34 NEURAL CONTROL

In Pursuit of Ecstasy

Ecstasy makes you feel socially accepted, relieves anxiety, and sharpens the senses while giving you a mild high. This psychoactive drug also can leave you dying in a hospital bed, foaming at the mouth and bleeding from all orifices as your temperature skyrockets. It can send family and friends spiraling into horror and disbelief as they watch you stop breathing. Lorna Spinks ended life that way. She was nineteen years old (Figure 34.1).

Her anguished parents released the photograph at far right, taken minutes after her death. They wanted others to know what their daughter did not: Ecstasy can kill.

Ecstasy's active chemical ingredient, MDMA, is a type of amphetamine, or "speed." Among other effects, MDMA disrupts controls over serotonin, a signaling molecule that works in the brain. It causes neurons to release too much serotonin. Serotonin molecules saturate their receptors on target cells and cannot be cleared away, so the cells cannot be released from overstimulation.

Feelings of energy, empathy, and euphoria correspond with the serotonin surge. So does a decrease in the body's ability to control its internal temperature. Spinks became dizzy, flushed, and incoherent after taking a single Ecstasy tablet. She died after her internal temperature soared high enough to shut down her organ systems.

The problem is this: The signaling pathways that MDMA disrupts do more than influence moods. They are vital for homeostasis. When MDMA acts, the pathways put the body on emergency footing. When Ecstasy users feel energized, their body is being subjected to nonstop signals for rapid breathing, dilated eyes, restricted urine formation, and a racing heart that makes blood pressure soar.

Few MDMA overdoses end in death. Ecstasy's short-term effects include panic attacks and temporary psychosis. We still do not know much about its long-term effects, so users are unwitting guinea pigs for unscripted experiments.

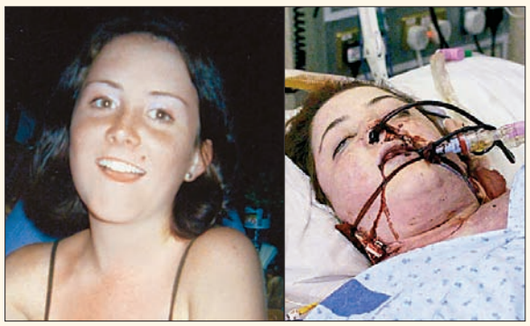
We do know that neurons do not rebound quickly when Ecstasy depletes the serotonin stores. In laboratory animals that were given multiple MDMA doses, the number and structure of serotonin-secreting neurons changed. In humans, lowered serotonin levels contribute to a loss of concentration, memory problems, and depression. Some studies link Ecstasy to depression, although it may be that depressed individuals are more likely to become users compared to individuals who are emotionally balanced.

The effects on memory are better understood. Memory loss increases as the frequency of drug use rises. At least over the short term, a normal capacity for memory seems to be restored when Ecstasy use stops, but it often takes many months to undo the neural imbalances.

Not surprisingly, no one is regulating the manufacture of Ecstasy. Tablets vary in their amount of MDMA. Often they contain a hodgepodge of other chemicals, such as methamphetamine, mescaline, ephedrine, and ketamine. Sometimes a drug called PMA is passed off as Ecstasy because it is easier and cheaper to make. PMA is far more potent and more likely to cause deadly reactions.

Figure 34.1 A psychoactive drug and the nervous system. The increased use of Ecstasy at all-night raves and other parties correlates with a rise in Ecstasy-related visits to emergency rooms. At far right, Lorna Spinks, who was pursuing a degree in sociology, died in the hospital. She was not an isolated case. For example, in 2004, Irma Perez, a fourteen-year-old from Belmont, California, took one Ecstasy tablet at a slumber party, became ill, and died in a hospital the next day.

IMPACTS, ISSUES



Think about it. The **nervous system** evolved as a way to sense and respond fast to changing conditions inside and outside the body. Sights, odors, hunger and passion, fear and rage—awareness of all forms of stimulation starts with a flow of information along communication lines of the nervous system. Even before you were born, excitable cells called neurons started organizing themselves into gridworks in newly forming tissues. They began to chatter among themselves. All through your life, in moments of danger or reflection, excitement or sleep, their chattering has continued and will continue as long as you do.

Each of us possesses a highly complex nervous system, a legacy of millions of years of evolution. Its architecture and its functioning give us a capacity, unparalleled in the living world, for learning and sharing experiences with others. Through the emergence of that capacity, the sense of history was born, and the sense of destiny. Perhaps the sorriest consequence of drug abuse is the implicit denial of this legacy—the denial of self when we choose not to assess the threats, or cease to care.

How Would You Vote?

Should people caught using illegal drugs be compelled to enter mandatory drug rehabilitation programs as an alternative to jail? Or does the threat of jail time in itself make some people think twice before experimenting with possibly dangerous drugs? See BiologyNow for details, then vote online.

Key Concepts

OVERVIEW OF NERVOUS SYSTEMS

Radial animals have a nerve net. Bilateral animals have a nervous system consisting of neurons, which interact as communication lines, and neuroglial cells that structurally and functionally support the neurons. Vertebrate nervous systems have central and peripheral regions. Section 34.1

HOW NEURONS WORK

Messages flow along a neuron's plasma membrane, from input to output zones. The "messages" are abrupt, self-propagating reversals in the distribution of electric charge across the membrane. At an output zone, messages are transduced into a chemical form that can stimulate or inhibit activity in another cell. Sections 34.2–34.5

THE SUPPORTING CAST

Diverse cells called neuroglia make up more than half the volume of vertebrate nervous systems. Neurons cannot function without them. Section 34.6

PATHS OF INFORMATION FLOW

Information flow through the nervous system depends on moment-by-moment integration of excitatory and inhibitory signals that act on each neuron in a pathway. Reflex arcs are the simplest routes of information flow. Section 34.7

VERTEBRATE NERVOUS SYSTEM

The central nervous system consists of the brain and spinal cord. The peripheral nervous system includes many pairs of nerves that connect the brain and spinal cord with the rest of the body. Sections 34.8, 34.9

CLOSER LOOK AT THE HUMAN BRAIN

The cerebral cortex is the most recently evolved part of the brain. In humans, it governs conscious behavior and interacts with the limbic system in forming and retrieving memories. Many drugs interfere with information flow in the human brain. Sections 34.10–34.13

Links to Earlier Concepts

In this chapter, you will draw on your knowledge of diffusion, concentration gradients (Section 5.3), and mechanisms of passive and active transport (5.4). You may wish to review an earlier explanation of how positive feedback mechanisms work (28.3). You will be revisiting the body plans of a few invertebrates (25.4, 25.6) and major trends in vertebrate evolution (26.2).

34.1 Evolution of Nervous Systems

LINKS TO SECTIONS 25.1–25.7, 26.2

All animals above the sponge level of organization have a nervous system, a means of sensing and responding to information about conditions inside and outside the body.

You probably know that your own nervous system has communication lines made of three classes of neurons. *Sensory* neurons detect information about stimuli, such as light. *Inter*neurons accept the sensory input, process it, and signal other neurons. *Motor* neurons relay new signals to effectors—muscles and glands—that carry out responses (Figure 34.2). Other cells—*neuroglia*—structurally and metabolically support the neurons. Your system is far more complex than the one in, say, a jellyfish. Nevertheless, even a jellyfish offers clues to how your own system originated.

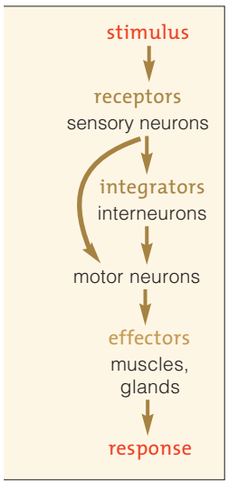


Figure 34.2 The line of communication.

REGARDING THE NERVE NET

Animals first evolved in the seas, and the ones with the simplest nervous systems still live in water. They are cnidarians, such as sea anemones, jellyfishes, and other groups having a *radial* body plan (Sections 25.2 and 25.4). Cnidarians have two epithelial tissues—an epidermis and a gastrodermis. An asymmetrical mesh of neurons, a **nerve net**, controls simple movements of both. Sensory neurons of the epidermis signal motor neurons that extend all through the two tissues. The motor neurons activate epithelial cells that have long contractile extensions, which are organized as sheets and rings in the body wall (Figure 34.3*a* and Section 37.1). By making them contract, the nerve net changes the diameter of the mouth or body or bends tentacles.

The cnidarians will never dazzle you with speed or acrobatics. Even so, their nerve net lets them capture food that randomly drifts into them and then move it into the gut. The radial system is equally responsive to tidbits arriving from any direction.

ON THE IMPORTANCE OF HAVING A HEAD

Bilateral animals, remember, have a top-to-bottom and front-to-back body plan, which master genes map out as the embryos develop (Section 25.2). These genes evolved before radial animals did, but their expression is mostly suppressed in cnidarians. Cnidarian nerve nets still control a bilateral array of muscles that ring the opening to the gut. In some groups, the nerve net also controls the motions of bilateral larvae.

Today, flatworms are the simplest animals with a bilateral nervous system. They have **nerves**, or long-distance cables. Branching nerves join two nerve cords in a ladderlike array (Figure 34.3*b*). In some species, nerve cords expand to form ganglia in their head end. A **ganglion** (plural, ganglia) is a cluster of nerve cell

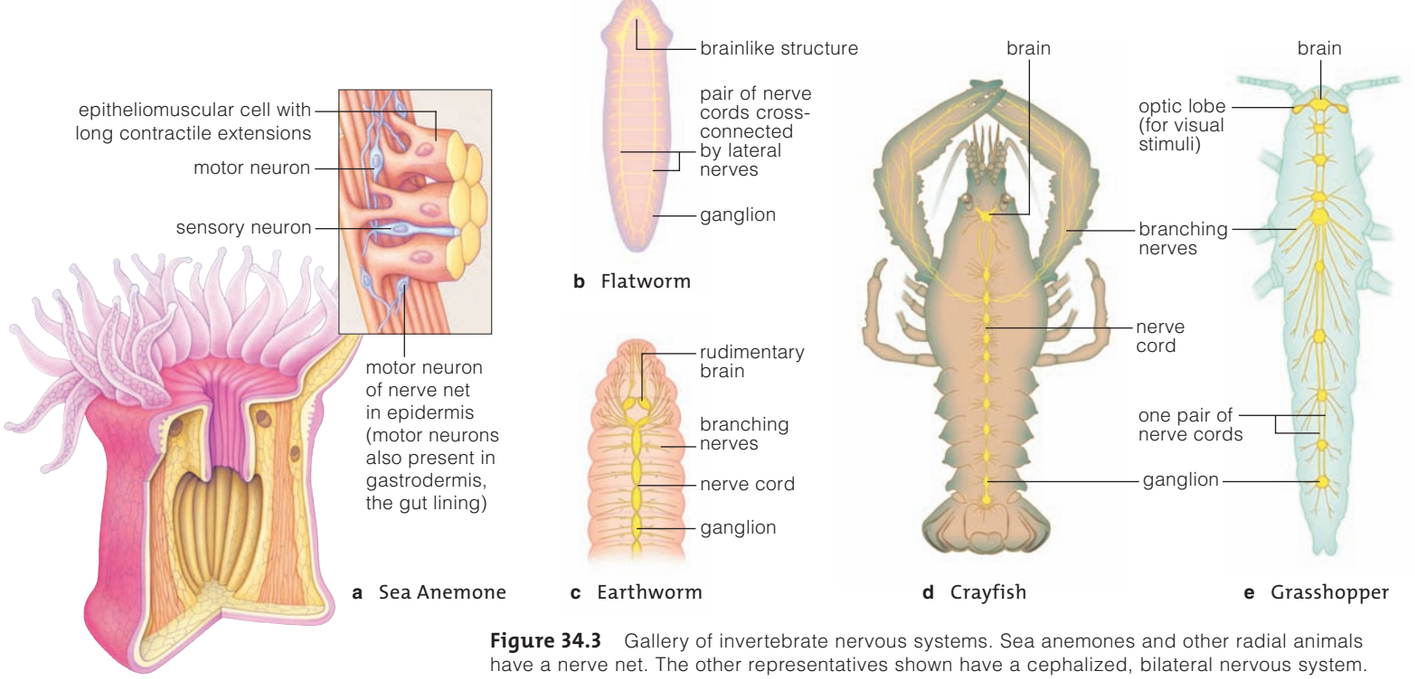


Figure 34.3 Gallery of invertebrate nervous systems. Sea anemones and other radial animals have a nerve net. The other representatives shown have a cephalized, bilateral nervous system.

bodies that function as a local integrating center. In flatworms, ganglia in the head end integrate signals from paired sensory organs, such as eyespots. Other ganglia in the body exert local control over nerves.

However it occurred, **cephalization**—the formation of a head—evolved in concert with bilateral nervous systems in nearly all animal groups. We see evidence of the bilateral heritage in the rudimentary brain and paired ganglia of most invertebrates (Figure 34.3*c–e*). We see it in paired sensory structures, brain centers, nerves, and skeletal muscles of all vertebrates.

So which lineages of bilateral animals are now the brainiest? Generally, when an animal has a big brain relative to its body size, it shows notable behavioral complexity. Cephalopods, again, are the brainiest of all invertebrates. They have a complex brain and sensory organs, and they precisely maneuver their streamlined body and its individual tentacles. Precision comes in handy when cephalopods hunt prey (Section 25.9).

What about vertebrates? Over evolutionary time, nervous tissue thickened at the anterior end of their dorsal nerve cord. In most lineages, brains got bigger because bigger brains gave individuals a competitive edge in assessing and responding to food and danger. Also, diverse stimuli greeted the first vertebrates that invaded land. In this new setting, agents of selection favored expansions of sensory structures, motor skills, and brain centers that could coordinate, process, and direct the body's responses to novel stimuli.

THE VERTEBRATE NERVOUS SYSTEM

The nervous system of vertebrates has two functional divisions (Figure 34.4). The brain and spinal cord are the *central* nervous system. Nerves extending through the rest of the body make up most of the *peripheral* nervous system (Figure 34.5). Their sensory fibers are *afferent*; they deliver signals into the central system. Motor fibers are *efferent*; they carry signals out of it.

Radial animals have a nerve net. Nearly all other animals have a bilateral, cephalized nervous system. All nervous systems evolved as an outcome of mutations in genes that control how the basic body plan develops in embryos.

In vertebrates, the nervous system has two functional divisions. The brain and spinal cord are the central nervous system. Threading through the rest of the body are spinal and cranial nerves, the major communication lines of the peripheral nervous system.

Inside the nerves, sensory fibers carry signals into the brain and spinal cord. Motor fibers carry signals away from them.

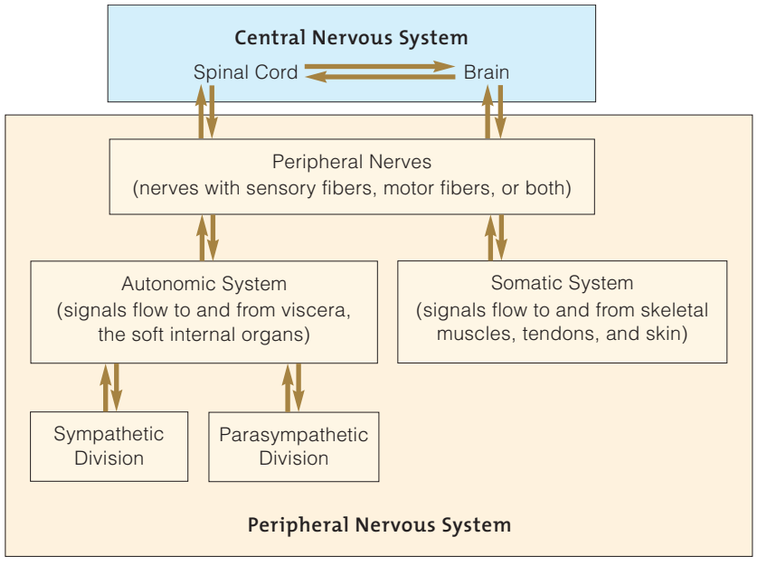


Figure 34.4 Functional divisions of vertebrate nervous systems. The spinal cord and brain are its central portion. The peripheral nervous system includes spinal nerves, cranial nerves, and their branchings, which extend through the rest of the body. They carry signals to and from the spinal cord and brain.

