Physiology

Nerve Impulses Neurons have two major functional properties: *irritability,* the ability to respond to a stimulus and convert it into a nerve impulse, and *conductivity,* the ability to transmit the impulse to other neurons, muscles, or glands. We will consider these functional abilities next.

The plasma membrane of a resting, or inactive, neuron is **polarized,** which means that there are fewer positive ions sitting on the inner face of the neuron's plasma membrane than there are on its outer face in the tissue fluid that surrounds it (Figure 7.9). The major positive ions inside the cell are potassium (K^+), whereas the major positive ions outside the cell are sodium (Na^+). As long as the inside remains more negative as compared to the outside, the neuron will stay inactive.

Many different types of stimuli excite neurons to become active and generate an impulse. For example, light excites the eye receptors, sound excites some of the ear receptors, and pressure excites some cutaneous receptors of the skin. However, *most* neurons in the body are excited by neurotransmitters released by other neurons, as will be described shortly. Regardless of what the stimulus is, the result is always the same—the permeability properties of the cell's plasma membrane change for a very brief period. *Normally,* sodium ions cannot diffuse through the plasma membrane to any great extent; but when the neuron is adequately stimulated, the "gates" of sodium channels in the membrane open. Because sodium is in much higher concentration outside the cell, it will then diffuse quickly into the neuron. (Remember the laws of diffusion?) This inward rush of sodium ions changes the polarity of the neuron's membrane at that site, an event called **depolarization.** Locally, the inside is now more positive, and the outside is less positive, a situation called a **graded potential.** However, if the stimulus is strong enough and the sodium influx is great enough, the local depolarization (graded potential) activates the neuron to initiate and transmit a long distance signal called an **action potential,** also called a **nerve impulse** in neurons. The nerve impulse is an *all-or-none response* like firing a gun. It is either propagated (conducted) over the entire axon, or it doesn't happen at all. The nerve impulse never goes partway along an axon's length, nor does it die out with distance as do graded potentials.

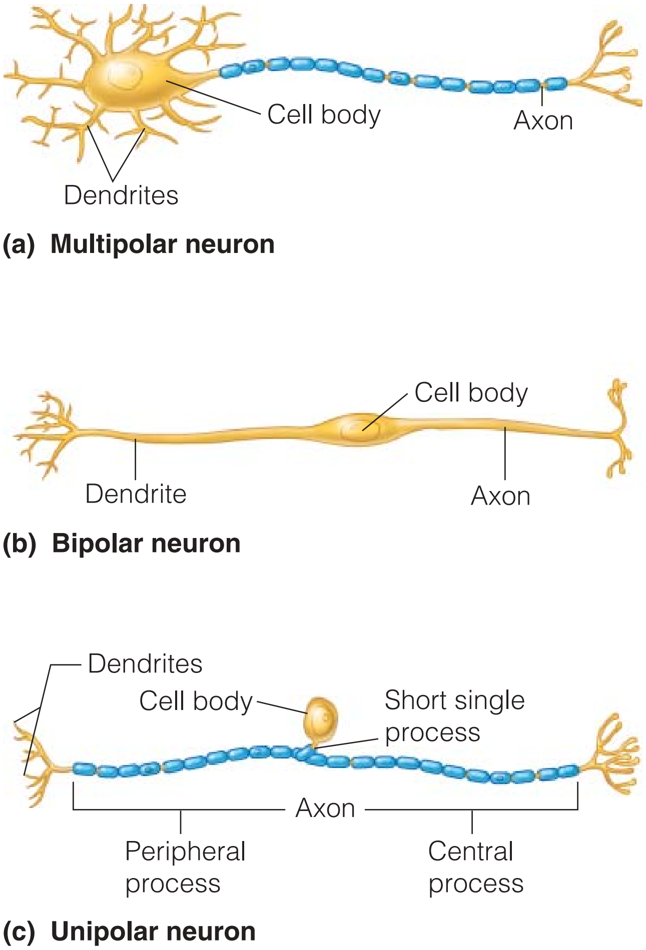

FIGURE 7.8 Classification of neurons on the basis of structure. (a) Multipolar. **(b)** Bipolar. **(c)** Unipolar.

