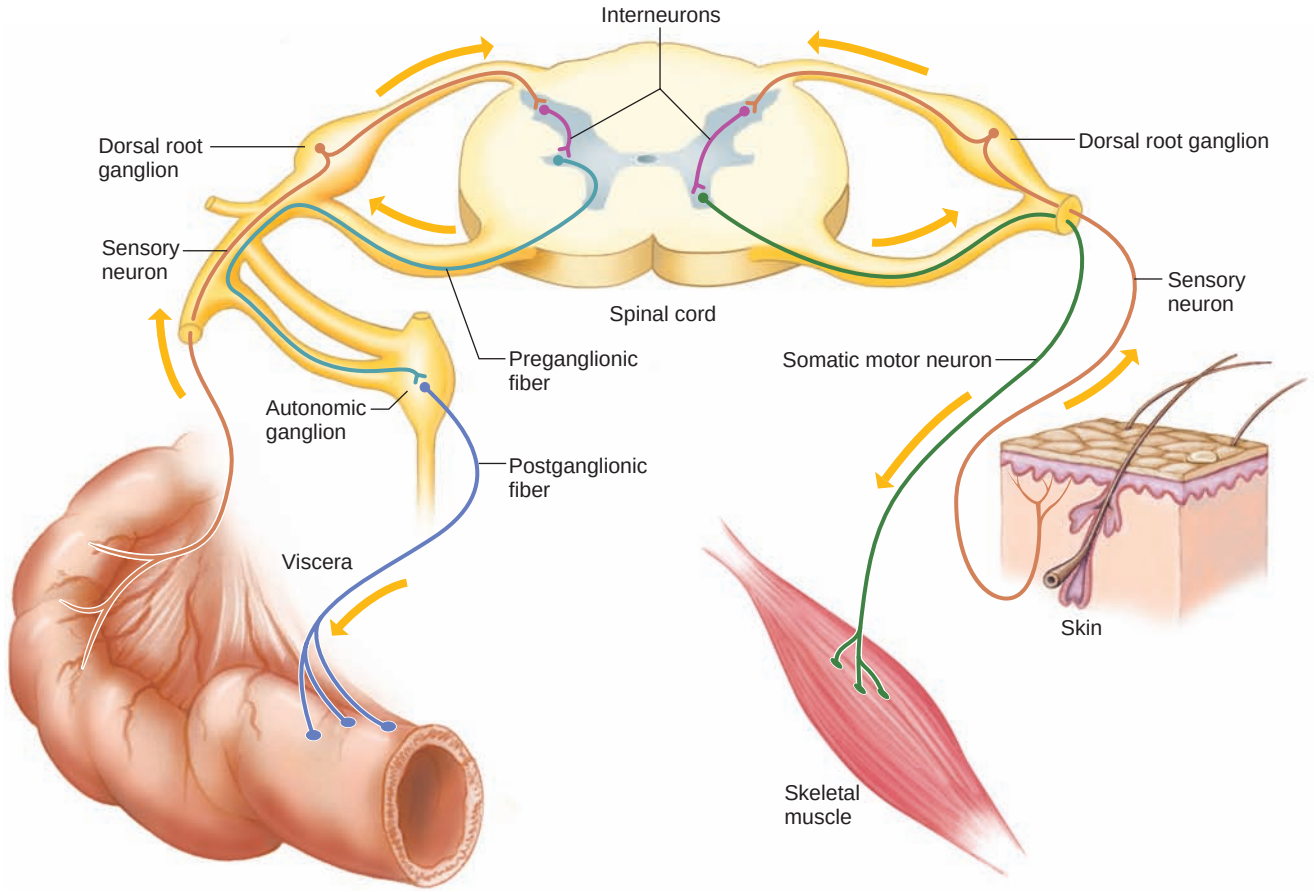


Figure 9.36

Motor pathways. (*a*) Autonomic pathways include two neurons between the CNS and an effector. (*b*) Somatic pathways usually have a single neuron between the CNS and an effector. Note that in both cases the motor fibers pass through the ventral root of the spinal cord.