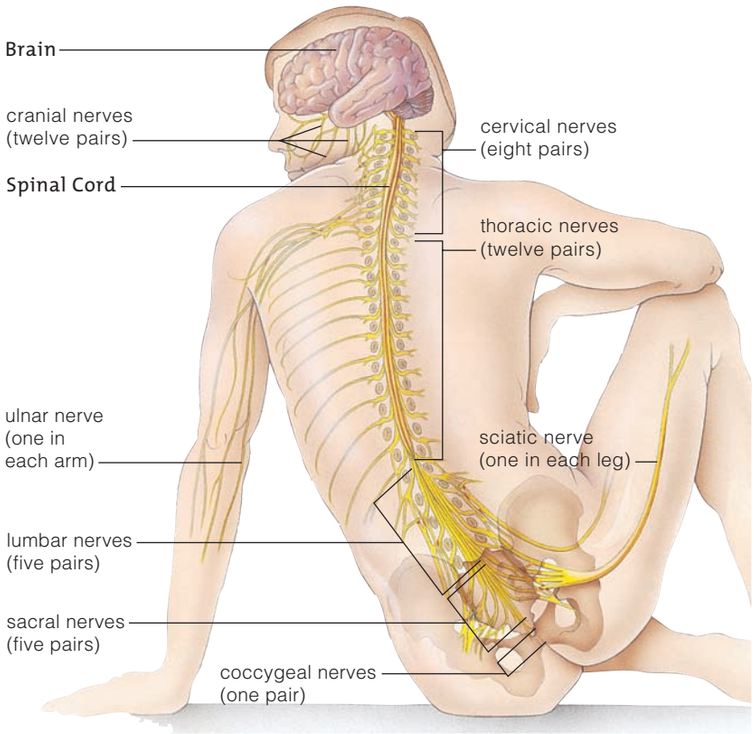


Figure 34.5 Some of the major nerves of the human nervous system.

34.2 Neurons—The Great Communicators

LINKS TO SECTIONS 5.2, 5.4, 5.5, 6.1

Nervous systems, again, evolved as a way to sense and respond faster and with precision to changing conditions inside and outside the body. They do so by way of many communication lines, the units of which are neurons.

NEURONS AND THEIR FUNCTIONAL ZONES

Let us now formally define the three classes of neurons in bilateral nervous systems. A **sensory neuron** detects a stimulus at one or more receptor endings and relays information about it to other neurons. A **motor neuron** delivers excitatory or inhibitory commands from other neurons to muscles or glands. Information from most sensory neurons flows through **interneurons** before it gets to motor neurons. Interneurons receive, process, and often store sensory information, and they interact to integrate most of the responses to it. Your brain and spinal cord contain hundreds of billions of them.

A neuron cell body has a nucleus and one or more fibers, or slender cytoplasmic extensions. Two classes of fibers—**dendrites** and **axons**—differ in number and length among neurons (Figure 34.6*a–c*). Most often, the cell body and dendrites are *input* zones, where signals arrive and cause an electrical disturbance across the plasma membrane. A large disturbance may spread to the *trigger* zone, an adjoining patch of the membrane where information about a stimulus becomes encoded in action potentials. As you will see, action potentials usually propagate themselves along an axon, which is a neuron's *conducting* zone. Most axons have branched endings that are *output* zones. Here, action potentials become transduced into signals that can be sent on to neighboring cells (Figure 34.6*d*).

MEMBRANE GRADIENTS AND POTENTIALS

When a neuron is "at rest," or not being stimulated, mechanisms are maintaining a slight electric gradient across the plasma membrane. The cytoplasmic fluid near the membrane has a slight negative charge with respect to the fluid outside. As in a car battery, these separated charges have potential energy, which can be measured in millivolts (thousandths of a volt). The steady voltage difference across the neuron's plasma membrane is called the **resting membrane potential**. In many cases, it is about –70 millivolts.

All living cells maintain an electric gradient across their plasma membrane, but only in neurons, muscle cells, and a few other *excitable* cells does that electric gradient briefly reverse itself in an abrupt response to stimulation. We call the reversal an **action potential**. It

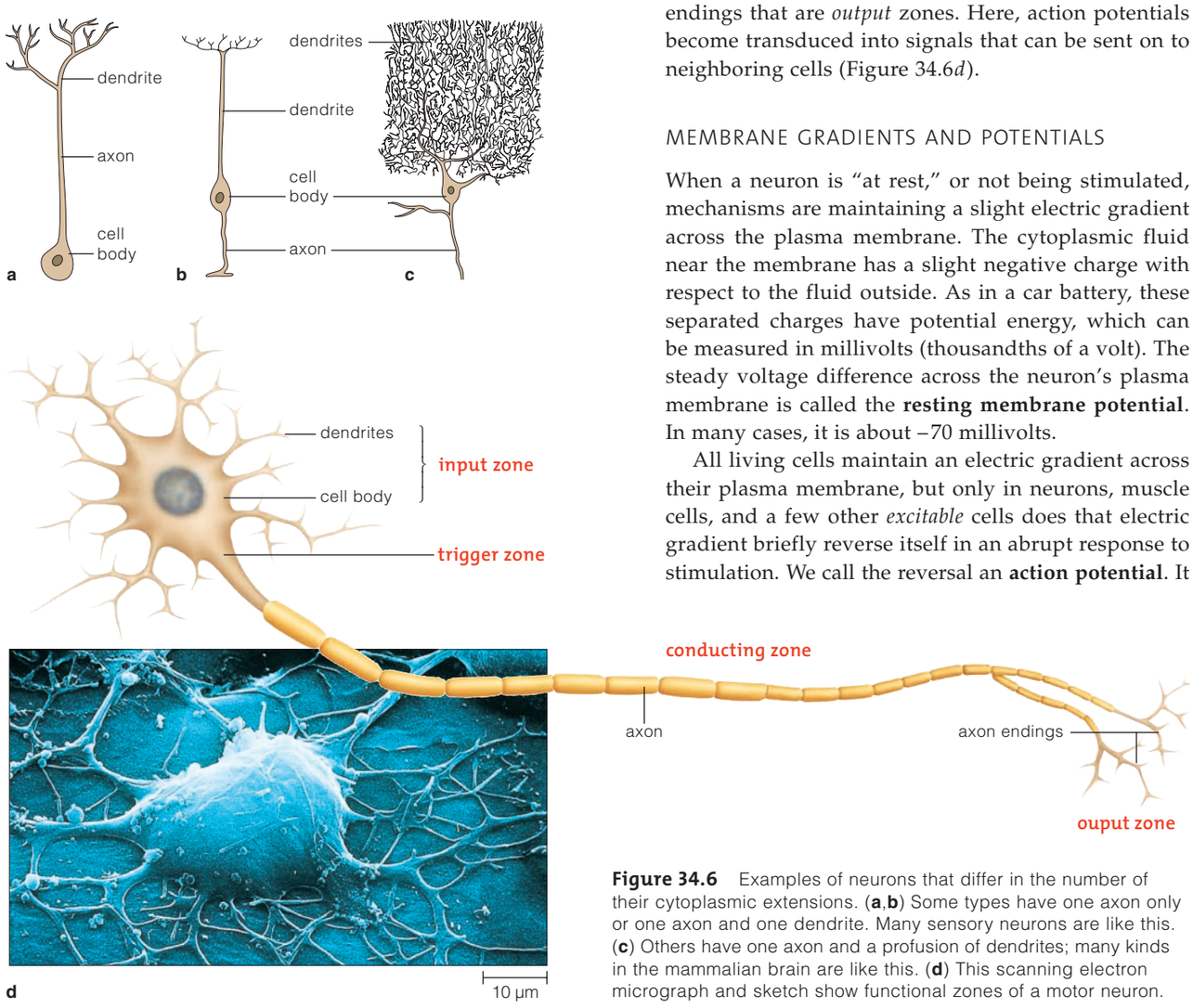


Figure 34.6 Examples of neurons that differ in the number of their cytoplasmic extensions. (**a**,**b**) Some types have one axon only or one axon and one dendrite. Many sensory neurons are like this. (**c**) Others have one axon and a profusion of dendrites; many kinds in the mammalian brain are like this. (**d**) This scanning electron micrograph and sketch show functional zones of a motor neuron.

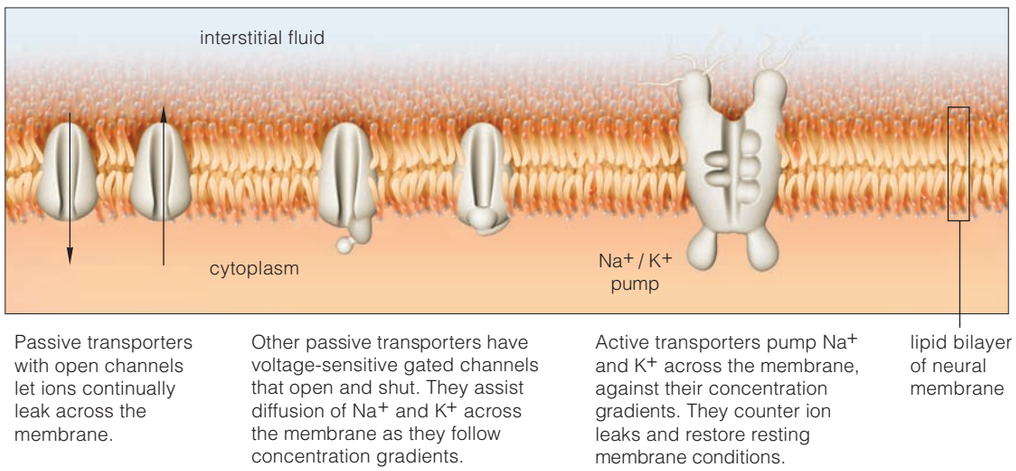


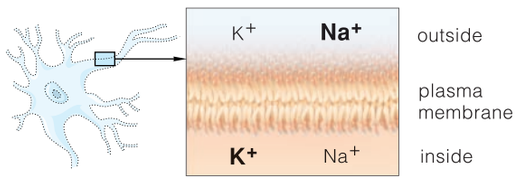
Figure 34.7 ***Animated!*** How ions cross the plasma membrane of a neuron. They are selectively allowed to cross at protein channels and pumps that span the membrane.

sets in motion a series of fleeting reversals that travels from a neuron's trigger zone to its output zone.

Before tracking an action potential, take a moment to become familiar with certain membrane properties on which it is based. Diverse transport proteins work with and against ion concentration gradients across a neuron's plasma membrane. Specifically, potassium ions (K^+), sodium ions (Na^+), and certain other ions cannot cross the lipid bilayer on their own. Transport proteins, of the sort represented in Figure 34.7, must passively or actively help them across.

As you know from Section 5.2, transporters have an interior channel that opens to both surfaces of the membrane. Some transporters are like open channels for certain ions, which leak through them all the time. Other transporters have a molecular gate at one end of the channel. The gates are tightly closed when the neuron is at rest. They open during action potentials.

When a neuron is at rest, there are about 15 sodium ions in the fluid just inside the plasma membrane for every 150 outside. There are 150 potassium ions inside for every 5 outside. We can show the ion concentration gradients across the membrane in this fashion, where larger letters represent the higher concentration:



Without these ion gradients, an action potential cannot arise. When a membrane is maintaining the gradients, it is largely impermeable to sodium, because the gates on Na^+ channels are shut. Some potassium is leaking out, through many open K^+ channels. The leaks make the cytoplasmic fluid slightly more negative, so some K^+ is attracted back inside. K^+ shows no more net movement when outward-directed diffusion balances the inward pull of electric charge.

Even so, a tiny fraction of the K^+ that leaked out is still outside, and a tiny fraction of Na^+ is leaking in through a few channels that are not *quite* shut. Do the leaks mean that the ion gradients will disappear? No. **Sodium–potassium pumps** maintain the ion gradients. They also restore the gradients after they are reversed during an action potential. These active transporters span the membrane (Section 5.4). When activated by a phosphate-group transfer from ATP, each pumps two K^+ ions into the cell and three Na^+ out of it. Both ions are pumped *against* their concentration gradient.

With this bit of background on the gradients across the neural membrane, we are ready to look at how an action potential can arise at the trigger zone and then propagate itself, undiminished, to an output zone.

Sensory neurons, interneurons, and motor neurons make up the communication lines of nervous systems.

In a neuron at rest, transport proteins are maintaining ion concentration gradients by assisting or restricting the diffusion of ions across the lipid bilayer of the plasma membrane. The steady voltage difference associated with the ion gradients is the resting membrane potential.

An action potential is an abrupt, fleeting reversal in the voltage difference across the plasma membrane of any excitable cell. Sodium–potassium pumps maintain and restore the ion gradients, which are required for a reversal.

34.3 A Look at Action Potentials

LINKS TO SECTIONS 5.4, 5.5, 28.3

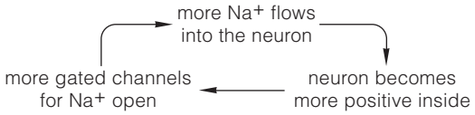
Action potentials are easy to understand when you remember that ions can cross cell membranes only through the interior of transport proteins.

APPROACHING THRESHOLD

Tap your wrist gently, and the mechanical pressure stimulates the receptor endings of sensory neurons in your skin. It slightly deforms the plasma membrane at the input zones of these neurons, which allows a few ions to slip across and shift the voltage difference just a bit. The light pressure has resulted in a local, *graded* potential. "Graded" means that disturbances to an input zone vary in magnitude, because some kinds of stimuli are more intense or last longer than others. Graded potentials do not spread far from the point of stimulation. It takes certain kinds of ion channels to spread farther, and the input zones of neurons simply do not have them.

When a stimulus *is* intense or long-lasting, graded signals spread from an input zone into an adjoining trigger zone. This membrane patch is richly endowed with voltage-sensitive gated channels for sodium ions. When the voltage difference across the membrane is disturbed by a certain amount—a *threshold* level—the gates open and trigger an action potential.

The opened gates allow positively charged sodium ions to flow through the interior of transport proteins and into the neuron (Figure 34.8). That influx makes the cytoplasmic side of the membrane less negative, which causes more gates to open and more sodium to enter. This ever increasing, inward flow of ions is one example of **positive feedback**. The activity intensifies as a result of its own occurrence:

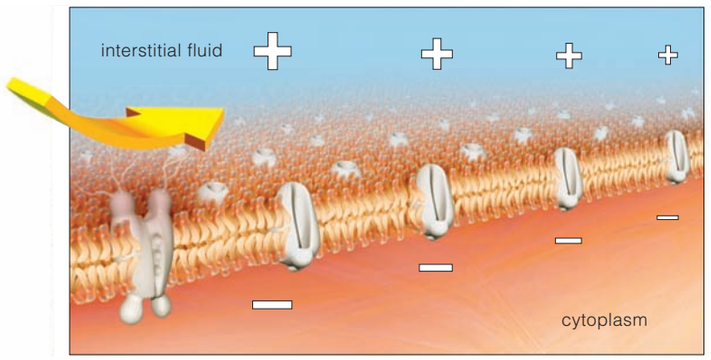


At threshold, the opening of sodium gates no longer depends on the strength of the stimulus. The positive feedback cycle is under way, and the inward-rushing sodium itself is enough to open more gates.