Almost immediately after the sodium ions rush into the neuron, the membrane permeability changes again, becoming impermeable to sodium ions but permeable to potassium ions. So potassium ions are allowed to diffuse out of the neuron into the tissue fluid, and they do so very rapidly. This outflow of positive ions from the cell restores the electrical conditions at the membrane to the polarized, or resting, state, an event called **repolarization.** *Until repolarization occurs, a neuron cannot conduct another impulse.* After repolarization occurs, the initial concentrations of the sodium and potassium ions inside and outside the neuron are restored by activation of the sodium-potassium pump. This pump uses ATP (cellular energy) to pump excess sodium ions out of the cell and to bring potassium ions back into it. Once begun, these sequential events spread along the entire neuronal membrane.

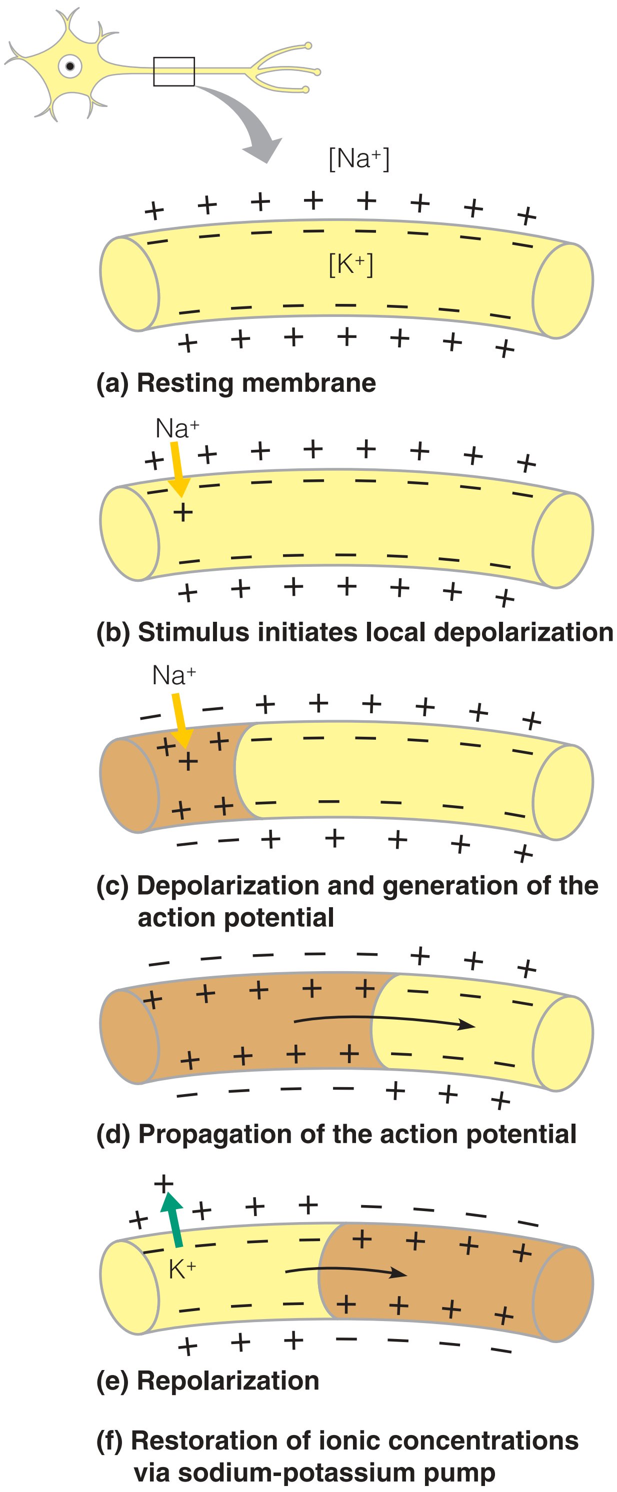

FIGURE 7.9 The nerve impulse. (a) Resting membrane electrical conditions. The external face of the membrane is slightly positive; its internal face is slightly negative. The chief extracellular ion is sodium (Na^+), whereas the chief intracellular ion is potassium (K^+). The membrane is relatively impermeable to both ions. **(b)** Stimulus initiates local depolarization. A stimulus changes the permeability of a "patch" of the membrane, and sodium ions diffuse rapidly into the cell. This changes the polarity of the membrane (the inside becomes more positive; the outside becomes more negative). **(c)** Depolarization and generation of an action potential. If the stimulus is strong enough, depolarization causes membrane polarity to be completely reversed and an action potential is initiated. **(d)** Propagation of the action potential. Depolarization of the first membrane patch causes permeability changes in the adjacent membrane, and the events described in (b) are repeated. Thus, the action potential propagates rapidly along the entire length of the membrane. **(e)** Repolarization. Potassium ions diffuse out of the cell as membrane permeability changes again, restoring the negative charge on the inside of the membrane and the positive charge on the outside surface. Repolarization occurs in the same direction as depolarization. **(f)** The ionic conditions of the resting state are restored later by the activity of the sodium-potassium pump.