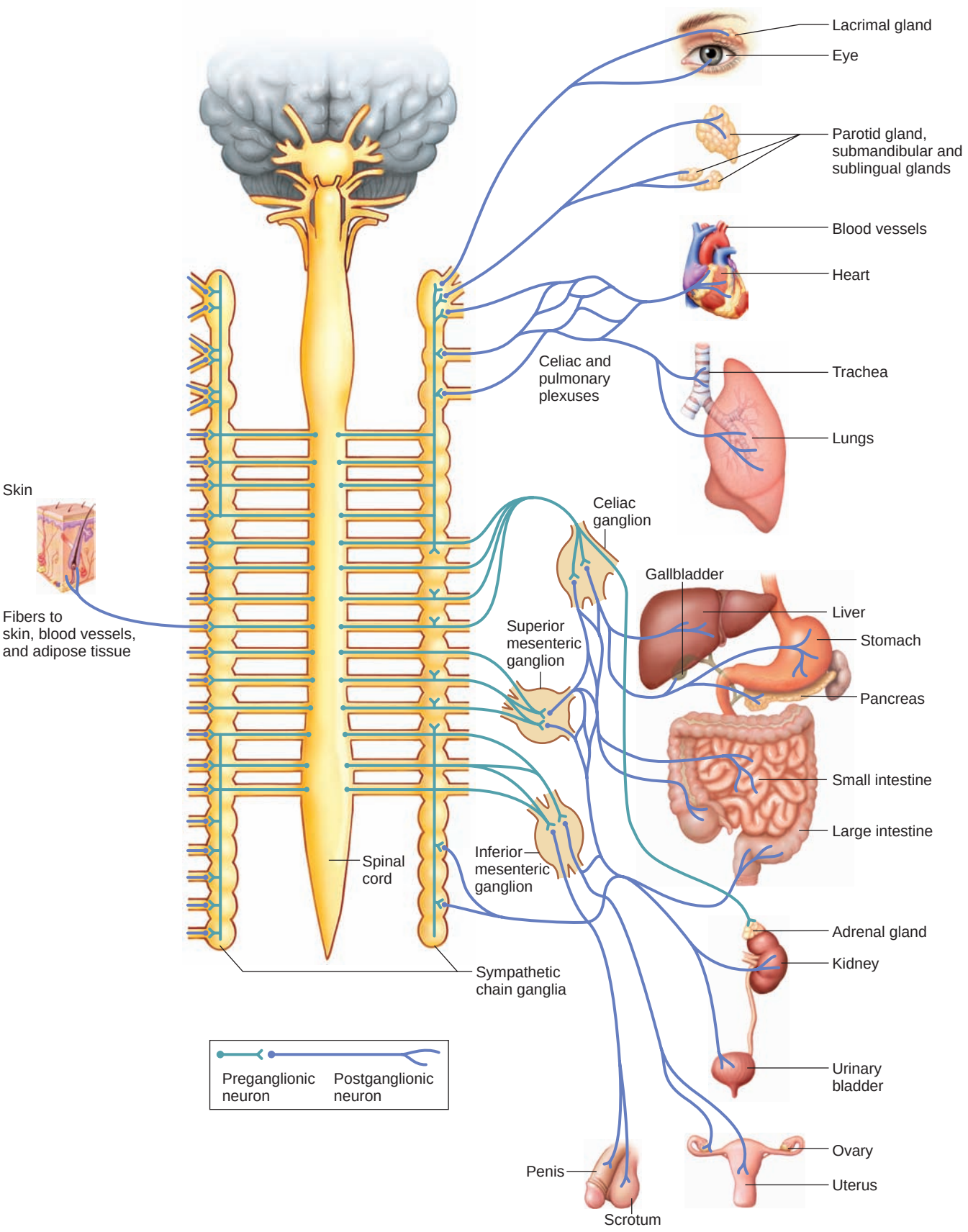


Figure 9.37

The preganglionic fibers of the sympathetic division of the autonomic nervous system arise from the thoracic and lumbar regions of the spinal cord (T1–L2). Note that the adrenal medulla is innervated directly by a preganglionic fiber.

the ventral roots of spinal nerves in the first thoracic through the second lumbar segments. After traveling a short distance, these fibers leave the spinal nerves, and each enters a member of a chain of sympathetic ganglia (*paravertebral ganglia*). One of these sympathetic chains extends longitudinally along each side of the vertebral column.

Within paravertebral ganglia, preganglionic fibers form synapses with second neurons. The axons of these neurons, the postganglionic fibers, typically return to spinal nerves and extend to visceral effectors.

Parasympathetic Division

The preganglionic fibers of the parasympathetic division arise from the brainstem and sacral region of the spinal cord (fig. 9.38). From there, they lead outward in cranial or sacral nerves to ganglia located near or within various viscera. The relatively short postganglionic fibers continue from the ganglia to specific muscles or glands within these viscera.

Check Your Recall

57. Describe the parts of the autonomic nervous system.
58. Distinguish between the divisions of the autonomic nervous system.
59. Describe a sympathetic nerve pathway and a parasympathetic nerve pathway.

Autonomic Neurotransmitters

The preganglionic fibers of the sympathetic and parasympathetic divisions all secrete *acetylcholine* and are therefore called **cholinergic fibers** (ko″lin-er′jik fi′berz). The parasympathetic postganglionic fibers are also cholinergic. One exception, parasympathetic neurons that secrete nitric oxide, is described in chapter 19 (p. 514). However, most sympathetic postganglionic neurons secrete *norepinephrine* (noradrenalin) and are called **adrenergic fibers** (ad″ren-ur′jik fi′berz) (fig. 9.39). The different postganglionic neurotransmitters cause the different effects that the sympathetic and parasympathetic divisions have on their effector organs.

Most organs receive innervation from both sympathetic and parasympathetic divisions, usually with opposing actions. For example, parasympathetic activity increases activity of the digestive system, whereas sympathetic activity decreases it. Similarly, sympathetic stimulation increases heart rate, but parasympathetic action slows heart rate.

Some viscera are controlled primarily by one division or the other. That is, the divisions are not always actively antagonistic. For example, the sympathetic division regulates the diameter of most blood vessels, which lack parasympathetic innervation. Smooth muscles in the walls of these vessels are continuously stimulated and thus are in a state of partial contraction (sympathetic tone). Decreasing sympathetic stimulation increases (dilates) the diameter of the vessels, which relaxes their muscular walls. Conversely, increasing sympathetic stimulation constricts the vessels. Table 9.7 summarizes the effects of stimulation by adrenergic and cholinergic fibers on some visceral effectors.

Control of Autonomic Activity

The brain and spinal cord largely control the autonomic nervous system, despite the system's independence resulting from the integrative function of its ganglia. For example, control centers in the medulla oblongata

Table 9.7 Effects of Neurotransmitter Substances on Visceral Effectors or Actions

Visceral Effector or Action	Response to Adrenergic Stimulation (Sympathetic)	Response to Cholinergic Stimulation (Parasympathetic)
Pupil of the eye	Dilation	Constriction
Heart rate	Increases	Decreases
Bronchioles of lungs	Dilation	Constriction
Muscles of intestinal wall	Slows peristaltic action	Speeds peristaltic action
Intestinal glands	Secretion decreases	Secretion increases
Blood distribution	More blood to skeletal muscles; less blood to digestive organs	More blood to digestive organs; less blood to skeletal muscles
Blood glucose concentration	Increases	Decreases
Salivary glands	Secretion decreases	Secretion increases
Tear glands	No action	Secretion
Muscles of gallbladder	Relaxation	Contraction
Muscles of urinary bladder	Relaxation	Contraction