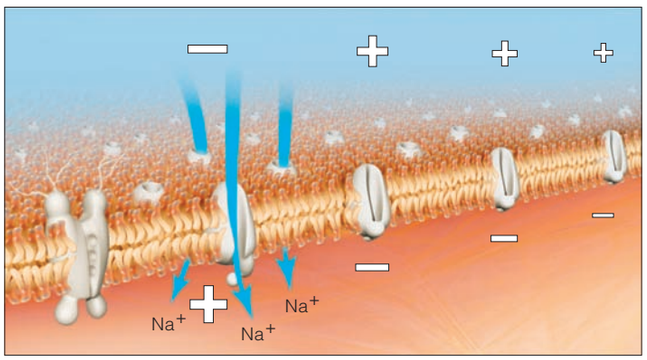
AN ALL-OR-NOTHING SPIKE

You can make a recording of an action potential by putting one electrode in an axon and another outside, and connecting both to a recording device. Figure 34.9 shows what a recording looks like before, during, and after an action potential. At threshold, the change in membrane potential for a given neuron always spikes with the same intensity, as an *all-or-nothing* event.

Each spike lasts for just a millisecond or so. Where the charge is reversed, gates on sodium channels shut and cut off the Na^+ inflow. Also, halfway through the reversal, gated *potassium* channels open, so K^+ flows out. The outflow restores the voltage difference at the membrane patch, but not the particular ion gradients that are required for another action potential. Again, sodium–potassium pumps adjust the distribution of Na^+ and K^+ across the plasma membrane after each action potential ends. These active transporters pump sodium out and potassium in (Figure 34.8*c*).



(a) Membrane at rest; inside of neuron negative with respect to the outside. An electrical disturbance (*yellow* arrow) spreads from an input zone to an adjacent trigger region of the membrane, which has a great number of gated sodium channels.



(b) A strong disturbance initiates an action potential. Sodium gates open. The sodium inflow decreases the negativity inside the neuron. The change causes more gates to open, and so on until threshold is reached and the voltage difference across the membrane reverses.

Figure 34.8 ***Animated!*** Propagation of an action potential along the axon of a motor neuron.

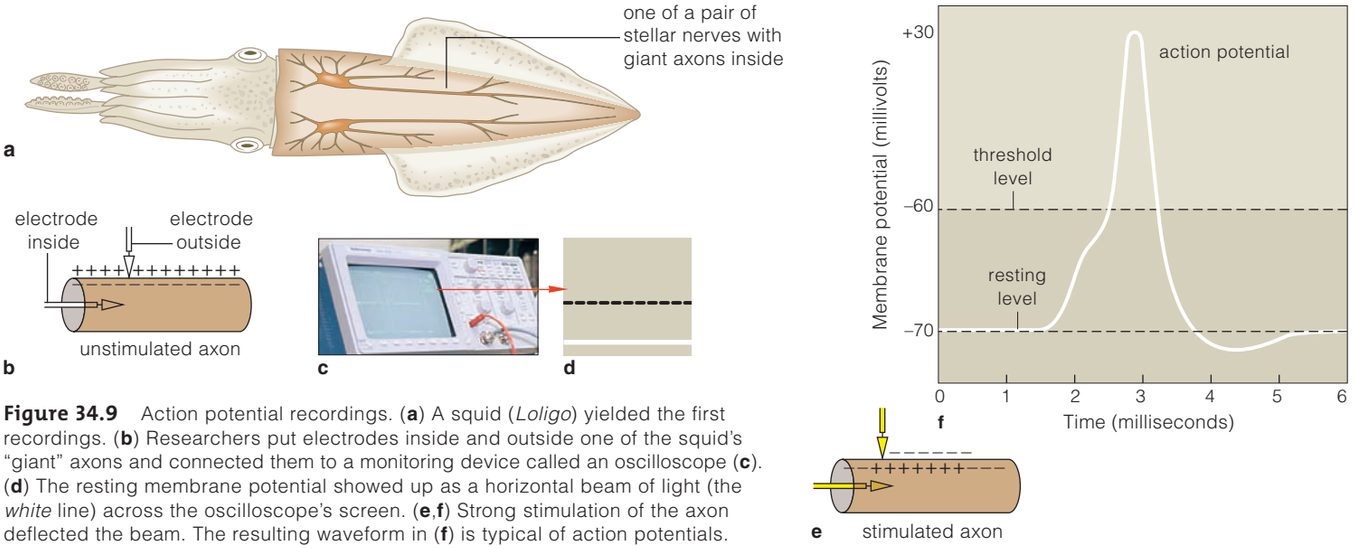


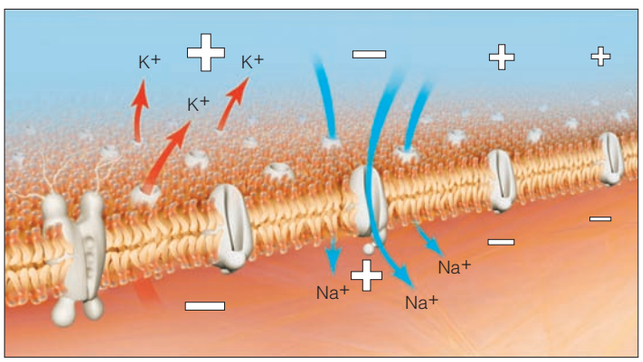
Figure 34.9 Action potential recordings. (**a**) A squid (*Loligo*) yielded the first recordings. (**b**) Researchers put electrodes inside and outside one of the squid's "giant" axons and connected them to a monitoring device called an oscilloscope (**c**). (**d**) The resting membrane potential showed up as a horizontal beam of light (the *white* line) across the oscilloscope's screen. (**e**,**f**) Strong stimulation of the axon deflected the beam. The resulting waveform in (**f**) is typical of action potentials.

DIRECTION OF PROPAGATION

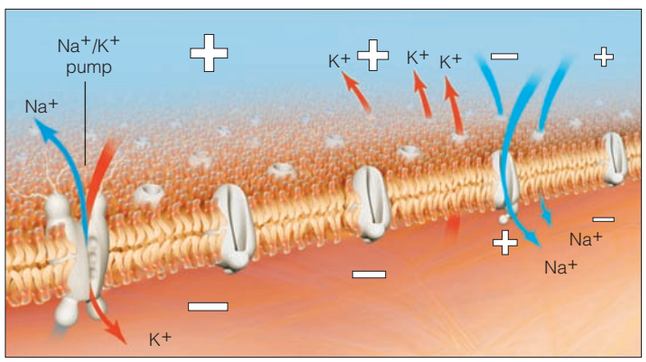
An action potential causes gated channels to open in an adjoining membrane patch, which causes channels to open in the *next* patch, and so on down the axon. This positive feedback event is self-propagating; it does not weaken with distance. In addition, it always moves *away* from the trigger zone. Why? As an action ends, gated sodium channels are inactivated until the sodium–potassium pumps are done restoring the ion gradients across the plasma membrane. Meanwhile, down the line, the adjoining patch of membrane has an abundance of sodium channels with closed gates that are ready to be opened.

In neurons, an action potential starts after the membrane potential reaches a threshold level. The voltage difference across the membrane reverses as gated sodium channels open in an ever accelerating way. The disturbance causes self-propagating reversals at each consecutive patch of membrane along an axon, with no loss in magnitude.

An action potential ends when potassium flows out of the neuron and restores the voltage difference. Gated sodium channels are inactivated until sodium–potassium pumps restore the ion gradients across the patch of membrane, which are required for the next action potential.



c With the reversal, sodium gates shut and potassium gates open (*red* arrows). Potassium follows its gradient out of the neuron. Voltage is restored. The disturbance triggers an action potential at the adjacent site, and so on, away from the point of stimulation.



d Following each action potential, the inside of the plasma membrane becomes negative once again. However, the sodium and potassium concentration gradients are not yet fully restored. Active transport at sodium–potassium pumps restores them.

34.4 How Neurons Send Messages to Other Cells

LINKS TO SECTIONS 5.4–5.6

So far, you have tracked the energy of a stimulus, from its transduction into the electrochemical energy of an action potential to its propagation down to the output zone of a neuron. What happens next?

CHEMICAL SYNAPSES

A thin cleft separates the output zone of one neuron from a neighboring neuron, gland cell, or muscle cell, as in Figure 34.10*a*,*b*. At this zone, the electrochemical energy of an action potential is transduced to the form of chemical signal that can diffuse across the cleft and activate or inhibit the target cell. Hence the name for this type of functional bridge between a neuron and some other cell: **chemical synapse**. *Synapse* is derived from a Greek word meaning to fasten together.

Figure 34.10 shows an axon ending of a *pre*synaptic neuron. Inside are many synaptic vesicles filled with **neurotransmitter**, a type of signaling molecule that is synthesized in neurons only. The plasma membrane has many gated channels for calcium ions. In between action potentials, there are more calcium ions outside than inside, and the gates stay shut tightly. An action potential, however, makes the gates open.

As calcium ions flow in, the synaptic vesicles move through the cytoplasm in the axon ending and fuse with the membrane. These exocytic vesicles lose their identity when they merge with the plasma membrane, and the neurotransmitter molecules are released into the synaptic cleft (Section 5.6).

Diffusion alone quickly moves neurotransmitters to receptors on the *post*synaptic cell membrane. In some cells, the receptors are part of proteins with gated ion channels. When neurotransmitter binds to them, the gates open, so ions diffuse in (Figure 34.10*c*). Different receptors indirectly induce change in the membrane's permeability. When neurotransmitter binds to them, it induces enzymes to enter reactions that open up ion channels elsewhere in the membrane.

A postsynaptic cell's response depends on the type and number of neurotransmitter molecules, receptors, and gated ion channels. Often a neurotransmitter has an *excitatory* effect, in that it can drive the membrane toward the threshold of an action potential. In other cases, it has an *inhibitory* effect; it pulls the membrane away from threshold.

To give one example, a **neuromuscular junction** is a type of chemical synapse between a motor neuron

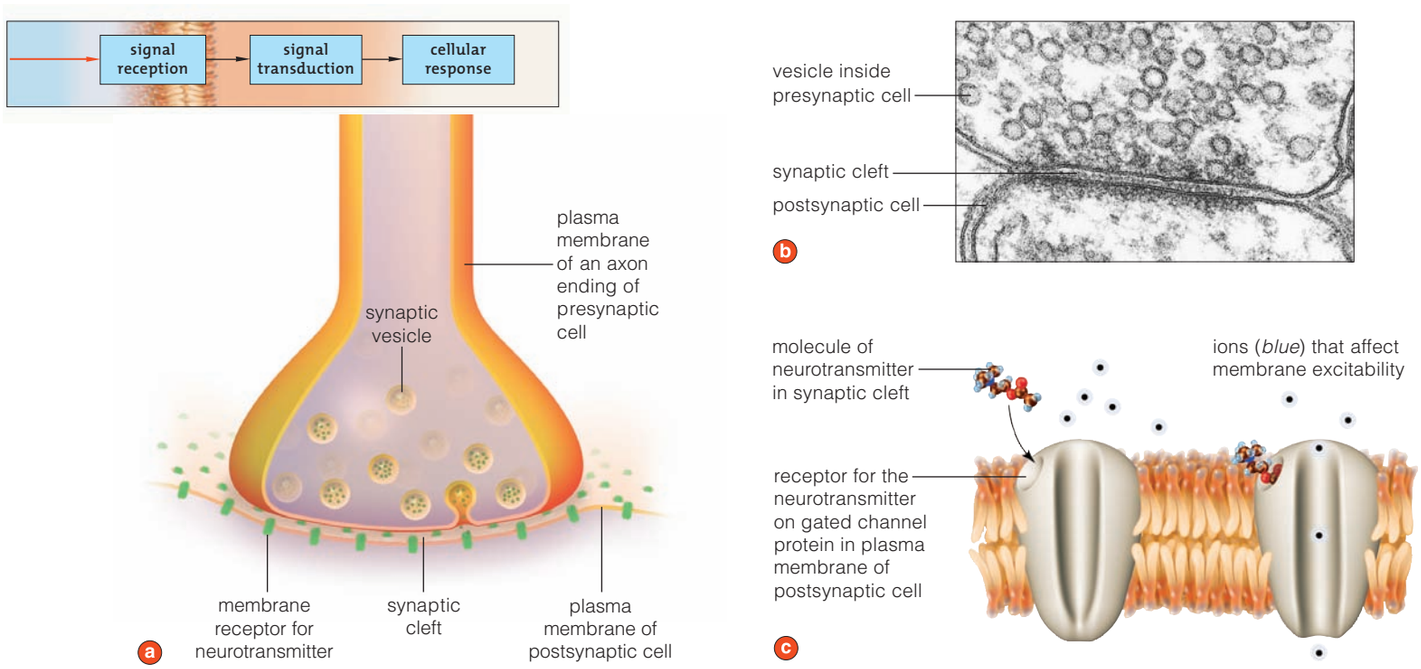


Figure 34.10 ***Animated!*** A chemical synapse, part of a signaling pathway in the nervous system. (**a**,**b**) An action potential arrriving at an axon ending of a presynaptic cell causes the release of neurotransmitter. (**c**) These signaling molecules diffuse across a cleft to a postsynaptic cell membrane. When they bind to receptors on gated membrane proteins, the gates open, and the signal is transduced into a flow of ions into the cell. That flow, a form of electrochemical energy, may activate or inhibit the target cell's activity.

and a skeletal muscle fiber. The motor neuron releases **acetylcholine**, or ACh, which diffuses across the cleft and binds to membrane receptors on muscle fibers (Figure 34.11). ACh has an excitatory effect on these cells and might stimulate muscle contraction (Section 37.7). However, as you will see later, ACh released by the axons of different nerves binds to cardiac muscle cells and inhibits contraction. Also, in the brain, ACh inhibits activity of cells that have roles in memory.

SYNAPTIC INTEGRATION

Between 1,000 and 10,000 communication lines reach a typical interneuron in your brain, which is only one of at least 100 billion others that may interact at 100 trillion synapses! At any time, many excitatory and inhibitory signals are helping to maintain the resting membrane potential of a given neuron or are driving it closer to or farther away from threshold.

Signals that cross a chemical synapse trigger two kinds of graded potentials in the postsynaptic cell. An **EPSP** (short for excitatory postsynaptic potential) has a *depolarizing* effect; it can drive a membrane closer to threshold. An **IPSP** (inhibitory postsynaptic potential) can have a *hyperpolarizing* effect. Depending upon the state of the target cell, it can help drive the membrane farther away from threshold or help maintain it at the resting level.

With **synaptic integration**, a postsynaptic neuron sums all signals that are arriving at its input zone on more than one communication line. Summation can have several outcomes. Two or more incoming signals might be dampened, suppressed, reinforced, or sent on to other cells. Figure 34.12 has an example of how this integrative process works. It is a composite of the recordings of an EPSP, an IPSP, and their summation.

Neurons also integrate signals that arrive one after another. For example, this happens when an ongoing stimulus triggers a series of action potentials in the presynaptic cell and stimulates it to bombard a target cell with waves of neurotransmitter molecules.

Neurotransmitters are signaling molecules secreted into a synaptic cleft from a neuron's output zone. They may have excitatory or inhibitory effects on a postsynaptic cell.

Synaptic integration is the summation of all excitatory and inhibitory signals that are arriving at a postsynaptic cell's input zone. By this process, the information flowing through different parts of the nervous system can be reinforced or downplayed, sent onward or suppressed.