The events just described explain propagation of a nerve impulse along unmyelinated fibers. Fibers that have myelin sheaths conduct impulses much faster because the nerve impulse literally jumps, or leaps, from node to node along the length of the fiber. This occurs because no current can flow across the axon membrane where there is fatty myelin insulation. This faster type of impulse propagation is called *saltatory* (sal′tah-to″re) *conduction* (*saltare* = to dance or leap).

Homeostatic Imbalance

A number of factors can impair the conduction of impulses. For example, sedatives and anesthetics block nerve impulses by altering membrane permeability to ions, mainly sodium ions. As we have seen, no sodium entry = no action potential.

Cold and continuous pressure hinder impulse conduction because they interrupt blood circulation (and hence the delivery of oxygen and nutrients) to the neurons. For example, your fingers get numb when you hold an ice cube for more than a few seconds. Likewise, when you sit on your foot, it "goes to sleep." When you warm the fingers or remove the pressure from your foot, the impulses begin to be transmitted once again, leading to an unpleasant prickly feeling. ▲

So far we have explained only the irritability aspect of neuronal functioning. What about conductivity—how does the electrical impulse traveling along one neuron get across the synapse to the next neuron (or effector cell) to influence its activity? The answer is that *it* doesn't! When the action potential reaches the axon terminal, the tiny vesicles containing the neurotransmitter chemical fuse with the axonal membrane, causing a porelike opening to form and releasing the neurotransmitter. The neurotransmitter molecules diffuse across the synapse* and bind to receptors on the membrane of the next neuron (Figure 7.10). If enough neurotransmitter is released, the whole series of events described above (sodium entry, depolarization, etc.) will occur, leading to generation of a nerve impulse in the neuron beyond the synapse. The electrical changes prompted by neurotransmitter binding are very brief because the neurotransmitter is quickly removed from the synapse, either by reuptake into the axonal terminal or by enzymatic breakdown. This limits the effect of each nerve impulse to a period shorter than the blink of an eye.

Notice that the transmission of an impulse is an *electrochemical event*. Transmission down the length of the neuron's membrane is basically *electrical*, but the next neuron is stimulated by a neurotransmitter, which is a *chemical*. Since each neuron both receives signals from and sends signals to scores of other neurons, it carries on "conversations" with many different neurons at the same time.