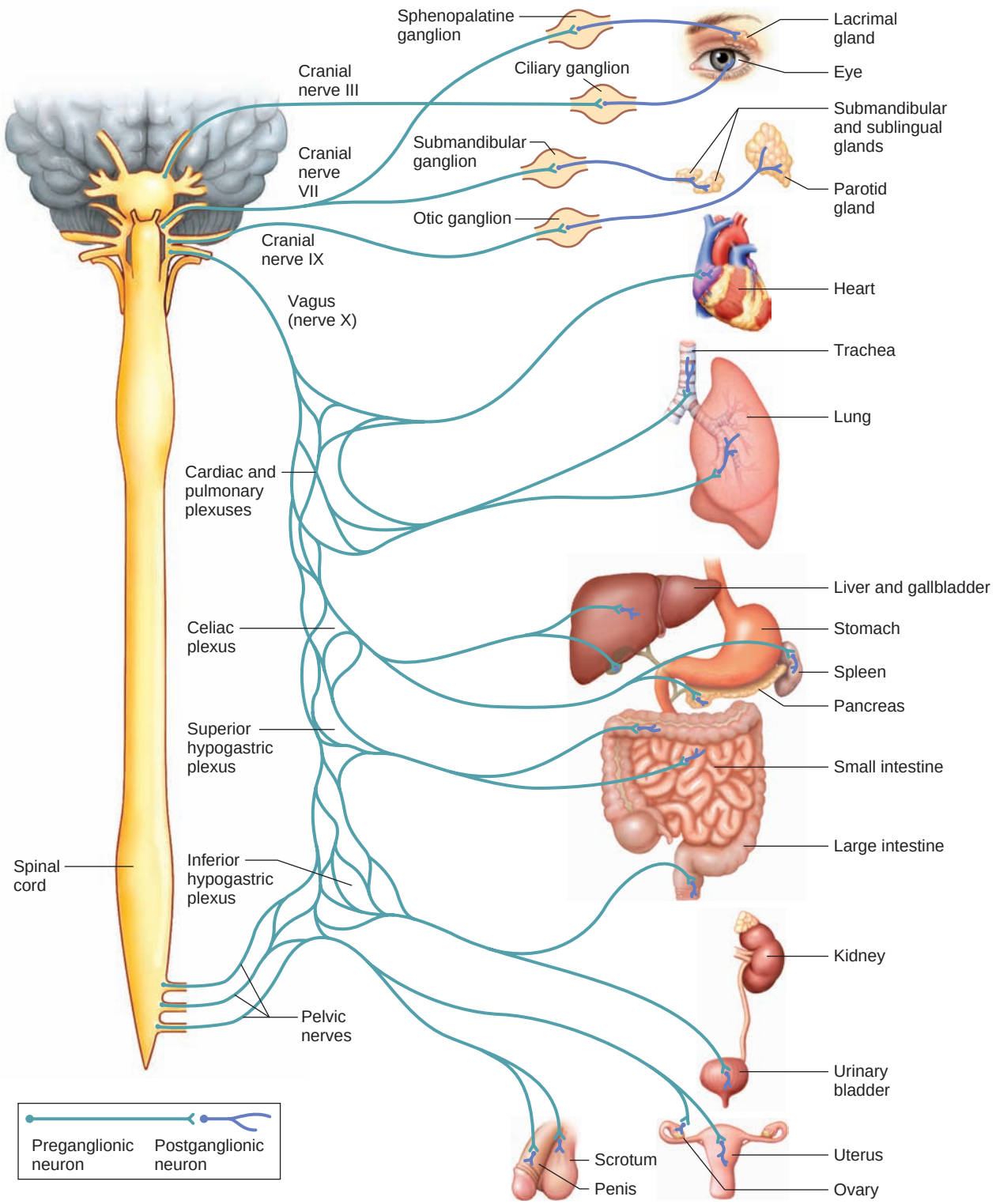


Figure 9.38

The preganglionic fibers of the parasympathetic division of the autonomic nervous system arise from the brainstem and sacral region of the spinal cord.

for cardiac, vasomotor, and respiratory activities receive sensory impulses from viscera on vagus nerve fibers and use autonomic nerve pathways to stimulate motor responses in muscles and glands. Similarly, the hypothalamus helps regulate body temperature, hunger, thirst, and water and electrolyte balance by influencing autonomic pathways.

More complex centers in the brain, including the limbic system and the cerebral cortex, control the autonomic nervous system during emotional stress. These