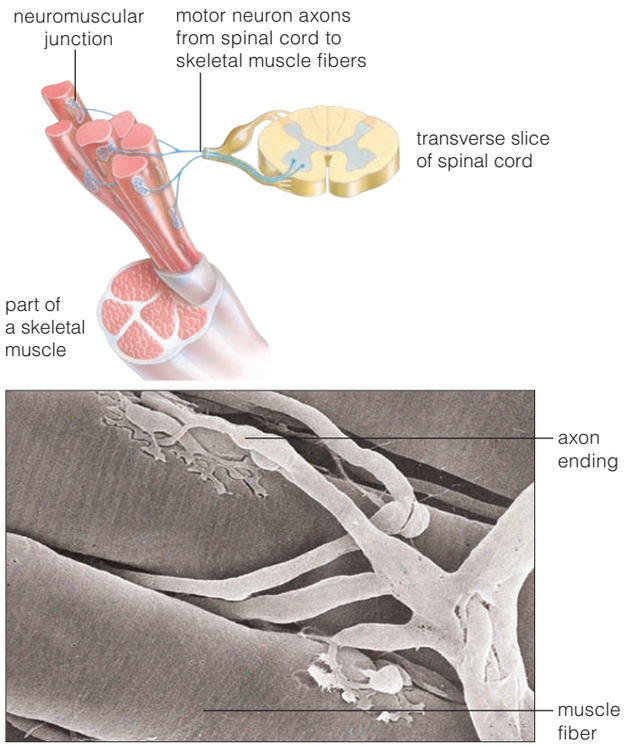


Figure 34.11 A common chemical synapse: a neuromuscular junction. Micrographs reveal many of these junctions between the axon endings of motor neurons and the muscle fibers in skeletal muscle.

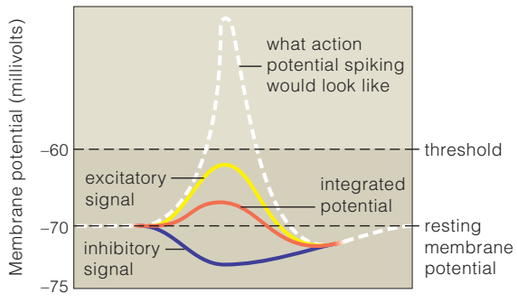


Figure 34.12 Synaptic integration. Typically, many excitatory and inhibitory signals arrive at the input zone of a postsynaptic neuron at the same time.

The *yellow* waveform in this composite graph shows how one postsynaptic cell responded to the arrival of an excitatory signal of a certain magnitude. This signal was not strong enough to drive the membrane to threshold. The *purple* waveform shows how it responded to an inhibitory signal. What if both signals arrived at the same time? The inhibitory signal would lower the excitatory signal's effect, so the *red* waveform would result. Summation of the two signals used in this example would not lead to an action potential (the *white* line).

34.5 A Smorgasbord of Signals

LINKS TO SECTION 6.4

What do neurotransmitters have to do with how we respond to a kiss, the perfect pair of shoes, a win by the home team? Everything. They are part of communication pathways that govern every sensation and every move we make.

NEUROTRANSMITTER DIVERSITY

In the early 1920s, Austrian scientist Otto Loewi was working to find out what controls the heart's beating. He surgically removed a frog heart—with a nerve still attached—and put it in saline solution. Loewi already knew that the heart would still beat on its own for a while. He stimulated the nerve and noticed that the heartbeat slowed a bit. Perhaps the stimulated nerve released a chemical signal. To test this hypothesis, he put two frog hearts into a saline-filled chamber and stimulated the nerve connected to one of them. Both hearts started to beat more slowly. As expected, the nerve had released a chemical that not only affected the attached heart, it also diffused through the liquid and slowed the beating of the second heart!

Loewi had discovered one of the responses to ACh, the neurotransmitter you read about in the preceding section. ACh acts on skeletal muscle, smooth muscle, the heart, a variety of glands, and the brain. When it binds to receptors in skeletal muscle, it can stimulate contraction. Binding causes sodium ions to enter the muscle fibers, which drives the membrane potential closer to threshold. When ACh binds to a different type of receptor in heart muscle, it slows contraction. It initiates a cascade of reactions in which different enzymes are activated in sequence. The result? Gated channels for potassium ions open, and the membrane potential is pulled away from threshold.

ACh is only one of many neurotransmitters. Other major types are **norepinephrine**, **epinephrine** (also called adrenalin), and **dopamine**. These three are made from the amino acid tyrosine. Both norepinephrine and epinephrine prime the body to respond to stress.

Dopamine affects fine motor control and pleasure-seeking behaviors. Destruction of dopamine-secreting neurons in one brain region causes *Parkinson's disease* (Figure 34.13). Usually, a minor tremor in the hands is the earliest symptom. The sense of balance is affected, so walking may become difficult. Heritable mutations increase the risk. Exposure to certain chemicals in the environment also may be a contributing factor.

Signaling pathways that involve dopamine are part of the learning process in vertebrates and a number of invertebrates. In humans, changes in dopamine levels influence mood, motivation, and attention spans. Some dopamine-secreting neurons fire off action potentials spontaneously. Injecting heroin into a vein accelerates the firing rate. The abnormal stimulation amplifies the sense of pleasure in addictive ways (Section 34.13).

Serotonin is a small neurotransmitter derived from the amino acid tryptophan. As you read earlier in the chapter, serotonin affects mood and memory. Ecstasy interferes with its functions. Low serotonin levels are related to depression. Prozac (fluoxetine) and similar antidepressants alter serotonin levels.

GABA (for gamma amino butyric acid) is derived from glutamate. In the brain, it is the major inhibitor of neurotransmitter release by other neurons.

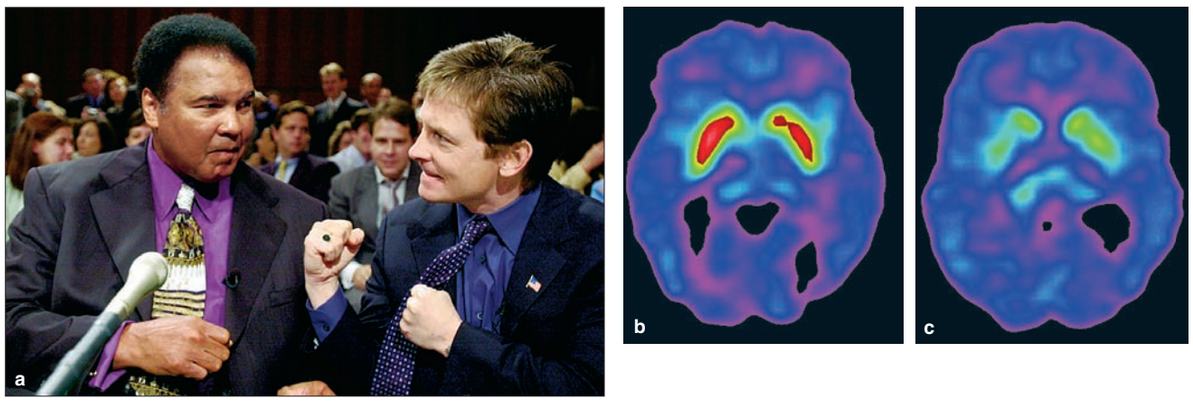


Figure 34.13 Battling Parkinson's disease. (**a**) At this writing, this neurological disorder has affected former heavyweight champion Muhammad Ali, actor Michael J. Fox, and about 500,000 other people in the United States. PET scans of an unaffected individual used as a control and (**b**) of an affected person (**c**). *Red* and *yellow* reveal the levels of metabolic activity by dopamine-secreting neurons.

CLEANING UP THE CLEFT

After they work, neurotransmitter molecules must be promptly removed from synaptic clefts so that new signals can be sent. Some diffuse away. Membrane transport proteins actively pump others back into the presynaptic cell or neuroglial cells. Enzymes secreted into the cleft break down specific molecules, as when acetylcholinesterase cleaves molecules of ACh.

When neurotransmitter accumulates inside the cleft, it disrupts the signaling pathways. That is how *sarin* and other nerve gases exert their effects. After sarin is inhaled, it binds to acetylcholinesterase and blocks its active site—so ACh cannot be degraded (Section 6.4). The ACh buildup causes paralysis of skeletal muscles, confusion, slurred speech, and headaches. High levels of sarin kill by interfering with signaling pathways that control breathing. In 1995, a few members of a cult released sarin gas into a crowded Tokyo subway. Eleven people died; about 5,000 required treatment.

Ecstasy, remember, slows serotonin uptake. Prozac and similar drugs do the same thing. We return to the topic of these and other psychoactive drugs later in this chapter.

THE NEUROPEPTIDES

Some neurons also produce neuropeptides, which are larger than neurotransmitter molecules. These act as **neuromodulators**; they magnify or reduce the effects of neurotransmitter on neurons that are either close to the secreting cell or some distance away.

One neuromodulator, **substance P**, enhances pain perception. **Enkephalins** and **endorphins** are natural painkillers and resemble morphine in their structure. Both inhibit the release of substance P, and both are secreted in response to strenuous activity or injuries. Endorphins also are released when people laugh, reach orgasm, or get a soothing acupuncture treatment or a calming massage. Besides suppressing pain, both of these neuropeptides reportedly can elevate mood and enhance the function of certain immune cells.

ACh, norepinephrine, epinephrine, dopamine, serotonin, and GABA are small neurotransmitters with diverse effects. All are derived from amino acids.

Once neurotransmitters work, they must be removed from the synaptic cleft to keep signaling pathways open.

Endorphins, enkephalins, and other neuromodulators magnify or reduce the effects of neurotransmitters.

34.6 Let's Hear It for Neuroglia!

Like celebrities, neurons get all the attention. Even so, they would quickly fall to pieces without their supporting staff. Similarly, we now know that neuroglia are more than bit players; neurons cannot act at all without them.

Neuroglial cells outnumber neurons in a human brain by about 10 to 1. Many are the framework that holds neurons in place; *glia* means glue in Latin. When the nervous system is developing, new neurons migrate to their final positions along highways of neuroglial fibers, which extend outward from the forming brain.

Oligodendrocytes in the brain make myelin, a fatty substance in the insulating sheaths of long-distance axons. Schwann cells do the same in peripheral nerves.

The brain's most abundant cells are star-shaped astrocytes (Figure 34.14). Astrocytes have diverse functions. They control local concentrations of ions and neurotransmitters. They play a role in immune defenses, make lactate that fuels active neurons, and make nerve growth factor.

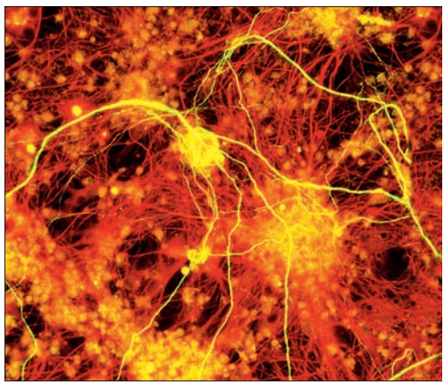


Figure 34.14 Astrocytes (*orange*) and a neuron (*yellow*) in brain tissue. The cells in this light micrograph were stained by immunofluorescence. This procedure attaches fluorescent dye molecules to antibodies designed to target specific molecules on a cell.

A **growth factor** is a type of signaling molecule secreted from one cell that targets receptors on another cell, which responds by dividing or differentiating.

Once most neurons mature, they no longer enter mitotic cell divisions. However, when they are exposed to nerve growth factor, they make more synaptic connections with neighboring cells. As you will see, this growth response also is the basis of new connections that are required in the storage of memories.

Microglia, another cell type, hang out in the brain in resting form. When a tissue is injured, they become active, motile cells. They prowl the brain and engulf dead or dying tissue. They also issue chemical signals that summon immune cells to the threatened tissue.

Most cells of the vertebrate nervous system are neuroglia. These diverse cells help organize neurons as the nervous system is developing. They structurally support and nourish neurons, and promote synapse formation and immunity.

Astrocytes, oligodendrocytes, and microglia are major components of the brain. Myelin-producing Schwann cells sheathe many axons of peripheral nerves.

34.7 Nerves and Reflex Arcs

Through synaptic integration, messages arriving at a neuron may be reinforced and sent on to its neighbors. In which direction will a given message travel? That depends on how neurons are organized in the body.

BLOCKS AND CABLES OF NEURONS

Remember, information about stimuli generally flows from sensory receptors to interneurons, then to motor neurons, then to effector cells. However, many signals also loop about in amazing ways.

Consider the billions of interneurons in your brain. They take part in circuits that integrate messages and organize responses. In the *diverging* circuits, dendrites and axons of neurons extend out from one block and communicate with other blocks. In *converging* circuits, signals from many neurons zero in on just a few. In certain circuits, neurons synapse back on themselves, repeating signals like gossip that just won't go away. As one example, such *reverberating* circuits make your eye muscles twitch rhythmically while you sleep.

Information also flows rapidly through **nerves**, the long-distance cables between body regions. A nerve contains dendrites of sensory neurons, axons of motor neurons, or both, bundled inside connective tissues. Figure 34.15*a* is an example of nerve structure.

The neuroglial cells called Schwann cells wrap like jelly rolls around axons of most peripheral nerves, one after another, as a **myelin sheath**. A sheath functions as an electronic insulator; it speeds the propagation of action potentials. How? Ions cannot cross the neural membrane at sheathed regions. The ion disturbances associated with an action potential must spread down the axon's cytoplasm until they reach a tiny exposed gap (node) between two Schwann cells (Figure 34.15*b*). The membrane at each node is loaded with gated Na^+ channels. When the gates open, the voltage difference reverses abruptly. By jumping from node to node, the signal can be moved as fast as 120 meters per second down long axons. By contrast, the maximum speed in unmyelinated axons is about 10 meters per second.

In *multiple sclerosis*, or MS, certain white blood cells wrongly identify a type of protein in myelin sheaths as foreign and destroy it. This autoimmune response leads to inflammation of axons in the brain and spinal cord and the death of oligodendrocytes. Some people are genetically predisposed to develop the disorder, but viral infection may set it in motion. Either way, information flow is disrupted. Dizziness, numbness, muscle weakness, fatigue, visual problems, and other symptoms follow. About 500,000 people in the United States are now affected by MS.

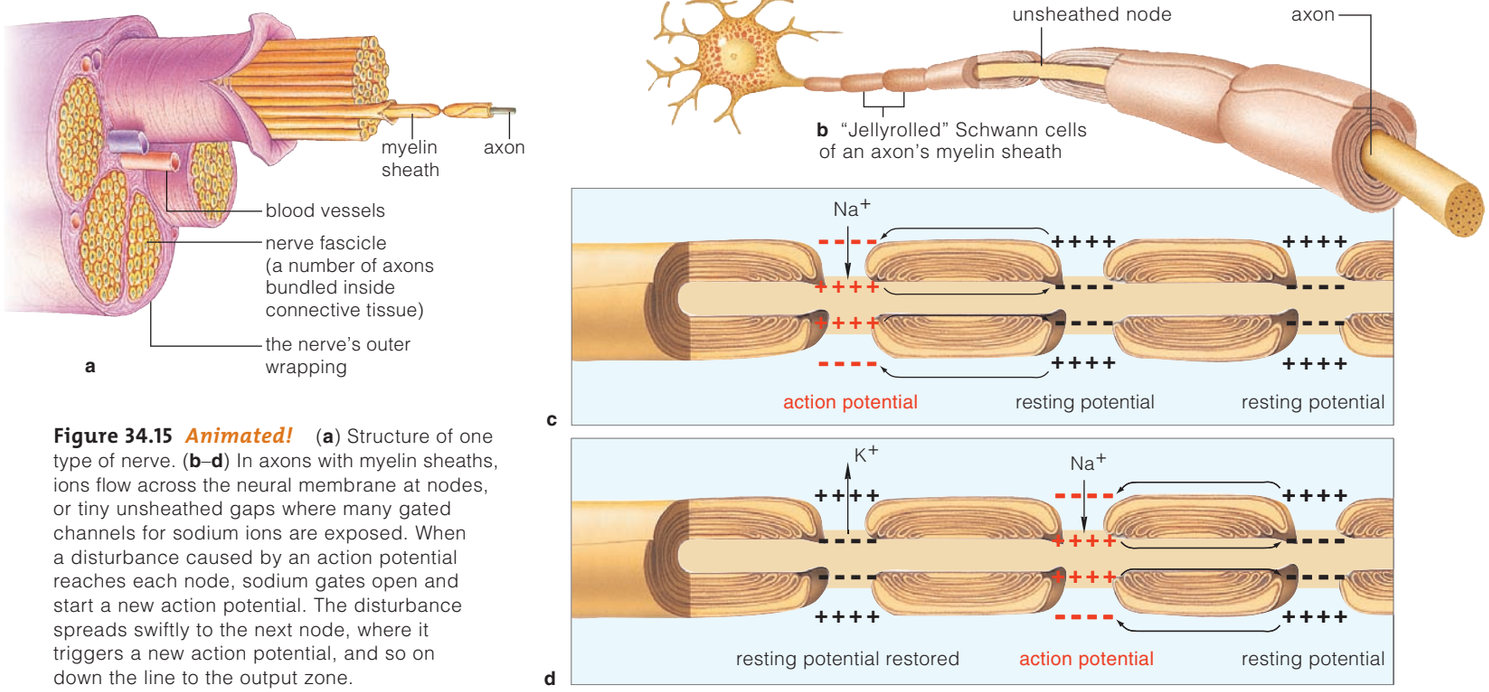


Figure 34.15 ***Animated!*** (**a**) Structure of one type of nerve. (**b**–**d**) In axons with myelin sheaths, ions flow across the neural membrane at nodes, or tiny unsheathed gaps where many gated channels for sodium ions are exposed. When a disturbance caused by an action potential reaches each node, sodium gates open and start a new action potential. The disturbance spreads swiftly to the next node, where it triggers a new action potential, and so on down the line to the output zone.