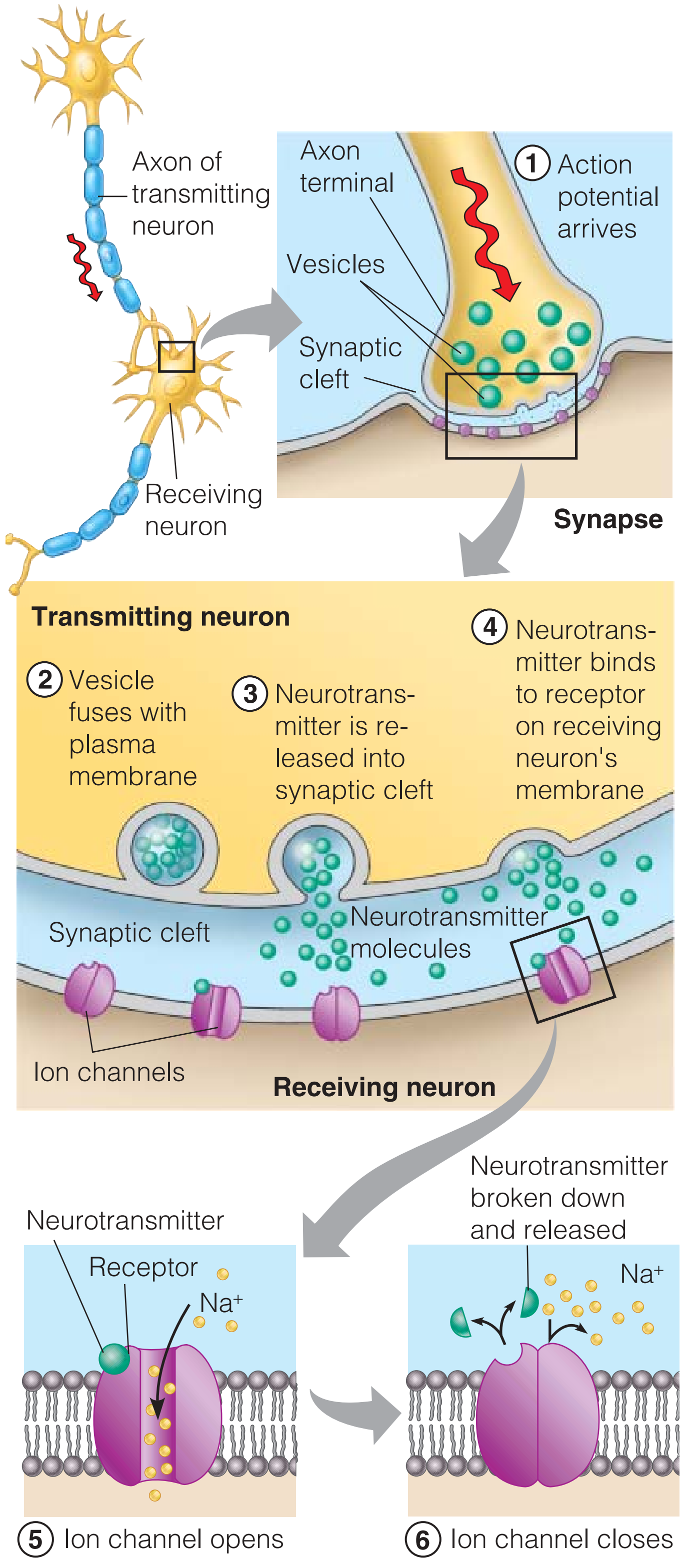

FIGURE 7.10 How neurons communicate at chemical synapses. The events occurring at the synapse are numbered in order.

---

*Although most neurons communicate via the *chemical* type of synapse described above, there are some examples of *electrical* synapses in which the neurons are physically joined by gap junctions and electrical currents actually flow from one neuron to the next.