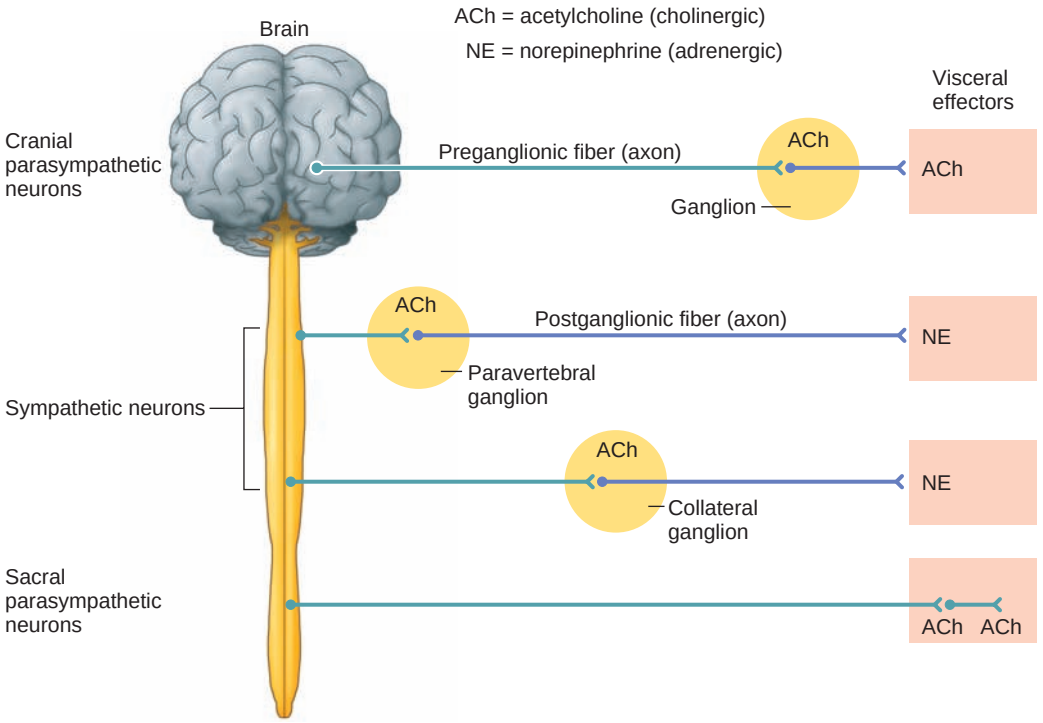


Figure 9.39

Most sympathetic fibers are adrenergic and secrete norepinephrine at the ends of the postganglionic fiber; parasympathetic fibers are cholinergic and secrete acetylcholine at the ends of the postganglionic fibers. Two arrangements of parasympathetic postganglionic fibers are seen in both the cranial and sacral portions. Similarly, sympathetic paravertebral and collateral ganglia are seen in both the thoracic and lumbar portions of the nervous system. (Note: This representation does not show dendrites.)

structures utilize autonomic pathways to regulate emotional expression and behavior.

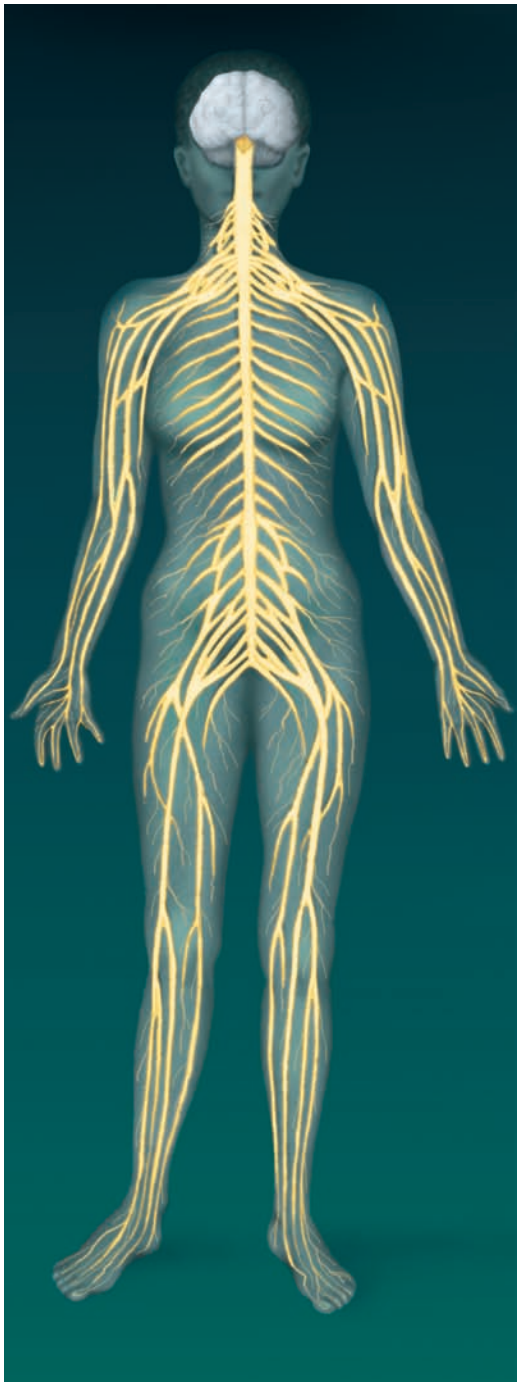
Check Your Recall

60. Which neurotransmitters operate in the autonomic nervous system?
61. How do the divisions of the autonomic nervous system regulate visceral activities?
62. How are autonomic activities controlled?

Clinical Terms Related to the Nervous System

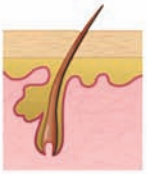
analgesia (an″al-je′ze-ah) Loss or reduction in the ability to sense pain, but without loss of consciousness.
analgesic (an″al-je′sik) Pain-relieving drug.
anesthesia (an″es-the′ze-ah) Loss of feeling.
aphasia (ah-fa′ze-ah) Disturbance or loss of the ability to use words or to understand them, usually due to damage to cerebral association areas.
apraxia (ah-prak′se-ah) Impairment in the ability to use objects.
ataxia (ah-tak′se-ah) Partial or complete inability to coordinate voluntary movements.
cerebral palsy (ser′ĕ-bral pawl′ze) Partial paralysis and lack of muscular coordination caused by damage to the cerebrum.
coma (ko′mah) Unconscious condition in which a person does not respond to stimulation.
cordotomy (kor-dot′o-me) Surgical procedure that severs a nerve tract within the spinal cord to relieve intractable pain.
craniotomy (kra″ne-ot′o-me) Surgical procedure that opens part of the skull.
electroencephalogram (EEG) (e-lek″tro-en-sef′ah-lo-gram″) Recording of the brain's electrical activity.
encephalitis (en″sef-ah-li′tis) Inflammation of the brain and meninges, producing drowsiness and apathy.
epilepsy (ep′ĭ-lep″se) Disorder of the central nervous system that temporarily disturbs brain impulses, producing convulsive seizures and loss of consciousness.
hemiplegia (hem″ĭ-ple′je-ah) Paralysis of one side of the body and the limbs on that side.
Huntington disease (hunt′ing-tun diz-ēz′) Inherited disorder of the brain causing involuntary, dancelike movements and personality changes.
laminectomy (lam″ĭ-nek′to-me) Surgical removal of the posterior arch of a vertebra, usually to relieve the symptoms of a ruptured intervertebral disc pressing on a spinal nerve.
monoplegia (mon″o-ple′je-ah) Paralysis of a single limb.
multiple sclerosis (mul′tĭ-pl skle-ro′sis) Loss of myelin and the appearance of scarlike patches throughout the brain or spinal cord or both.
neuralgia (nu-ral′je-ah) Sharp, recurring pain associated with a nerve; usually caused by inflammation or injury.
neuritis (nu-ri′tis) Inflammation of a nerve.
paraplegia (par″ah-ple′je-ah) Paralysis of both lower limbs.
quadriplegia (kwod″rĭ-ple′je-ah) Paralysis of all four limbs.
vagotomy (va-got′o-me) Surgical severing of a vagus nerve—for example, to reduce acid secretion in a patient with ulcers nonresponsive to other treatment.