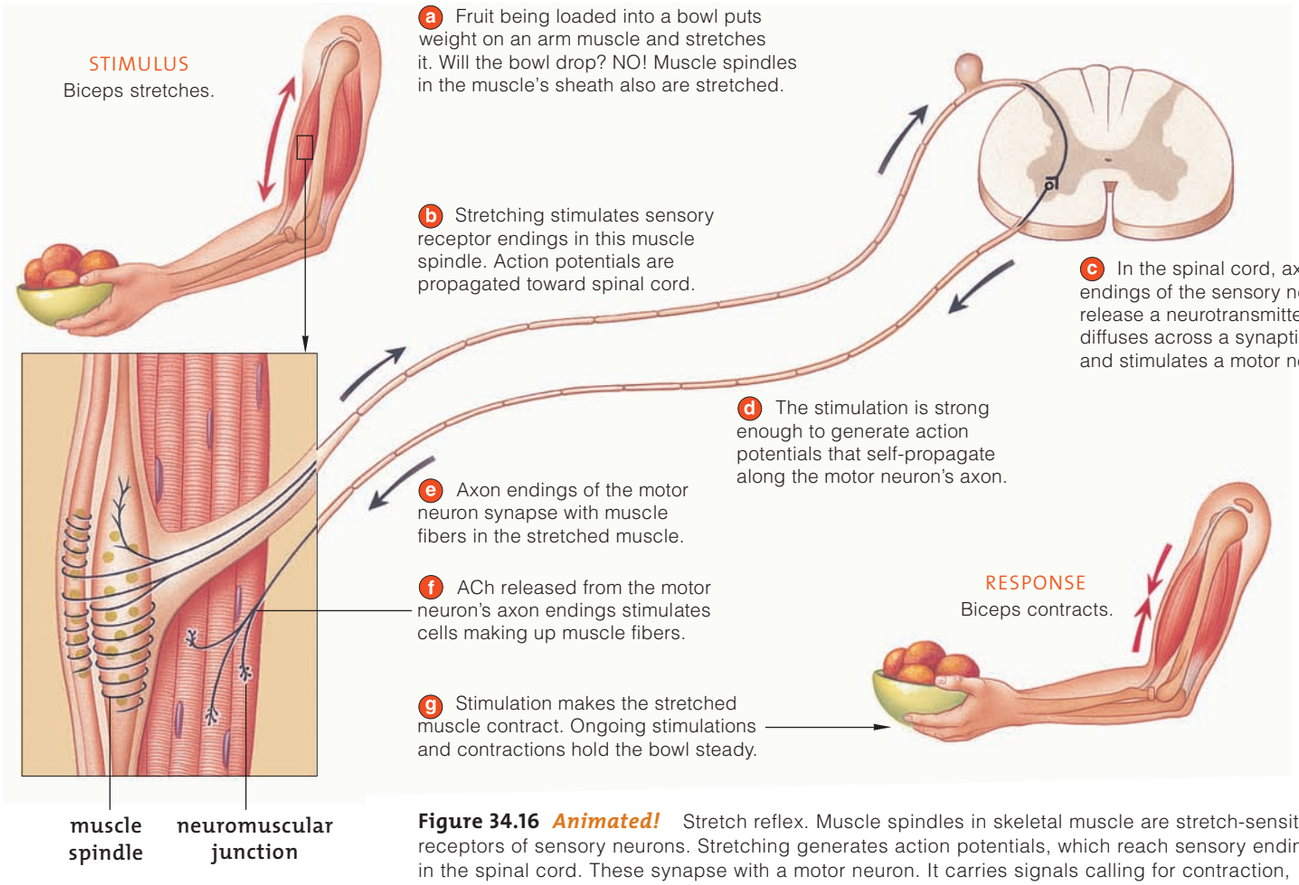


Figure 34.16 ***Animated!*** Stretch reflex. Muscle spindles in skeletal muscle are stretch-sensitive receptors of sensory neurons. Stretching generates action potentials, which reach sensory endings in the spinal cord. These synapse with a motor neuron. It carries signals calling for contraction, from the spinal cord back to the stretched muscle. The muscle contracts, steadying the arm.

REFLEX ARCS

Reflexes are the most ancient paths of information flow. A **reflex** is a movement or some other response to a stimulus that happens automatically, no thought required. In the simplest reflex arcs, sensory neurons synapse directly on motor neurons. In more complex reflexes, sensory neurons interact with one or more interneurons, which then stimulate or suppress all motor neurons required for a coordinated response.

The *stretch reflex* is a simple reflex arc that causes a muscle to contract after gravity or some other force stretches it. Suppose you hold a bowl while someone puts peaches into it. The load makes your hand drop a bit, which stretches an arm muscle called a biceps. As a biceps is stretched, the receptor endings of some sensory organs within it are stretched as well. These organs are **muscle spindles**. Their endings, enclosed in a sheath that runs parallel with the muscle, are the input zones of certain sensory neurons (Figure 34.16).

The rate of signal transmission along the axons of these sensory receptors depends on the extent to which the muscle is stretched. In the spinal cord, axons of muscle spindles synapse with motor neurons—the axons of which lead directly back to the muscle. The action potentials reach the axon endings of the motor neurons, where they trigger the release of ACh. This neurotransmitter causes the biceps to contract, which helps steady the arm against the added load.

The knee-jerk reflex is a type of stretch reflex. A tap just below the knee shortens the thigh muscle, signals flow to the spinal cord, and the leg jerks in response.

In complex animals, neurons are organized in blocks and in cables, some of which arc back to the point of stimulation.

Nerves are long-distance cables between body regions. Most long axons of their sensory neurons, motor neurons, or both have a myelin sheath, which speeds signal propagation.

Reflex arcs, in which sensory neurons synapse directly on motor neurons, are the simplest paths of information flow.

34.8 What Are the Major Expressways?

Now you are ready to consider the peripheral nervous system and the spinal cord. The two interconnect as the body's main expressways for information flow.

PERIPHERAL NERVOUS SYSTEM

Somatic and Autonomic Systems In humans, the peripheral nervous system includes thirty-one pairs of *spinal* nerves, which connect with the spinal cord. It also has twelve pairs of *cranial* nerves, which connect directly with the brain. Most cranial nerves, and all spinal nerves, contain bundles of sensory and motor fibers inside a tough outer wrapping.

Nerves of the peripheral system are classified by function. The sensory part of **somatic nerves** relays information from receptors in the skin, tendons, and skeletal muscles to the central nervous system. Their motor axons deliver commands from the brain and spinal cord to skeletal muscles. The **autonomic nerves** relay information to and from the viscera. *Viscera* refers to the soft internal organs, such as cardiac muscles, smooth muscles, and glands.

Sympathetic and Parasympathetic Divisions The nerves of the autonomic system fall in two categories: sympathetic and parasympathetic. Both service most organs and work antagonistically, meaning the signals from one type oppose signals from the other (Figure 34.17). **Sympathetic neurons** are most active in times of stress, excitement, and danger. Their axon endings release norepinephrine. **Parasympathetic neurons** are most active in times of relaxation. The release of ACh from their axon endings promotes daily housekeeping tasks, such as digestion and urine production.

What happens when something startles or scares you? The parasympathetic input decreases and gives

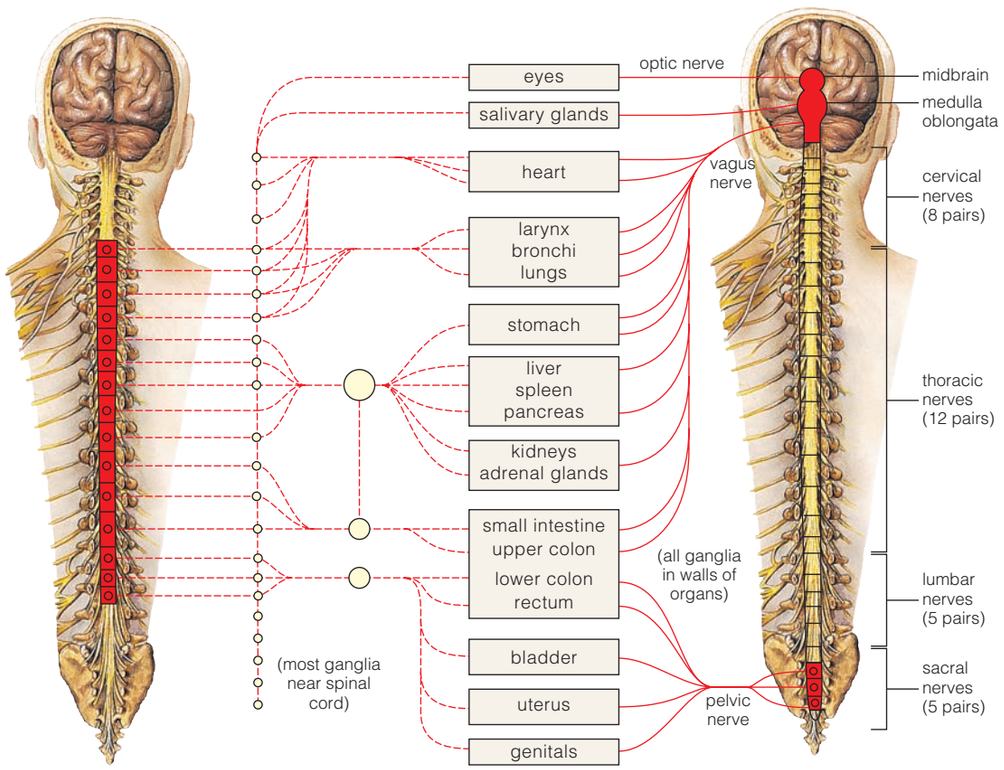


Figure 34.17 ***Animated!*** (**a**) Major sympathetic and (**b**) parasympathetic neurons of the autonomic system. These nerves are paired; the body's right and left halves have one of each. The ganglia (clusters of nerve cell bodies) are local control centers. Their axons are bundled together inside nerves.

a Sympathetic outflow from the spinal cord

Some Responses to Sympathetic Outflow
Heart rate increases
Pupils of eyes dilate (widen, let in more light)
Glandular secretions decrease in airways to lungs
Salivary gland secretions thicken
Stomach and intestinal movements slow down
Sphincters (rings of muscle) contract

b Parasympathetic outflow from the spinal cord and brain

Some Responses to Parasympathetic Outflow
Heart rate decreases
Pupils of eyes constrict (keep more light out)
Glandular secretions increase in airways to lungs
Salivary gland secretions become dilute
Stomach and intestinal movements increase
Sphincters (rings of muscle) relax

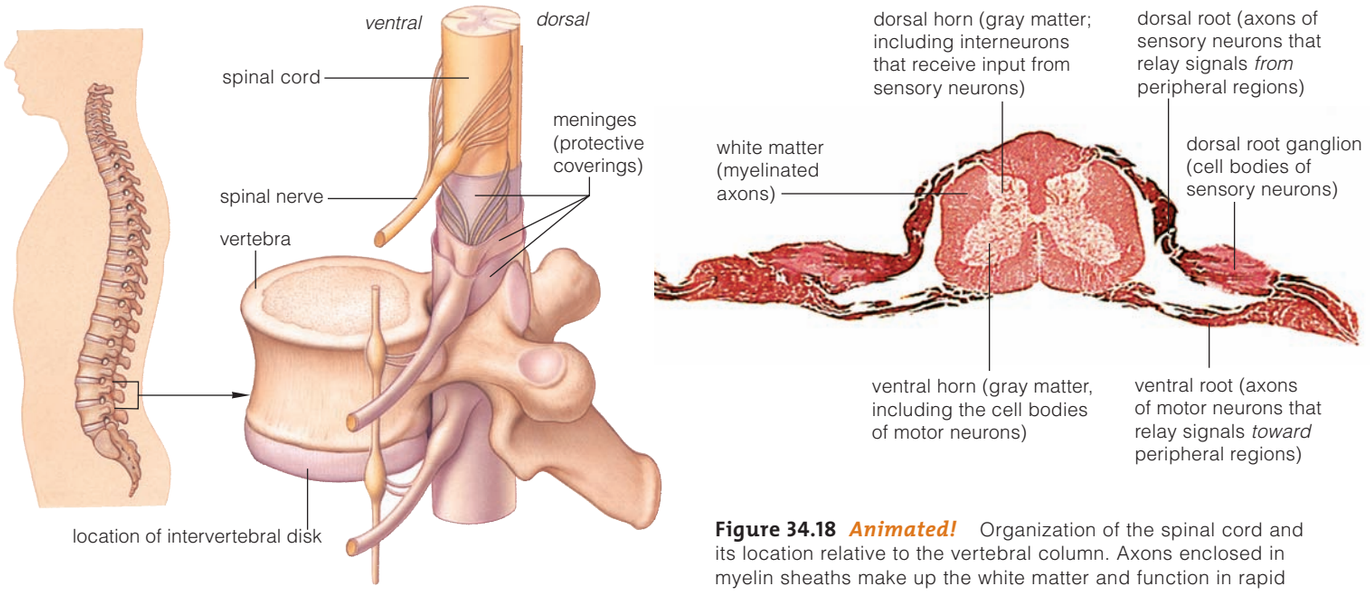


Figure 34.18 ***Animated!*** Organization of the spinal cord and its location relative to the vertebral column. Axons enclosed in myelin sheaths make up the white matter and function in rapid signal transmission. Cell bodies, dendrites, and unmyelinated axons of neurons, along with neuroglia, make up the gray matter.

way to sympathetic signals. These signals raise your heart rate and blood pressure, make you sweat more and breathe faster, and make adrenal glands secrete epinephrine. By their action, the signals help put you in a state of intense arousal, primed to fight or make a fast getaway. Hence the term *fight–flight response*.

An organ often receives opposing sympathetic and parasympathetic signals. Consider the smooth muscle cells in the gut wall. Even as sympathetic neurons are releasing norepinephrine at synapses with the smooth muscle cells, parasympathetic neurons are releasing ACh at other synapses with the same cells. One signal tells the gut to slow its contraction; the other calls for increased activity. Synaptic integration finely adjusts the muscle's actual response.

SPINAL CORD

Inside the spinal cord and deep in the brain is *white matter*, or specialized tracts of myelin-sheathed axons. The rest of the nerve tissue is *gray matter*—neuroglia and cell bodies, dendrites, and (mostly) unmyelinated axons of motor neurons and interneurons.

The **spinal cord** connects the peripheral nervous system with the brain and controls some reflexes. The reflexes affect basic tasks, such as bladder emptying and limb movements; remember the stretch reflex?