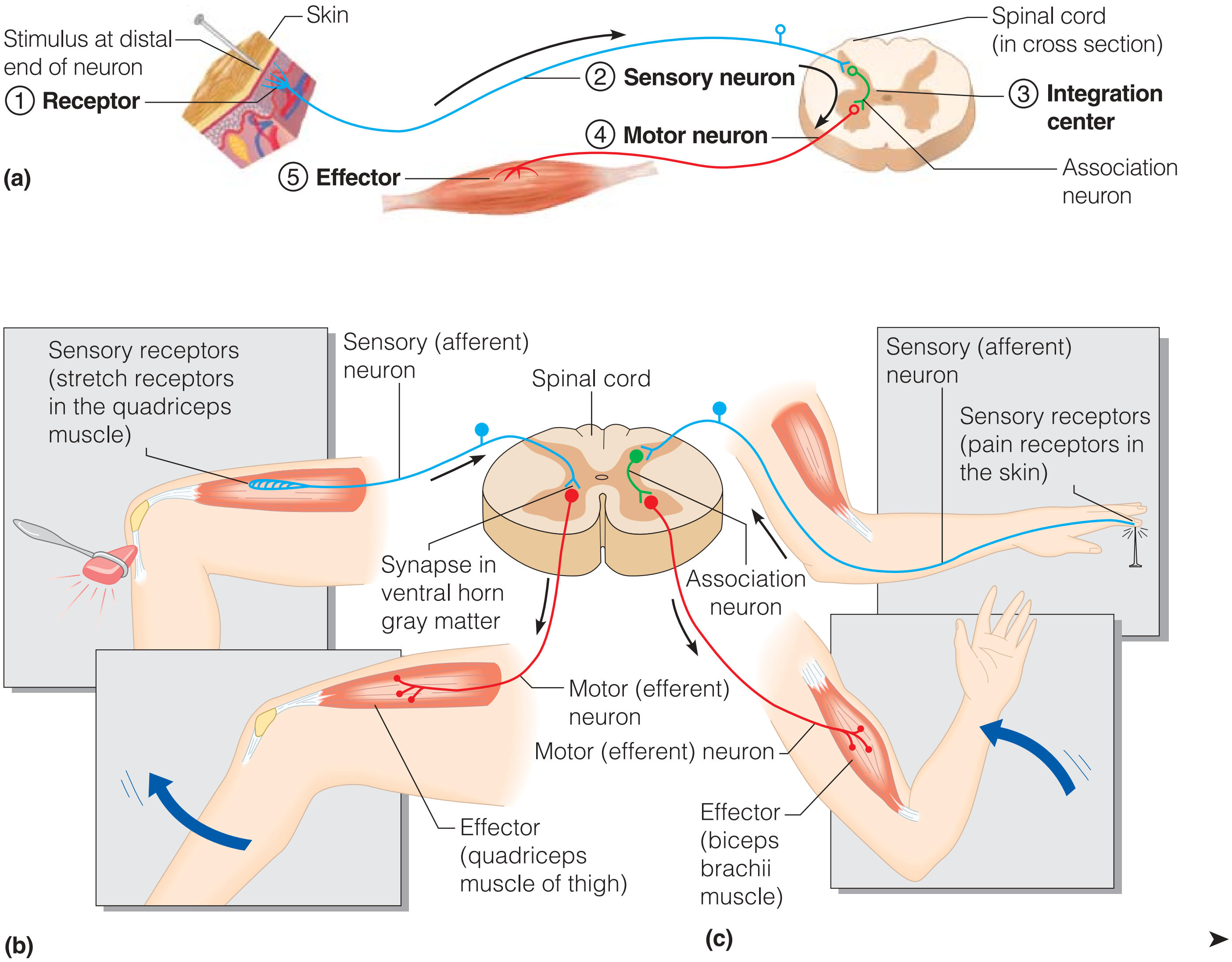

FIGURE 7.11 Simple reflex arcs. (a) The five basic elements of all reflex arcs. **(b)** A two-neuron reflex arc (example, patellar reflex). **(c)** A three-neuron reflex arc (example, the flexor reflex).

Reflexes Although there are many types of communication between neurons, much of what the body *must* do every day is programmed as reflexes. **Reflexes** are *rapid, predictable, and involuntary responses* to stimuli. They are much like one-way streets—once a reflex begins, it always goes in the same direction. Reflexes occur over neural pathways called **reflex arcs,** and involve both CNS and PNS structures.