Nervous System



Neurons carry impulses that allow body systems to communicate.

Integumentary System



Sensory receptors provide the nervous system with information about the outside world.

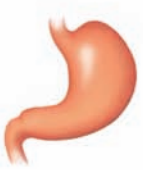
Lymphatic System

Stress may impair the immune response.

Skeletal System

Bones protect the brain and spinal cord and help maintain plasma calcium, which is important to neuron function.

Digestive System

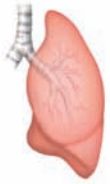


The nervous system can influence digestive function.

Muscular System

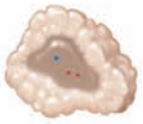
Nerve impulses control movement and carry information about the position of body parts.

Respiratory System



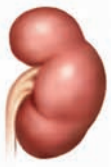
The nervous system alters respiratory activity to control oxygen levels and blood pH.

Endocrine System



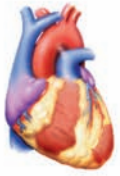
The hypothalamus controls secretion of many hormones.

Urinary System



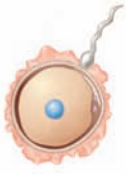
Nerve impulses affect urine production and elimination.

Cardiovascular System



Nerve impulses help control blood flow and blood pressure.

Reproductive System



The nervous system plays a role in egg and sperm formation, sexual pleasure, childbirth, and nursing.

Clinical Connection

In the 1970s, researchers discovered that the body produces its own compounds that bind to the same receptors on brain neurons as do opiate drugs such as morphine. The opiates presumably exert their effects by interfering with this system. In 1992, researchers discovered a compound in the body that binds the same receptors on brain neurons as does the active ingredient in marijuana. The existence of this compound, called anandamide, explains why marijuana exerts psychoactive and other effects. Anandamide normally is released from postsynaptic neurons stimulated by calcium ion influx, and then binds to the presynaptic cell, temporarily shutting down neurotransmission. When a person takes in the plant version of anandamide through smoke, these neural connections are overwhelmed, and somehow this interference produces marijuana's effects on mood and thinking.

Like the opiates, which come from the poppy plant, marijuana has medicinal applications, and is available by prescription in several states to treat pain and to stimulate appetite. In 1985, the Food and Drug Administration approved Marinol, a drug based on the most active chemical in marijuana, to treat nausea and vomiting resulting from cancer chemotherapy. In 1992, the agency approved Marinol to treat AIDS-related anorexia. A drug is being developed from a different chemical found in marijuana smoke called ajulemic acid. It relieves pain, but without psychoactive effects.

SUMMARY OUTLINE

9.1 Introduction (p. 212)

1. Nervous tissue includes neurons, which are the structural and functional units of the nervous system, and neuroglial cells.
2. Organs of the nervous system are divided into the central and peripheral nervous systems.

9.2 General Functions of the Nervous System (p. 213)

1. Sensory functions receive stimulation from receptors that detect internal and external changes.
2. Integrative functions collect sensory information and make decisions that motor functions carry out.
3. Motor functions stimulate effectors to respond.

9.3 Neuroglial Cells (p. 214)

1. Neuroglial cells in the central nervous system include microglial cells, oligodendrocytes, astrocytes, and ependymal cells.
2. In the peripheral nervous system, Schwann cells form myelin sheaths.

9.4 Neurons (p. 214)

1. A neuron includes a cell body, dendrites, and an axon.
2. Dendrites and the cell body provide receptive surfaces.
3. A single axon arises from the cell body and may be enclosed in a myelin sheath and a neurilemma.
4. Classification of neurons
   a. Neurons are classified structurally as multipolar, bipolar, or unipolar.
   b. Neurons are classified functionally as sensory neurons, interneurons, or motor neurons.

9.5 The Synapse (p. 219)

A synapse is a junction between two neurons.

1. A presynaptic neuron carries an impulse into a synapse; a postsynaptic neuron responds.
2. Axons have synaptic knobs at their distal ends, which secrete neurotransmitters.
3. A neurotransmitter is released when a nerve impulse reaches the end of an axon.
4. A neurotransmitter reaching the postsynaptic neuron membrane is either excitatory or inhibitory.

9.6 Cell Membrane Potential (p. 220)

A cell membrane is usually polarized as a result of unequal ion distribution.

1. Distribution of ions
   a. Pores and channels in cell membranes that allow passage of some ions but not others set up differences in the concentrations of specific ions inside and outside a neuron.
   b. Potassium ions pass more easily through cell membranes than do sodium ions.
2. Resting potential
   a. A high concentration of sodium ions is outside a cell membrane, and a high concentration of potassium ions is inside.
   b. Many negatively charged ions are inside a cell.
   c. In a resting cell, more positive ions leave than enter, so the outside of the cell membrane develops a positive charge, while the inside develops a negative charge.
3. Potential changes
   a. Stimulation of a cell membrane affects the membrane's resting potential.
   b. When its resting potential becomes less negative, a membrane becomes depolarized.
   c. Potential changes are subject to summation.
   d. Achieving threshold potential triggers an action potential.
4. Action potential
   a. At threshold, sodium channels open, and sodium ions diffuse inward, depolarizing the membrane.
   b. About the same time, potassium channels open, and potassium ions diffuse outward, repolarizing the membrane.
   c. This rapid change in potential is an action potential.
   d. Many action potentials can occur before active transport reestablishes the resting potential.

9.7 Nerve Impulses (p. 224)

A wave of action potentials is a nerve impulse.