The spinal cord threads through ligaments and the bones of the vertebral column, which protect it. It also is protected by three coverings, called the meninges, that enclose the brain as well. In *meningitis*, a viral or bacterial infection has inflamed the coverings. Severe headaches, fever, a stiff neck, and nausea are among the symptoms that follow.

Sensory neurons, which are afferent, connect to the spinal cord at one of a pair of structures called dorsal roots. Motor neurons, which are efferent, connect to the spinal cord at ventral roots. A ganglion is visible as a bulge in each dorsal root (Figure 34.18).

In amphibians, spinal reflexes play a greater role in motor activity. Between the frog brain and spinal cord are circuits that make bent legs straighten. Cut these circuits near the brain and the legs become paralyzed—but only for about a minute. Reflex pathways in the spinal cord set the frog hopping again. Humans and other primates depend more on brain centers, so they show little or no recovery from a similar injury.

Nerves of the peripheral nervous system connect the brain and spinal cord with the rest of the body.

The somatic division of the peripheral nervous system deals with skeletal muscle movements. Its autonomic division deals with smooth muscle, cardiac muscle, and glands.

The spinal cord is a vital expressway for signals between the brain and the peripheral nerves.

34.9 The Vertebrate Brain

LINKS TO SECTIONS 25.1, 26.2, 26.13

The spinal cord is continuous with the brain, the body's master control center. The brain receives, integrates, stores, retrieves, and issues information. It coordinates responses to sensory input. As is the case for the spinal cord, bones and membranes (meninges) enclose and protect the brain.

THE BRAIN'S SUBDIVISIONS

A hollow, tubular nerve cord forms in every chordate embryo. In vertebrates, it develops into a spinal cord and brain. Genes that control segmented body plans divide the brain into specialized regions: the forebrain, midbrain, and hindbrain (Figure 34.19). A **brain stem**, the most ancient nervous tissue, persists in all three regions and is continuous with the spinal cord.

The hindbrain's **medulla oblongata** houses reflex centers for respiration, circulation, and other essential tasks. It integrates motor responses and governs some reflexes, such as coughing. It also affects sleep. The **cerebellum** uses inputs from the eyes, ears, muscle spindles, and forebrain regions to help control motor skills and posture. Axons from its two halves reach the **pons** (meaning bridge). The pons is like a traffic officer; it controls signal flow between the cerebellum and integrating centers in the forebrain.

Fishes and amphibians have the most pronounced midbrain, which sorts out most of their sensory input and initiates motor responses. In all vertebrates, the midbrain has centers for visual input. Especially when primates evolved, the forebrain took over the task of integrating most visual stimuli (Section 26.13).

Vertebrates first evolved in water, where chemical odors diffusing from predators, prey, and mates were vital cues. They relied heavily on olfactory lobes and paired outgrowths from the brain stem that integrated olfactory input and responses to it. Especially among land vertebrates, the outgrowths expanded into two halves of the **cerebrum**, the two cerebral hemispheres.

The **thalamus** became a forebrain center for sorting out sensory input and relaying it to the cerebrum. The **hypothalamus** ("under the thalamus") evolved into the main center for homeostatic control of the internal environment. It assesses and regulates all behaviors related to internal organ activities, such as thirst, sex, and hunger. It also governs related emotions, such as sweating with passion and vomiting from fear.

PROTECTION AT THE BLOOD–BRAIN BARRIER

The neural tube's lumen (the space inside it) persists in adult vertebrates as a system of cavities and canals filled with a clear *cerebrospinal fluid* (Figure 34.20). The fluid forms inside the brain ventricles, but it seeps out and bathes the tissues of the brain and spinal cord. It cushions them against potentially jarring movements.

A **blood–brain barrier** protects the spinal cord and brain from harmful substances. It exerts some control over which solutes enter cerebrospinal fluid. No other

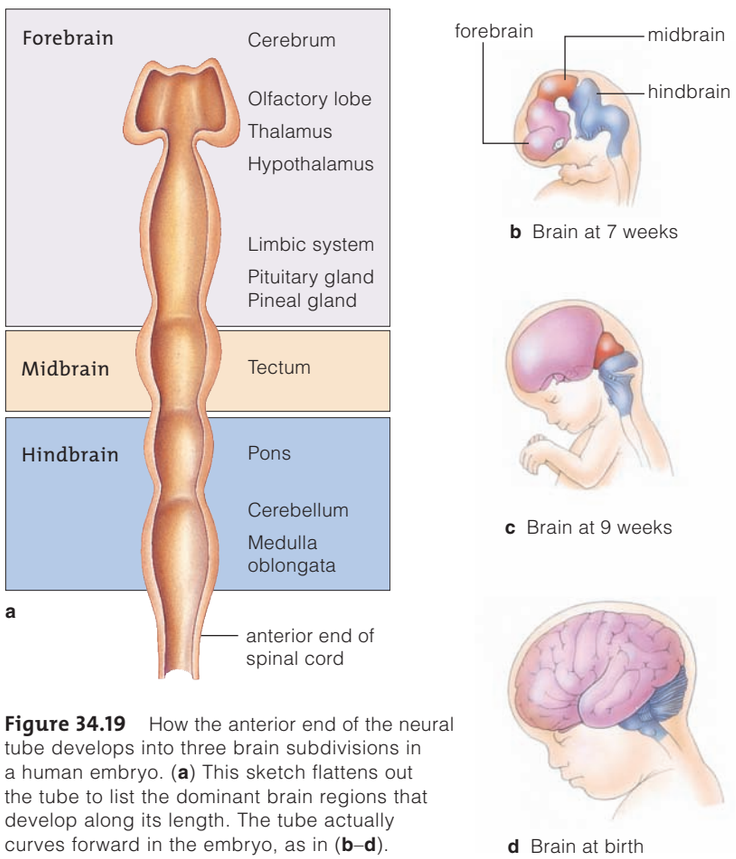


Figure 34.19 How the anterior end of the neural tube develops into three brain subdivisions in a human embryo. (**a**) This sketch flattens out the tube to list the dominant brain regions that develop along its length. The tube actually curves forward in the embryo, as in (**b**–**d**).

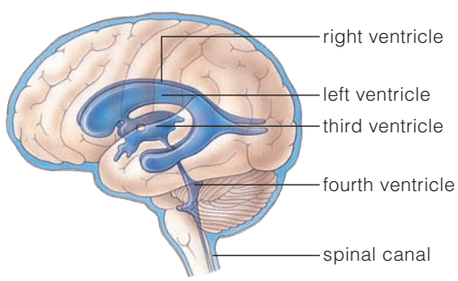


Figure 34.20 Cerebrospinal fluid (*blue*). This extracellular fluid is produced in the brain's four interconnected ventricles (cavities) and in the spinal cord's central canal.

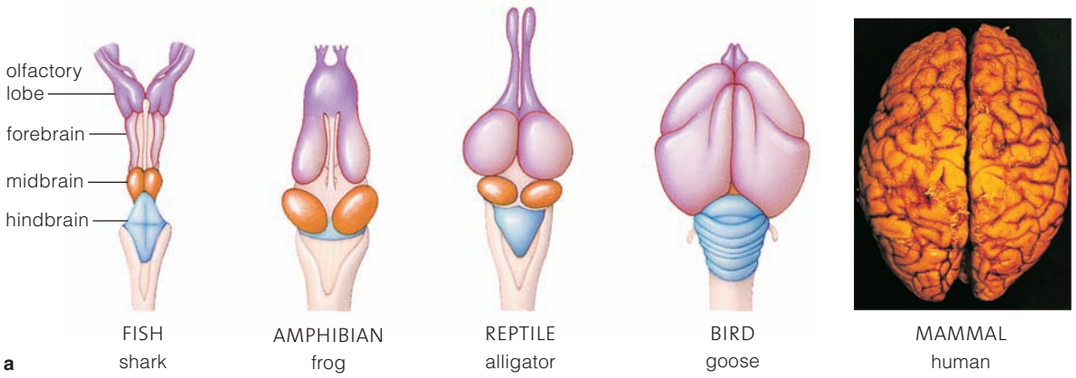
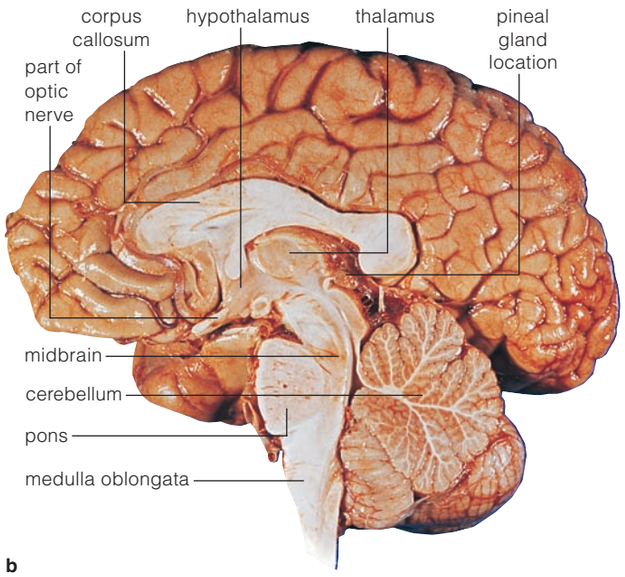


Figure 34.21 ***Animated!*** (**a**) Major brain regions for five vertebrates, dorsal views. The sketches are not to the same scale. (**b**) This photograph shows more detail for the right half of the human brain, sagittal view. Meninges protect the brain tissue but these coverings were removed for instructional purposes.

part of extracellular fluid has solute concentrations maintained within such narrow limits. Even changes brought on by eating and exertion are limited. Why? Hormones and other chemicals in the blood can alter neural function. Also, changes in ion concentrations can alter the threshold for action potentials.

The barrier works at the wall of blood capillaries that service the brain. In most parts of the brain, tight junctions form a seal between the abutting cells of the capillary wall, so water-soluble substances must pass *through* the cells to reach the brain. Transport proteins in the plasma membrane of these cells allow glucose, other vital nutrients, and some ions to cross. They bar many toxins and wastes, including urea. The barrier does not keep out small, fat-soluble molecules, such as oxygen, carbon dioxide, alcohol, caffeine, nicotine, and mercury vapor. Inflammation or traumatic blows can damage it and compromise neural function.



SOME ARE BRAINIER THAN OTHERS

On average, the human brain weighs 1,300 grams, or 3 pounds. Again, it has about 100 billion interneurons, and neuroglia makes up more than half of its volume. Compared to the brains of other vertebrates, including those in Figure 34.21, the human midbrain is smaller. The hindbrain's cerebellum is larger. It is about the size of a fist and has more interneurons than all other brain regions combined. As in other vertebrates, it deals with the sense of balance and coordination but took on other functions as humans evolved. It affects learning of motor and mental skills, such as language.

What about the forebrain? A deep fissure divides its cerebrum into two halves, the cerebral hemispheres (Figure 34.21). The next section takes a look at their thin outer layers, the cerebral cortex. Each half deals mainly with input from the opposite side of the body. For instance, signals about pressure on the right arm travel to the left hemisphere. Activities of both halves are coordinated by signals that flow both ways across a thick band of nerve tracts, the corpus callosum.

The pineal gland is located near the hypothalamus. The hypothalamus receives signals about light sources from the retina and relays them to this light-sensitive endocrine gland. Chapter 36 describes the functions of these forebrain regions and explores connections between the nervous and endocrine systems.

The vertebrate brain develops from a hollow neural tube, the lumen of which persists in adults as a system of cavities and canals filled with cerebrospinal fluid. The fluid cushions nervous tissue from sudden, jarring movements.

Nervous tissue is subdivided into a hindbrain, forebrain, and midbrain. The brain stem is the most ancient tissue. The forebrain has the most complex integrating centers.

34.10 The Human Cerebrum

LINKS TO SECTIONS 5.3, 26.2, 26.4, 26.10

Our "humanness" starts in the outer layer of gray matter of our cerebral cortex, which governs conscious behavior. The cerebral cortex processes and coordinates responses to sensory input. It interacts with the limbic system, which governs emotions and contributes to memory.

FUNCTIONAL AREAS OF THE CORTEX

Each half of the cerebrum, or cerebral hemisphere, is divided into four lobes: frontal, temporal, occipital, and parietal. At the **cerebral cortex**—the gray matter at the surface of each lobe—distinct areas receive and process different signals, but they still interact. *Motor* areas influence voluntary motor activity. *Sensory* areas assist in our perceptions of what a specific sensation means. Diverse *association* areas integrate information that brings about conscious actions.

The two hemispheres overlap in function, but there are some specialized differences. For example, the left hemisphere's cortex is more concerned with analytical skills, mathematics, and speech. The cortex of the right hemisphere interprets music, judges spatial relations, and assesses visual inputs.

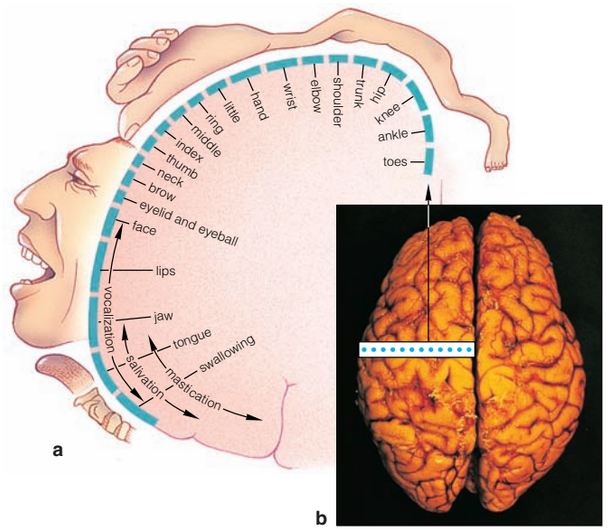


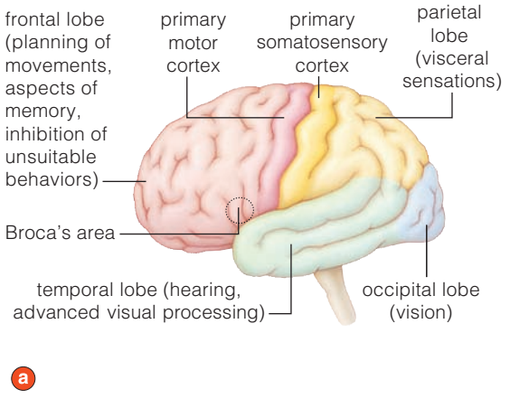
Figure 34.22 (**a**) A slice of the primary motor cortex, through the region indicated in (**b**). The sizes of body parts draped over the artful slice are distorted to show which ones get the most precise control.

Motor Areas The body is spatially mapped out in the primary motor cortex of each frontal lobe—which controls and coordinates the movements of skeletal muscles on the opposite side of the body. Much of the motor cortex is devoted to finger, thumb, and tongue muscles. Figure 34.22 hints at the control required for voluntary hand movements and verbal expression.

The premotor cortex of each frontal lobe governs learned patterns of motor skills. Dribble a basketball, play a piano, use a keyboard—repetitive movements are evidence that simultaneous and sequential actions of different muscle groups are being coordinated.

Broca's area helps translate thoughts into speech by controlling tongue, throat, and lip muscles. It gives us our capacity to create complex sentences. In most individuals, Broca's area is in the frontal cortex of the left hemisphere (Figure 34.23*a*). Damage to it prevents normal speech, although an affected individual is still able to understand language.