The types of reflexes that occur in the body are classed as either somatic or autonomic reflexes. **Somatic reflexes** include all reflexes that stimulate the skeletal muscles. When you quickly pull your hand away from a hot object, a somatic reflex is working. **Autonomic reflexes** regulate the activity of smooth muscles, the heart, and glands. Secretion of saliva (salivary reflex) and changes in the size of the eye pupils (pupillary reflex) are two such reflexes. Autonomic reflexes regulate such body functions as digestion, elimination, blood pressure, and sweating.

All reflex arcs have a minimum of five elements (Figure 7.11a): a *sensory receptor* (which reacts to a stimulus), an *effector organ* (the muscle or gland eventually stimulated), and *sensory* and *motor neurons* to connect the two. The synapse between the sensory and motor neurons represents the central element—the CNS *integration center.*

(d)

FIGURE 7.11 (*continued*) **(d)** Photo of a physician testing the patellar (knee jerk) reflex.

The simple *patellar* (pah-tel′ar), or *knee-jerk, reflex,* shown in Figure 7.11b and d, is an example of a two-neuron reflex arc, the most simple type in humans. The patellar reflex (in which the quadriceps muscle attached to the hit tendon is stretched) is familiar to most of us. It is usually tested during a physical exam to determine the general health of the motor portion of the nervous system. Most reflexes are much more complex than the two-neuron reflex, involving synapses between one or more association neurons in the CNS (integration center). A three-neuron reflex arc, the *flexor,* or *withdrawal, reflex,* in which the limb is withdrawn from a painful stimulus, is diagrammed in Figure 7.11c. The three-neuron reflex arc consists of five elements—receptor, sensory neuron, association neuron, motor neuron, and effector. Since there is always a delay at synapses (it takes time for the neurotransmitter to diffuse through the synaptic cleft), the more synapses there are in a reflex pathway, the longer the reflex takes to happen.

Many spinal reflexes involve only spinal cord neurons and occur without brain involvement. As long as the spinal cord is functional, spinal reflexes such as the flexor reflex will work. On the other hand, some reflexes require that the brain become involved because many different types of information have to be evaluated to arrive at the "right" response. The response of the pupils of the eyes to light is a reflex of this type.

As noted earlier, reflex testing is an important tool in evaluating the condition of the nervous system. Whenever reflexes are exaggerated, distorted, or absent, nervous system disorders are indicated. Reflex changes often occur before the pathological condition has become obvious in other ways.

Central Nervous System

During embryonic development, the CNS first appears as a simple tube, the **neural tube,** which extends down the dorsal median plane of the developing embryo's body. By the fourth week, the anterior end of the neural tube begins to expand, and brain formation begins. The rest of the neural tube posterior to the forming brain becomes the spinal cord. The central canal of the neural tube, which is continuous between the brain and spinal cord, becomes enlarged in four regions of the brain to form chambers called **ventricles** (see Figure 7.17a and b, p. 243).

Functional Anatomy of the Brain

The adult brain's unimpressive appearance gives few hints of its remarkable abilities. It is about two good fistfuls of pinkish gray tissue, wrinkled like a walnut, and with the texture of cold oatmeal. It weighs a little over three pounds. Because the brain is the largest and most complex mass of nervous tissue in the body, it is commonly discussed in terms of its four major regions—*cerebral hemispheres, diencephalon* (di″en-sef′ah-lon), *brain stem,* and *cerebellum* (Figure 7.12).

Cerebral Hemispheres

The paired **cerebral** (ser′e-bral) **hemispheres,** collectively called the **cerebrum,** are the most superior part of the brain and together are a good deal larger than the other three brain regions combined. In fact, as the cerebral hemispheres develop and grow, they enclose and obscure most of the brain stem, so many brain stem structures cannot normally be seen unless a sagittal section is