1. Impulse conduction
   a. Unmyelinated axons conduct impulses over their entire surfaces.
   b. Myelinated axons conduct impulses more rapidly.
   c. Axons with larger diameters conduct impulses faster than those with smaller diameters.
2. All-or-none response
   a. A nerve impulse is conducted in an all-or-none manner whenever a stimulus of threshold intensity is applied to an axon.
   b. All the impulses conducted on an axon are of the same strength.

9.8 Synaptic Transmission (p. 225)

1. Excitatory and inhibitory actions
   a. Neurotransmitters that trigger nerve impulses are excitatory. Those that inhibit impulses are inhibitory.
   b. The net effect of synaptic knobs communicating with a neuron depends on which knobs are activated from moment to moment.
2. Neurotransmitters
   a. The nervous system produces many different neurotransmitters.
   b. Neurotransmitters include acetylcholine, monoamines, amino acids, and peptides.
   c. A synaptic knob releases neurotransmitters when an action potential increases membrane permeability to calcium ions.
   d. After being released, neurotransmitters are decomposed or removed from synaptic clefts.

9.9 Impulse Processing (p. 227)

How the nervous system processes and responds to nerve impulses reflects the organization of neurons in the brain and spinal cord.

1. Neuronal pools
   a. Neurons form pools within the central nervous system.
   b. Each pool receives impulses, processes them, and conducts impulses away.
2. Facilitation
   a. Each neuron in a pool may receive excitatory and inhibitory stimuli.
   b. A neuron is facilitated when it receives subthreshold stimuli and becomes more excitable.
3. Convergence
   a. Impulses from two or more incoming axons may converge on a single neuron.
   b. Convergence enables impulses from different sources to have an additive effect on a neuron.
4. Divergence
   a. Impulses leaving a pool may diverge by passing into several output neurons.
   b. Divergence amplifies impulses.

9.10 Types of Nerves (p. 228)

1. Nerves are cordlike bundles (fascicles) of nerve fibers (axons).
2. Nerves are sensory, motor, or mixed, depending on which type of fibers they contain.

9.11 Nerve Pathways (p. 228)

A nerve pathway is the route an impulse follows through the nervous system.

1. A reflex arc usually includes a sensory neuron, a reflex center composed of interneurons, and a motor neuron.
2. Reflex behavior
   a. Reflexes are automatic, subconscious responses to changes.
   b. They help maintain homeostasis.
   c. Two neurons carry out the patellar reflex.
   d. Withdrawal reflexes are protective.

9.12 Meninges (p. 230)

1. Bone and meninges surround the brain and spinal cord.
2. The meninges are the dura mater, arachnoid mater, and pia mater.
3. Cerebrospinal fluid fills the space between the arachnoid and pia maters.

9.13 Spinal Cord (p. 232)

The spinal cord is a nerve column that extends from the brain into the vertebral canal.

1. Structure of the spinal cord
   a. Each of the spinal cord's thirty-one segments gives rise to a pair of spinal nerves.
   b. The spinal cord has a cervical enlargement and a lumbar enlargement.
   c. A central core of gray matter lies within white matter.
   d. White matter consists of bundles of myelinated axons.
2. Functions of the spinal cord
   a. The spinal cord provides a two-way communication system between the brain and other body parts and serves as a center for spinal reflexes.
   b. Ascending tracts carry sensory impulses to the brain. Descending tracts carry motor impulses to muscles and glands.

9.14 Brain (p. 234)

The brain is subdivided into the cerebrum, diencephalon, brainstem, and cerebellum.

1. Structure of the cerebrum
   a. The cerebrum consists of two cerebral hemispheres connected by the corpus callosum.
   b. The cerebral cortex is a thin layer of gray matter near the surface.
   c. White matter consists of myelinated axons that connect neurons within the nervous system and communicate with other body parts.
2. Functions of the cerebrum
   a. The cerebrum provides higher brain functions.
   b. The cerebral cortex consists of sensory, motor, and association areas.
   c. One cerebral hemisphere usually dominates for certain intellectual functions.
3. Ventricles and cerebrospinal fluid
   a. Ventricles are interconnected cavities within the cerebral hemispheres and brainstem.
   b. Cerebrospinal fluid fills the ventricles.
   c. The choroid plexuses in the walls of the ventricles secrete cerebrospinal fluid.
4. Diencephalon
   a. The diencephalon contains the thalamus, which is a central relay station for incoming sensory impulses, and the hypothalamus, which maintains homeostasis.
   b. The limbic system produces emotions and modifies behavior.
5. Brainstem
   a. The brainstem consists of the midbrain, pons, and medulla oblongata.
   b. The midbrain contains reflex centers associated with eye and head movements.

c. The pons transmits impulses between the cerebrum and other parts of the nervous system and contains centers that help regulate the rate and depth of breathing.
d. The medulla oblongata transmits all ascending and descending impulses and contains several vital and nonvital reflex centers.
e. The reticular formation filters incoming sensory impulses, arousing the cerebral cortex into wakefulness when significant impulses arrive.

6. Cerebellum
   a. The cerebellum consists of two hemispheres.
   b. It functions primarily as a reflex center for integrating sensory information required in the coordination of skeletal muscle movements and the maintenance of equilibrium.

9.15 Peripheral Nervous System (p. 242)

The peripheral nervous system consists of cranial and spinal nerves that branch from the brain and spinal cord to all body parts. It is subdivided into the somatic and autonomic systems.

1. Cranial nerves
   a. Twelve pairs of cranial nerves connect the brain to parts in the head, neck, and trunk.
   b. Most cranial nerves are mixed, but some are purely sensory, and others are primarily motor.
   c. The names of the cranial nerves indicate their primary functions or the general distributions of their fibers.
   d. Some cranial nerves are somatic, and others are autonomic.
2. Spinal nerves
   a. Thirty-one pairs of spinal nerves originate from the spinal cord.
   b. These mixed nerves provide a two-way communication system between the spinal cord and parts of the upper and lower limbs, neck, and trunk.
   c. Spinal nerves are grouped according to the levels from which they arise, and they are numbered in sequence.
   d. Each spinal nerve emerges by a dorsal and a ventral root.
   e. Each spinal nerve divides into several branches just beyond its foramen.
   f. Most spinal nerves combine to form plexuses in which nerve fibers are sorted and recombined so that those fibers associated with a particular part reach it together.