Sensory Areas The primary somatosensory cortex is located at the front of the parietal lobe. Like the motor cortex, it is organized as a map that corresponds to the



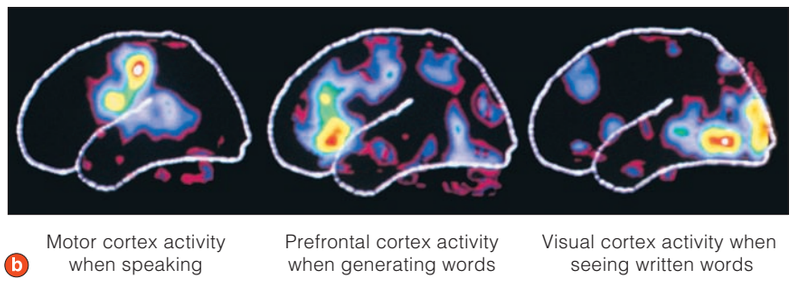


Figure 34.23 (**a**) Primary receiving and integrating centers of the human cerebral cortex. Association areas coordinate and process sensory input from diverse receptors. (**b**) Three PET scans identifying which areas were active when an individual performed three different tasks.

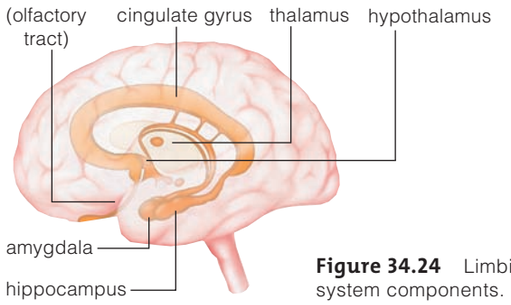


Figure 34.24 Limbic system components.

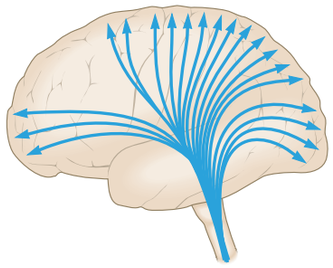


Figure 34.25 Communication pathways making up the reticular formation. This evolutionarily ancient and diffuse network of neurons extends from the spinal cord into the highest integrative areas of the cerebral cortex. Parts of the reticular formation can release serotonin and help control states of consciousness.

body's parts. It is a receiving center for sensory input from skin and joints (Section 35.2). Also in the cortex of the parietal lobe, another sensory area deals with taste perception. At the back of the occipital lobe, the primary visual cortex receives signals from the eyes. Perceptions of sound and odor arise in sensory areas of each temporal lobe.

Association Areas Association areas are scattered through the cortex, but not in the primary motor and sensory areas. Each integrates diverse inputs (Figure 34.23*a*). For instance, a visual association area around the primary visual cortex compares what we see with visual memories. The most recently evolved area, the prefrontal cortex, is the foundation of our personality and intellect, of abstract thought, judgment, planning, and concern for others.

CONNECTIONS WITH THE LIMBIC SYSTEM

The **limbic system** encircles the upper brain stem. It governs emotions, assists in memory, and correlates organ activities with self-gratifying behavior, such as eating and sex. That is why the limbic system is called our emotional–visceral brain. It can put a heart on fire with passion and a stomach on fire with indigestion. These and other "gut reactions" can be overridden by signals from the prefrontal cortex.

The system includes the hypothalamus, part of the thalamus, and the cingulate gyrus, hippocampus, and amygdala (Figure 34.24). The cingulate (belt-shaped) gyrus is a fold in brain tissue right above the corpus callosum. It affects motivation, and it is more active in extroverts and risk takers than in the introverted or cautious. The hypothalamus correlates emotions with visceral activities. The almond-shaped amygdala is necessary for emotional stability and for interpreting social cues. It is responsive to fright and anxiety.

The limbic system is evolutionarily related to the olfactory lobes. Olfactory input causes signals to flow to the hippocampus, amygdala, and hypothalamus as well as the olfactory cortex. That is one reason why you feel warm and fuzzy when you recall the scent of someone special. Signals about taste also travel to the limbic system and can call up emotional responses.

THE RETICULAR FORMATION

An ancient network of interneurons extends from the upper spinal cord, through the brain stem, and into the cerebral cortex. This **reticular formation** is a low-level path to motor centers in the medulla oblongata and spinal cord. It affects many parts of the nervous system, including the cerebral cortex (Figure 34.25).

Part of the reticular formation promotes chemical changes that affect states of consciousness, such as sleeping or waking. One of its sleep centers produces serotonin. High serotonin levels cause drowsiness and sleep. Substances released from another brain center counter the effect and bring about wakefulness.

Electroencephalograms, or *EEGs*, are recordings of the summed electrical activity of the brain's neurons. They are used to study states of consciousness. EEGs from electrodes placed on the scalp show up as wave forms. The pattern for a person who is meditating is an alpha rhythm. During the transition to sleep, wave forms become larger, more widely spaced, and more erratic. People who are aroused from slow-wave sleep usually say that they were not dreaming; often they were mulling over recent, ordinary events. Slow-wave sleep is punctuated by a pattern of REM sleep, with rapid eye movements, irregular breathing, increased heartbeat, twitching fingers, and often vivid dreams.

The cerebral cortex, each hemisphere's outermost layer of gray matter, contains motor, sensory, and association areas that interact to govern conscious behavior. It also interacts with the limbic system, which affects emotions and contributes to memory.

34.11 Sperry's Split-Brain Experiments

FOCUS ON SCIENCE

The two cerebral hemispheres are connected by a thick band of axons called the corpus callosum. Neurobiologist Roger Sperry discovered the importance of this connection and revealed the dual nature of human consciousness.

As mentioned in the preceding section, the two cerebral hemispheres look alike but differ a bit in their functions. The differences first became apparent in the mid-1800s, through studies of people who had injuries to particular brain regions. For instance, damage to Broca's area in the left frontal cortex interfered with the ability to vocalize words. Injury to Wernike's area in the left temporal lobe did not interfere with the capacity to say words, but the affected person could not put words into sentences.

Fast-forward to the 1960s. Evidence of the importance of the left hemisphere continued to flow in, and doctors were wondering what role, if any, the right hemisphere plays in the advanced functions of typical right-handed people. Roger Sperry and his coworkers decided to find out.

Sperry was interested in "split-brain" patients—people who had undergone surgery to sever the corpus callosum. At the time, this was an experimental way to treat severe *epilepsy*. Epileptic seizures are like electrical storms in the brain. Surgeons severed a patient's corpus callosum to stop the flow of disturbed electrical signals from one hemisphere to the other. After a brief recovery period, patients were able to lead what seemed to be normal lives, with fewer seizures.

But were those patients really normal? The surgery had stopped the flow of information across 200 million or so axons in the corpus callosum. Surely *something* had to be different. Something was.

Sperry devised elegant experiments to examine the split-brain experience by presenting the two halves of affected patients with two different parts of a visual stimulus. At the time, researchers already knew that the visual connections to and from one hemisphere are mainly concerned with the opposite half of the visual field, as in Figure 34.26. Sperry projected a word—say, COWBOY—onto a screen so that COW fell in the left half of the visual field, and BOY fell in the right (Figure 34.27).

The subjects of this experiment reported *seeing* the word BOY. The left hemisphere, which controls language, recognized the word. However, when asked to *write* the word with the left hand—which was hidden from view—the subject wrote COW. The right hemisphere "knew" the other half of the word (COW) and had directed the left hand's motor response. But it could not tell the left hemisphere what was going on because of the severed corpus callosum. The subject knew a word was being written but could not say what it was!

"The surgery," Sperry reported, "left these people with two separate minds—two spheres of consciousness." Sperry concluded that both hemispheres contribute to normal perception by sharing information that shapes the experience we call consciousness.

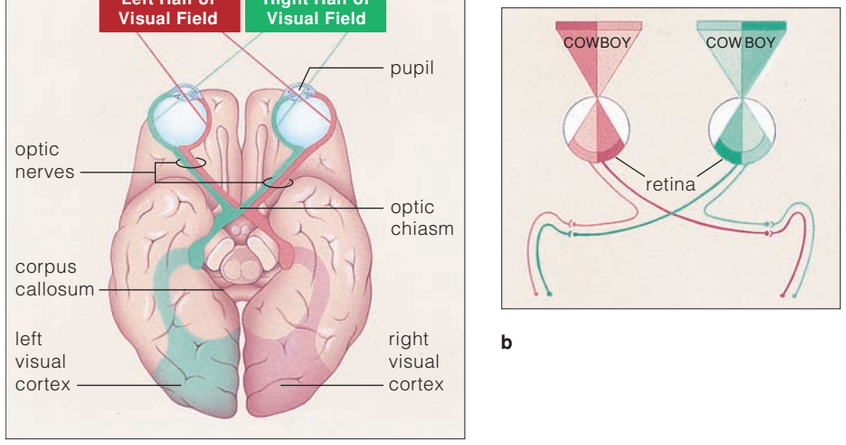


Figure 34.26 ***Animated!*** (**a**) Pathway by which sensory input about visual stimuli reaches the visual cortex of the human brain.

(**b**) Each eye gathers visual information at the retina, a thin layer of densely packed photoreceptors at the back of the eyeball (Section 35.7). Light from the *left* half of the visual field strikes receptors on the right side of both retinas. Parts of two optic nerves carry signals from the receptors to the right cerebral hemisphere. Light from the *right* half of the visual field strikes receptors on the left side of both retinas. Parts of the optic nerves carry signals from them to the left hemisphere.

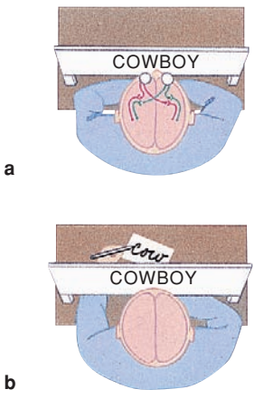


Figure 34.27 One example of the response of a split-brain patient to visual stimuli. As described in the text, this type of experiment demonstrated the importance of the corpus callosum in coordinating activities between the two cerebral hemispheres.

34.12 Storing and Retrieving Memories

*What do we know about **memory**—the brain's capacity to retrieve information about past sensory experiences?*

Embedded in your brain are memory banks. Without them, learning and behavioral adjustments based on experiences would be impossible. The cerebral cortex is bombarded with sensory information, but only a tiny fraction become memories, which form in stages.

Short-term memory lasts just a few seconds or hours. This stage holds a few bits of information—a set of numbers, the words of a sentence, and so on. In *long-term memory*, a seemingly unlimited quantity of larger bits is stored more or less permanently (Figure 34.28).

Different forms of input are stored and called up by different mechanisms. Retention is greatest for *skill* memories. Once you learn how to drive a car, dribble a basketball, or play a violin, you don't forget how—even if you rarely do so again. The skill memories are created when you consciously repeat an activity over and over. As the skill is being learned, the prefrontal cortex signals motor areas of the cortex. Signals flow to the sensory cortex, the cerebellum, and the corpus striatum—a part of the basal ganglia (Figure 34.29*a*). Once the skill is mastered, the corpus striatum is able to call for appropriate movements, which frees you from having to consciously think about how to make the movements on a second-by-second basis.

Declarative memory allows you to remember how a lemon smells, that a quarter is worth more than a dime, and where you had breakfast yesterday. It starts with signals from the sensory cortex to the amygdala, which acts as the memory gatekeeper. The amygdala connects to the hippocampus, which functions as an association center (Figure 34.29*b*). Signals must loop repeatedly through the hippocampus and cortex, basal ganglia, and thalamus for a memory to be retained.

Emotional states influence memory retention. For instance, epinephrine released in stressful times can assist the shuffling of short-term memories into long-term storage. This makes evolutionary sense, because an animal that recalls what happened when it dealt with a threat or some other stress may be more likely to survive if the threat recurs. This mechanism makes it difficult for us to forget traumatic events. Chapter 36 returns to the effects of long-term stress on memory.

Amnesia is the loss of declarative memory. It often happens when the hippocampus, amygdala, or both have been damaged. *Alzheimer's disease* usually starts late in life and involves changes in the hippocampus and cerebral cortex. Commonly, the affected person is able to recall long-known facts, including a childhood address, but has trouble remembering recent events.

Memory, the storage and retrieval of sensory information, arises from circuits between the cerebral cortex and the limbic system, thalamus, and hypothalamus.

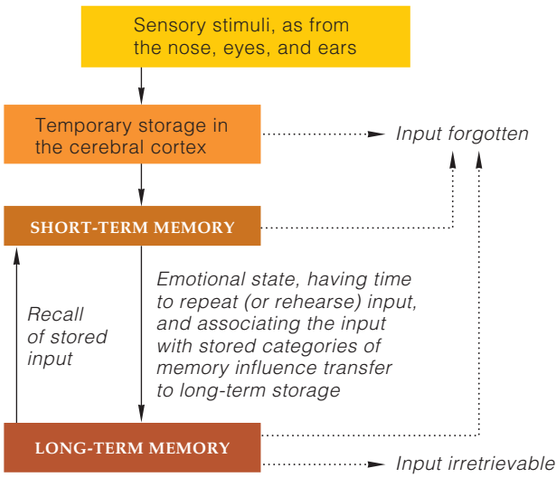


Figure 34.28 Stages of memory processing, starting with temporary storage of sensory inputs in the cerebral cortex.

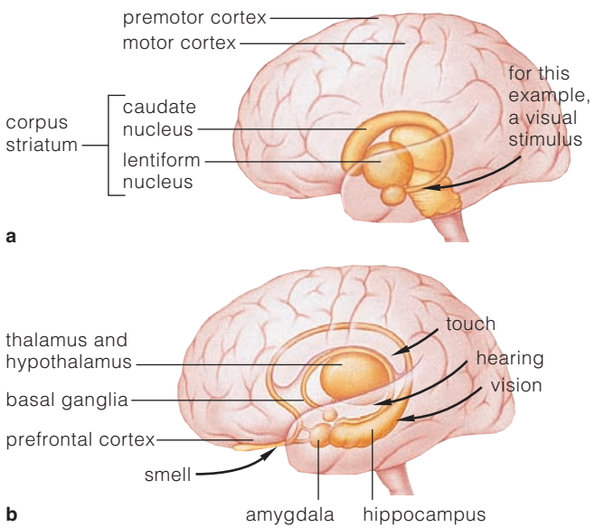


Figure 34.29 Simple diagrams of possible circuits involved in (**a**) skill memory and (**b**) declarative memory.

34.13 Drugs, The Brain, and Behavior

LINKS TO CHAPTER 6 INTRODUCTION

Psychoactive drugs are substances that affect the function or action of neurotransmitters. Some induce the release of a neurotransmitter. Others prevent its breakdown or uptake. Still others block receptors on the membrane of a postsynaptic cell where it would bind.

ROOTS OF ADDICTION

People take some legal or illegal pyschoactive drugs to mediate illness or stress. They take others to fan the pleasure associated with sex and other self-gratifying behaviors. Even when the body functions well without them, a user may continue to take drugs for real or imagined relief. The body often develops a tolerance of such drugs; it takes larger or more frequent doses to get the same effect. Habituation and tolerance lead into **drug addiction**, a form of chemical dependence in which a drug has rewired the brain and assumed an "essential" biochemical role in the body. Table 34.1 lists warning signs of drug addiction. Three or more may be cause for concern.

Addicts abruptly deprived of their drugs undergo biochemical upheaval, which causes physical pain and mental anguish. However, continued addiction is far more harmful. Besides rewiring the brain, drugs that are inhaled can damage airways and lungs. Sharing needles may invite AIDS, hepatitis B, and hepatitis C, and damage blood vessels. The liver and kidneys are strained when they detoxify and eliminate any drug.

Addictive drugs stimulate the release of dopamine, the neurotransmitter directly involved in the sense of pleasure. For instance, most people think smoking is just a habit. Actually, when nicotine binds to neurons in the brain, it causes a dopamine spike. All addicts specifically crave the dopamine spike.

Table 34.1 Warning Signs of Drug Addiction

1. Tolerance—it takes increasing amounts of the drug to get the same effect.
2. Habituation—it takes continued drug use over time to maintain the self-perception of functioning normally.
3. Inability to stop or curtail drug use, even if the desire to do so persists.
4. Concealment—not wanting others to know of the drug use.
5. Extreme or dangerous actions to get and use a drug, as by stealing, by asking more than one doctor for prescriptions, or by jeopardizing employment by using drugs at work.
6. Deterioration of professional and personal relationships.
7. Anger and defensiveness if someone suggests there may be a problem.
8. Drug use preferred over previous customary activities.

EFFECTS OF PSYCHOACTIVE DRUGS

Stimulants These drugs make you alert, then they depress you. An example is the *caffeine* in coffee, tea, chocolate, and many soft drinks. Low doses acting in the cerebral cortex increase nervousness and suppress fine motor coordination. *Nicotine* in tobacco products is a stimulant that mimics ACh. It affects a variety of sensory receptors. Chapter 40 looks at the impacts of nicotine addiction on health.

Millions are *cocaine* abusers. This stimulant creates feelings of pleasure by blocking uptake of dopamine, norepinephrine, and other signals. Postsynaptic cells are not released from stimulation. Blood pressure and sexual appetite rise. In time, the signaling molecules are cleared away, but the body can't replace them fast enough. The sense of pleasure is permanently lost as hypersensitized postsynaptic cells demand and cannot get stimulation. Figure 34.30 shows a long-term effect.

Abusers inhale granular cocaine or burn crack and inhale the smoke. This extremely addictive drug has staggering social and economic costs. Also, there is no antidote for overdoses, which have caused seizures, respiratory failure, and heart failure.

Amphetamines induce the oversecretion of dopamine and norepinephrine. Addicts smoke, snort, inject, or ingest various forms. Each form can trigger euphoria, sexual arousal, heart pounding, agitation, dry mouth, tremors, and often paranoia. Amphetamines kill the appetite; some people became addicted while taking them to lose weight. Dopamine and norepinephrine synthesis decline over time because the brain depends more and more on the artificial stimulation.

You already read about the synthetic amphetamine MDMA (*Ecstasy*, Adam, or XTC). Methamphetamine hydrochloride, also known as *crystal meth*, is another widely abused form. It is easy to produce, and its use is epidemic, especially in rural areas. During 2004, law enforcement personnel shut down 1,472 meth labs in the state of Iowa alone. The labs themselves can be a danger to public health. They release toxic fumes and have a tendency to explode.

Depressants, Hypnotics Depressants sedate, and hypnotics induce sleep (not a hypnotic trance). Their effects depend on the dose and on physiological and emotional states. They invite calm, drowsiness, sleep, coma, and even death. Low doses impact inhibitory synapses the most, so users get excited or euphoric at first. Larger doses suppress excitatory synapses and lead to depression. Both drugs amplify each other, as when alcohol and barbiturates heighten depression.

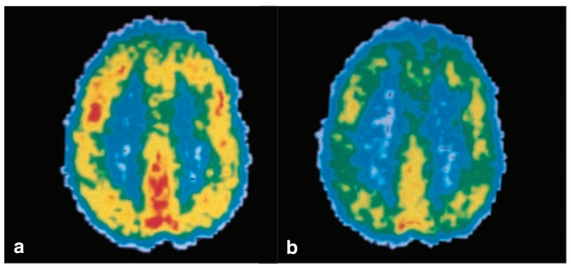


Figure 34.30 Want to be one of the brain-dead? (**a**) This is a PET scan of normal brain activity. (**b**) This PET scan reveals cocaine's long-term effect. *Red*, regions of greatest activity, then *yellow*, *green*, and *blue* for the least activity.

Alcohol, or ethyl alcohol, has wide-ranging effects on the nervous system. Like nicotine and cocaine, it can cross the blood–brain barrier. Among its effects is a rise in the hypothalamic production of endorphins. It binds to membrane proteins, including receptors for GABA, dopamine, serotonin, and norepinephrine. Binding alters receptor shapes and activities. Even one drink skews judgment and motor skills. Liver failure results from chronic alcohol abuse (Chapter 6).

Analgesics When severe stress leads to pain, your brain makes endorphins and enkephalins. These are natural *analgesics*, or pain killers. Narcotic analgesics include *morphine*, *codeine*, and *heroin*, as well as newer prescription drugs, such as *fentanyl* and *oxycodone*. In addition to pain relief, the drugs cause euphoria and lead to severe addiction. Withdrawal symptoms may include chills, fever, anxiety, vomiting, and diarrhea.

Hallucinogens These drugs alter the user's sensory perception. *LSD* (*lysergic acid diethylamide*) mimics the effects of serotonin. It is not addictive, but distorted perceptions can be deadly. For instance, some users leaped out of buildings, believing that they could fly.

Ketamine and *PCP* (phencyclidine), two chemically related drugs, were developed as anesthetics. Ketamine is still used as one. Both give users an out-of-the-body experience and numb the extremities by slowing the clearing of dopamine, norepinephrine, and serotonin. Both can trigger seizures, hyperthermia, and kidney failure. PCP is also known as angel dust. It can induce schizophrenia-like psychosis and agitation which, in some individuals, lasts for more than a week.

The hallucinogen *marijuana* is made from parts of the plant *Cannabis*. In low doses it is like a depressant. It slows but does not stop motor activity. It relaxes the body and may elicit mild euphoria, but it may cause acute panic attacks. Marijuana often disrupts short-term memory. As alcohol does, it affects how well we do complicated tasks, such as driving a car. Smoking marijuana, like smoking tobacco, invites respiratory ailments and cancers of the mouth, throat, and lungs. Frequent marijuana use lowers testosterone levels in blood and sperm counts. It results in abnormal sperm. Researchers are not sure how this drug exerts effects on sperm, but they agree that men who wish to be fathers should avoid using it.

BRAIN DEVELOPMENT AND RISK BEHAVIOR

At one time the brain was said to be fully developed, with all 100 billion neurons hardwired, before the end of puberty. However, all of the necessary connections are not completed until the early twenties. Like arms, legs, and other body parts, different parts of the brain develop on different schedules.

For instance, the prefrontal cortex is one of the last brain regions to finish developing. This coordinating center, recall, keeps tabs on other regions, including the limbic system. It mediates decision making, sifts through and makes sense of ambiguous signals, and reinforces or dampens raw emotions that arise in the limbic system. The limbic system develops faster than the prefrontal cortex. In effect, a teenager is like a car with a revved-up engine and no brakes.

Without a finished prefrontal cortex to act as traffic cop, teenagers are more open than adults to invading the brain's dopamine-releasing pleasure center. Novel behaviors, especially those with an element of risk or danger, stimulate that center. Sneak out late for a rock concert? Sure. Snort cocaine? Why not?

If you are not yet in your twenties, don't jump to the conclusion that you do not have to nurture your brain (as by reading) or make choices (as in behaving responsibly instead of impulsively). How you decide to exercise your brain helps shape the forming neural circuits, which in turn will profoundly influence your behavior and success later in life.

Here is the connection: It took hundreds of millions of years to put together all of the intricate wiring and signaling mechanisms in the human brain. Those mechanisms can unravel in one individual's lifetime.

Summary

Section 34.1 Radial animals have simple nerve nets. Most animals have a bilateral nervous system with a brain at their head end. Vertebrate nervous systems are functionally divided into central and peripheral regions. The central nervous system consists of a brain and spinal cord. The peripheral nervous system's paired nerves connect the brain and spinal cord to the rest of the body.

Section 34.2 Neurons are excitable cells. In most bilateral animals, sensory neurons relay signals into a spinal cord and brain. Interneurons in both receive, process, and integrate information. Motor neurons carry signals to effectors (muscles and glands). Neurons have input, conducting, and output zones for signals.

Biology Now

Study the structure and membrane properties of neurons with the animation on BiologyNow.

Table 34.2 Summary of the Central Nervous System*

FOREBRAIN	Cerebrum	Localizes, processes sensory inputs; initiates, controls skeletal muscle activity. Governs memory, emotions, abstract thought in the most complex vertebrates
	Olfactory lobe	Relays sensory input from nose to olfactory centers of cerebrum
	Thalamus	Has relay stations for conducting sensory signals to and from cerebral cortex; has role in memory
	Hypothalamus	With pituitary gland, a homeostatic control center; adjusts volume, composition, temperature of internal environment. Governs organ-related behaviors (e.g., sex, thirst, hunger) and expression of emotions
	Limbic system	Governs emotions; has roles in memory
	Pituitary gland (Chapter 36)	With hypothalamus, provides endocrine control of metabolism, growth, development
	Pineal gland (Chapter 36)	Helps control some circadian rhythms; also has role in mammalian reproductive physiology
MIDBRAIN	Roof of midbrain (tectum)	In fishes and amphibians, its centers coordinate sensory input (as from optic lobes), motor responses. In mammals, its reflex centers swiftly relay sensory input to forebrain
HINDBRAIN	Pons	Tracts bridge cerebrum and cerebellum; other tracts connect spinal cord with forebrain. With the medulla oblongata, controls rate and depth of respiration
	Cerebellum	Coordinates motor activity for moving limbs and maintaining posture, and for spatial orientation
	Medulla oblongata	Its tracts relay signals between spinal cord and pons; its reflex centers help control heart rate, adjustments in blood vessel diameter, respiratory rate, vomiting, coughing, other vital functions
SPINAL CORD		Makes reflex connections for limb movements. Its tracts connect brain, peripheral nervous system

*The reticular formation extends from the spinal cord to the cerebral cortex.

Section 34.3 In a resting neuron, transport proteins are maintaining ion concentration gradients by assisting or restricting the diffusion of ions across the lipid bilayer of the plasma membrane. The steady voltage difference associated with the ion gradients is the resting membrane potential. In any excitable cell, an action potential is an abrupt, fleeting reversal in the voltage difference across the plasma membrane. The action of sodium–potassium pumps maintains and restores the ion gradients, and so keeps the membrane ready for another action potential.

Biology Now

View an action potential step by step with the animation on BiologyNow.

Section 34.4 Neurons signal other neurons, muscle cells, or gland cells at chemical synapses. Arrival of an action potential at a presynaptic cell's output zone triggers the release of neurotransmitter molecules. These diffuse across a thin cleft and bind to postsynaptic cell receptors. All signals arriving in the same interval are summed by a process of synaptic integration.

Biology Now

See what occurs at a synapse between a motor neuron and a muscle cell with the animation on BiologyNow.

Sections 34.5, 34.6 Many neurotransmitters bind to a variety of receptor proteins on different cells, with different effects. Neuromodulators can mediate the effects. Vertebrate nervous systems have many diverse neuroglial cells that support, protect, and assist neurons.

Section 34.7 Nerves are long-distance cables, with bundles of fibers that carry signals through the body. Myelin sheaths enclose most of their axons and speed signal conduction rates. Reflexes are simple, automatic responses to stimulation. In the simplest reflex arcs, a sensory neuron synapses directly on a motor neuron.

Biology Now

Observe what happens during a stretch reflex with the animation on BiologyNow.

Section 34.8 The peripheral nervous system's somatic nerves act on skeletal muscles; its autonomic nerves act on soft internal organs. Its sympathetic and parasympathetic divisions often work in opposition to control the same organs. Sympathetic signals dominate during danger or heightened awareness. In less stressful times, parasympathetic signals dominate. The spinal cord links the peripheral nervous system to the brain.

Biology Now

Explore the structure of the spinal cord and compare the effects of sympathetic and parasympathetic stimulation with the animation on BiologyNow.

Section 34.9 In vertebrate embryos, a neural tube develops into a spinal cord and brain. The brain stem is the most evolutionarily ancient neural tissue. It governs many reflex centers for breathing and other vital tasks.

Cells making up blood capillaries in the brain form a blood–brain barrier that stops many harmful substances from reaching brain cells. The cerebral cortex, the most recently evolved neural tissue, governs most complex

Figure 34.31 Sea hare (*Aplysia*). This brainless mollusk is a boon for studies into the neural basis of behavior in a simple organism.

functions. Table 34.2 lists the central nervous system's components and functions.

Biology Now

Review the structure and function of human brain regions with the interaction on BiologyNow.

Sections 34.10, 34.11 The cerebral cortex has motor, sensory, and association areas. It is the seat of conscious behavior. Its centers also interact with the limbic system to control emotion and memory. The reticular formation connects lower brain centers with the cerebral cortex.

Section 34.12 Memory forms in multiple stages by different pathways. Emotional states affect the transfer of memories from short-term to long-term storage.

Biology Now

Read the InfoTrac Article, "Alzheimer's—Searching for a Cure," Linda Bren, FDA Consumer, *July–August 2003.*

Section 34.13 Psychoactive drugs act at synapses, where they mimic neurotransmitters or disrupt their release or uptake. Habitual use of psychoactive drugs can rewire the brain and cause addiction.

Self-Quiz

Answers in Appendix II

1. _____ relay messages from the brain and spinal cord to muscles and glands.
   a. Motor neurons
   b. Sensory neurons
   c. Interneurons
   d. Neuroglia

2. When a neuron is at rest _____ .
   a. it is at threshold potential
   b. gated sodium channels are open
   c. the sodium–potassium pump is operating
   d. both a and c

3. Action potentials occur when _____ .
   a. a neuron receives adequate stimulation
   b. sodium gates open in an ever accelerating way
   c. sodium–potassium pumps kick into action
   d. both a and b

4. Neurotransmitters are released by _____ .
   a. axon endings
   b. the cell body
   c. dendrites
   d. the myelin sheath

5. The most abundant cells in the brain are _____ .
   a. Schwann cells
   b. microglia
   c. astrocytes
   d. neurons

6. Skeletal muscles are controlled by _____ .
   a. sympathetic signals
   b. parasympathetic signals
   c. somatic nerves
   d. both a and b

7. When you sit quietly on the couch reading, output from the _____ system prevails.
   a. sympathetic
   b. parasympathetic
   c. both
   d. neither

8. Skeletal muscles contract in response to _____ .
   a. ACh
   b. dopamine
   c. serotonin
   d. all of the above

9. The cerebrum is part of the _____ .
   a. forebrain
   b. midbrain
   c. hindbrain
   d. brain stem

10. Match each item with its description.

____ muscle spindle	a. start of brain, spinal cord
____ neurotransmitter	b. connects the hemispheres
____ limbic system	c. protects brain and spinal cord from some toxins
____ corpus callosum	d. type of signaling molecule
____ cerebral cortex	e. neurons' support team
____ neural tube	f. stretch-sensitive receptor
____ neuroglia	g. roles in emotion, memory
____ gray matter	h. most complex integration
____ blood–brain barrier	i. unmyelinated axons and cell bodies

Additional questions are available on Biology Now™

Critical Thinking

1. The sea hare *Aplysia californica* is a marine mollusk about the length of your hand (Figure 34.31). Its nervous system only has 20,000 or so neurons, some with large cell bodies that make it easy for scientists to place electrodes or inject dyes. The limited behavior includes responses to food and to touch. Researchers found that dopamine affects its feeding behavior. This neurotransmitter affects human reward-seeking behavior, including addiction to drugs. How might studies of dopamine's effects on sea hares help shed light on treating drug addiction?

2. In human newborns, especially premature ones, the blood–brain barrier is not yet fully developed. Why is this one reason to pay careful attention to their early diet?

3. In humans, the axons of some motor neurons extend from the base of the spinal cord to the big toe, a distance of more than a meter. In a giraffe the longest axons are several meters long. What are some of the functional challenges involved in the development and maintenance of such lengthy cellular extensions?

4. When Jennifer was six years old, a man lost control of his car and hit a tree in front of her house. She ran over to him and screamed when she saw blood from a wound dripping on a bush of red roses. Thirty-five years later, someone gave her a bottle of *Tea Rose* perfume. When she sniffed it, she became frightened and extremely anxious. A few minutes later she also had a vivid recollection of the accident. Explain this incident in terms of what you learned about memory, olfaction, and the limbic system.

5. Eric typically drinks one cup of coffee nearly every hour, all day long. By midafternoon, he has a lot of trouble concentrating on his studies, and he becomes tired and more than a little clumsy. Drinking another cup of coffee does not make him more alert. Explain how the caffeine in coffee might produce such symptoms.