9.16 Autonomic Nervous System (p. 248)

The autonomic nervous system functions without conscious effort. It regulates the visceral activities that maintain homeostasis.

1. General characteristics
   a. Autonomic functions are reflexes controlled from nerve centers in the brain and spinal cord.
   b. The autonomic nervous system consists of two divisions—the sympathetic and the parasympathetic.
   c. The sympathetic division responds to stressful and emergency conditions.
   d. The parasympathetic division is most active under ordinary conditions.
2. Autonomic nerve fibers
   a. Autonomic nerve fibers are motor fibers.
   b. Sympathetic fibers leave the spinal cord and synapse in paravertebral ganglia.
   c. Parasympathetic fibers begin in the brainstem and sacral region of the spinal cord and synapse in ganglia near viscera.
3. Autonomic neurotransmitters
   a. Sympathetic and parasympathetic preganglionic fibers secrete acetylcholine.
   b. Parasympathetic postganglionic fibers secrete acetylcholine. Sympathetic postganglionic fibers secrete norepinephrine.
   c. The different effects of the autonomic divisions are due to the different neurotransmitters the postganglionic fibers release.
   d. The two divisions usually have opposite actions.
4. Control of autonomic activity
   a. The autonomic nervous system is somewhat independent.
   b. Control centers in the medulla oblongata and hypothalamus utilize autonomic nerve pathways.
   c. The limbic system and cerebral cortex control the autonomic system during emotional stress.

CHAPTER ASSESSMENTS

9.1 Introduction

1. The general function of neurons is to _____, whereas the general functions of neuroglia are to _____. (p. 212)
2. Match the neuron part on the left to its description on the right. (p. 212)

(1) dendrite	A. A cell process that sends information
(2) axon	B. One of usually several cell processes that receive information
(3) cell body	C. The rounded part of a neuron

3. Explain the relationship between the CNS and the PNS. (p. 212)

9.2 General Functions of the Nervous System

4. List the general functions of the nervous system. (p. 213)

9.3 Neuroglial Cells

5. Match the types of neuroglial cells on the left to their functions on the right. (p. 214)

(1) ependymal cells	A. Form a myelin sheath around peripheral nerves
(2) oligodendrocytes	B. Phagocytize cellular debris and bacteria
(3) astrocytes	C. Line inner parts of ventricles and spinal cord
(4) Schwann cells	D. Form scar tissue and regulate ion and nutrient concentrations in the CNS
(5) microglial cells	E. Form a myelin sheath around neurons in the CNS

9.4 Neurons

6. Describe three structures found in neurons that are also in other cell types, and describe two structures that are unique to neurons. (p. 214)
7. The part of a Schwann cell that contributes to the myelin sheath is the _____, and the part that contributes to the neurilemma is the _____. (p. 215)
8. Distinguish between myelinated and unmyelinated axons. (p. 217)
9. Distinguish among multipolar, bipolar, and unipolar neurons. (p. 218)
10. Distinguish among sensory neurons, interneurons, and motor neurons. (p. 218)
11. Distinguish between ganglia and nuclei. (p. 218)

9.5 The Synapse

12. Define *synapse*. (p. 219)
13. Explain how information passes from one neuron to another. (p. 220)

9.6 Cell Membrane Potential

14. Explain how a membrane becomes polarized. (p. 220)

15. Describe how ions associated with nerve cell membranes are distributed. (p. 220)
16. Define *resting potential*. (p. 221)
17. Explain the relationship between threshold potential and an action potential. (p. 223)
18. List the events that occur during an action potential. (p. 223)

9.7 Nerve Impulses

19. Choose the correct sequence of events along an axon: (p. 224)
    a. Resting potentials are propagated along a stimulated axon, causing an overall action potential.
    b. A threshold stimulus opens K^+ channels and the ions diffuse in, depolarizing the cell membrane. Then Na^+ channels open, Na^+ exits, and the cell membrane repolarizes, generating an action potential that stimulates adjacent cell membrane, forming the nerve impulse.
    c. A threshold stimulus opens Na^+ channels and the ions diffuse in, depolarizing the cell membrane. Then K^+ channels open, K^+ exits, and the cell membrane repolarizes, generating an action potential that stimulates adjacent cell membrane, forming the nerve impulse.
    d. A threshold stimulus opens Na^+ channels and the ions diffuse in, depolarizing the cell membrane. Then K^+ channels open, K^+ exits, and the cell membrane repolarizes, generating a nerve impulse that stimulates adjacent cell membrane, forming the action potential.
    e. Action potentials occur at different points along an axon, then join to generate a nerve impulse.
20. Explain why a myelin sheath covering an entire axon would inhibit conduction of a nerve impulse. (p. 225)
21. "All-or-none" response in nerve impulse conduction means that _____. (p. 225)

9.8 Synaptic Transmission

22. Distinguish between excitatory and inhibitory actions of neurotransmitters. (p. 225)
23. Neurotransmitters are synthesized in _____ and are stored in _____. (p. 226)
24. Match the neurotransmitter on the left to its description on the right. (p. 226)

(1) monoamine	A. Short chains of amino acids
(2) acetylcholine	B. A modified amino acid
(3) neuropeptide	C. An amino acid
(4) GABA	D. Stimulates skeletal muscle contraction

25. Explain what happens to neurotransmitters after they are released. (p. 226)

9.9 Impulse Processing

26. Describe the components of a neuronal pool. (p. 227)
27. "Facilitation in a neuronal pool" refers to _____. (p. 227)
28. Distinguish between convergence and divergence in a neuronal pool. (p. 227)

9.10 Types of Nerves

29. Describe how sensory, motor, and mixed nerves differ. (p. 228)

9.11 Nerve Pathways

30. Distinguish between a reflex arc and a reflex. (p. 228)
31. Describe the components of a reflex arc and their functions. (p. 228)
32. List three body functions that reflexes control. (p. 228)

9.12 Meninges

33. Match the layer of the meninges on the left to its description on the right. (p. 230)

(1) dura mater	A. The thin, innermost layer, containing blood vessels and nerves
(2) arachnoid mater	B. The tough, outermost layer, consisting mostly of connective tissue
(3) pia mater	C. The lacy membrane, lacking blood vessels, sandwiched between the other two layers

9.13 Spinal Cord

34. Describe the structure of the spinal cord. (p. 232)
35. Distinguish between the ascending and descending tracts of the spinal cord. (p. 233)

9.14 Brain

36. Name the four major parts of the brain and describe their general functions. (p. 234)
37. The area of the brain that connects parts of the nervous system to particular visceral activities is the: (p. 234)
    a. cerebrum
    b. cerebellum
    c. brainstem
    d. diencephalon
    e. corpus callosum
38. The structure that connects the cerebral hemispheres is the _____. (p. 235)
39. Distinguish between a sulcus and a fissure. (p. 236)
40. Relate the lobes of the cerebral hemispheres to the skull bones. (p. 236)
41. Locate the motor, sensory, and association areas of the cerebral cortex, and describe the general functions of each. (p. 237)
42. Define *hemisphere dominance*. (p. 237)
43. The function of the basal nuclei is to _____. (p. 238)
44. Locate the ventricles in the brain. (p. 238)
45. Explain how cerebrospinal fluid is produced and how it functions. (p. 239)
46. The part of the diencephalon that regulates hunger, weight, water and electrolyte balance, sleep and wakefulness, temperature, arterial blood pressure, heart rate, production of substances that stimulate the pituitary gland, and movement and secretion in areas of the digestive tract is the: (p. 240)
    a. thalamus
    b. pineal gland
    c. infundibulum
    d. hypothalamus
    e. mammillary bodies
47. Define *limbic system,* and explain its functions. (p. 240)
48. The parts of the brainstem are the _____, _____, and _____. (p. 241)
49. List the functions of the three parts of the brainstem. (p. 241)
50. Vomiting is controlled by: (p. 242)
    a. the reticular formation
    b. a nucleus within the medulla oblongata
    c. the midbrain
    d. the pons
    e. the thalamus

51. Describe what happens to the body when the reticular formation receives sensory impulses, and what happens when it does not receive stimulation. (p. 242)
52. Describe the functions of the cerebellum. (p. 242)

9.15 Peripheral Nervous System

53. Distinguish between the somatic nervous system and the autonomic nervous system. (p. 242)
54. Distinguish between cranial nerves and spinal nerves. (pp. 243, 247)
55. Match the cranial nerves (on the left) to the body parts or functions that they affect (on the right). More than one nerve pair may correspond to the same structure or function. (pp. 243–246)

(1) olfactory nerves (I)	A. Vision
(2) optic nerves (II)	B. Hearing and equilibrium
(3) oculomotor nerves (III)	C. Muscles of the larynx, pharynx, soft palate, sternocleidomastoid and trapezius muscles
(4) trochlear nerves (IV)	D. Heart, various smooth muscles and glands in the thorax and abdomen
(5) trigeminal nerves (V)	E. Taste, facial expressions, secretion of tears and saliva
(6) abducens nerves (VI)	F. Sense of smell
(7) facial nerves (VII)	G. Tongue movements and swallowing
(8) vestibulocochlear nerves (VIII)	H. Face and scalp
(9) glossopharyngeal nerves (IX)	I. Eye movements
(10) vagus nerves (X)	
(11) accessory nerves (XI)	
(12) hypoglossal nerves (XII)	

56. Explain how the spinal nerves are classified and numbered. (p. 247)
57. Describe the structure of a spinal nerve. (p. 248)
58. Define *plexus,* and locate the major plexuses of the spinal nerves. (p. 248)

9.16 Autonomic Nervous System

59. Describe the general functions of the autonomic nervous system. (p. 248)
60. Distinguish between the sympathetic and parasympathetic divisions of the autonomic nervous system. (p. 249)
61. Distinguish between preganglionic and postganglionic nerve fibers. (p. 249)
62. The effects of the sympathetic and parasympathetic autonomic divisions differ because _____. (p. 251)
63. List two ways in which the CNS controls autonomic activities. (p. 251)

INTEGRATIVE ASSESSMENTS/ CRITICAL THINKING

OUTCOMES 9.1, 9.13, 9.14

1. Discuss the rationale for considering the nervous system in two parts, central and peripheral.

OUTCOMES 9.3, 9.4

2. State two reasons why rapidly growing brain cancers are composed of neuroglial cells rather than neurons.

OUTCOMES 9.3, 9.4, 9.7, 9.13, 9.14

3. In multiple sclerosis, nerve fibers in the CNS lose their myelin. Explain why this loss affects skeletal muscle function.

OUTCOMES 9.4, 9.5, 9.11, 9.13, 9.14

4. List four skills encountered in everyday life that depend on nervous system function, and list the part of the nervous system responsible for each.

OUTCOMES 9.6, 9.8

5. Compare and contrast the roles of potassium and calcium ions in nerve transmission.

OUTCOMES 9.11, 9.13

6. The biceps-jerk reflex is carried out by motor neurons that exit the spinal cord in the fifth spinal nerve (C5). The triceps-jerk reflex uses motor neurons in the seventh spinal nerve (C7). Describe how these reflexes might be tested to help pinpoint damage in a patient with a neck injury.

OUTCOMES 9.11, 9.14

7. Describe the roles of the cerebrum and cerebellum in athletics.

OUTCOMES 9.13, 9.14

8. Describe expected functional losses in a patient who has suffered injury to the right occipital lobe of the cerebral cortex compared to injury in the right temporal lobe of the cerebral cortex.

OUTCOME 9.14

9. Select three parts of the brain and explain why they are essential for survival.

WEB CONNECTIONS

Visit the text website at **aris.mhhe.com** for additional quizzes, interactive learning exercises, and more.

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