The Neural Bases Of Behavior

The brain is a grapefruit-size mass of tissue that feels like jelly and looks like a grayish gnarled walnut. One of the true marvels of nature, it has been termed “our three-pound universe” (Hooper & Teresi, 1986). To understand how the brain controls our experience and behavior, we must first understand how its individual cells function and how they communicate with one another.

Neurons

Specialized cells called neurons are the basic building blocks of the nervous system. These nerve cells are linked together in circuits, not unlike the electrical circuits in a computer. At birth your brain contained about 100 billion neurons (Bloom, 2000; Kolb & Whishaw, 1989). To put this number in perspective, if each neuron were an inch long and they were placed end to end, the resulting chain would circle the earth more than 63 times. It is fortunate that humans have this many neurons, for it is estimated that through the normal process of cell death that accompanies aging, about 10,000 of them are lost each day of our lives (Fiogamo, 1998).

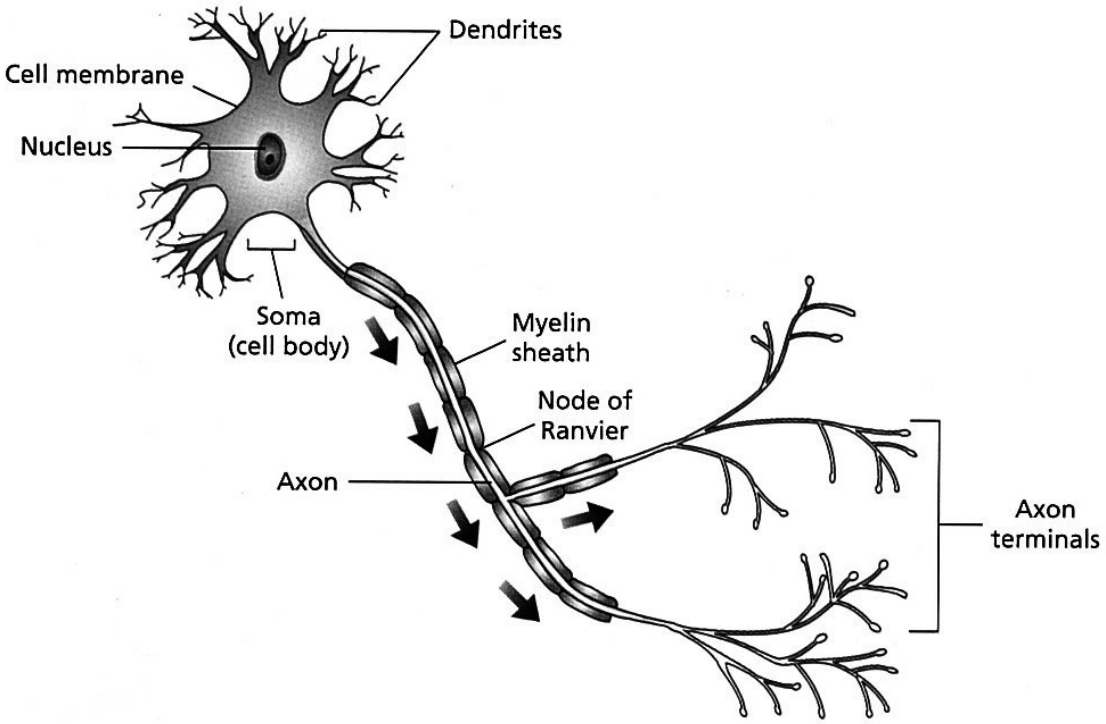

FIGURE 3.2 Structural elements of a typical neuron. Stimulation received by the dendrites or soma (cell body) may trigger a nerve impulse, which travels down the axon to stimulate other neurons, muscles, or glands. Some axons have a fatty myelin sheath interrupted at intervals by the nodes of Ranvier. The myelin sheath helps increase the speed of nerve conduction.

Each neuron has three main parts: a cell body, dendrites, and an axon (Figure 3.2).
The cell body or soma, contains the biochemical structures needed to keep the neuron alive, and its nucleus carries the genetic information that determines how the cell develops and functions. Emerging from the cell body are branch fibers called dendrites (from the Greek word meaning “tree”). These specialized receiving units are like antennas that collect messages from neighboring neurons and send them on to the cell body. There the incoming information is combined and processed. The many branches of the dendrites can receive input from 1,000 or more neighboring neurons. The surface of the cell body also has receptor areas that can be directly stimulated by other neurons. Extending from one side of the cell body is a single axon, which conducts electrical impulses away from the cell body to other neurons, muscles, or glands. The axon branches out at its end to form a number of axon terminals— as

many as several hundred in some cases. Each axon terminal may connect with dendritic branches from numerous neurons, making it possible for a single neuron to pass messages to as many as 50,000 other neurons (Fain, 1999; Shepherd, 1997). Given the structure of the dendrites and axons, it is easy to see how there can be trillions of interconnections in the brain, making it capable of performing the complex psychological activities that are of interest to psychologists.

Neurons can vary greatly in size and shape. More than 200 different types of neurons have been viewed through electron microscopes (Nolte, 1998). A neuron with its cell body in your spinal cord may have an axon that extends several feet to one of your fingertips, equivalent in scale to a basketball attached to a cord 4 miles long; a neuron in your brain may be no more than a thousandth of an inch long. Regardless of their shape or size, neurons have been exquisitely sculpted by nature to perform their function of receiving, processing, and sending messages.

Neurons are supported in their functions by glial cells, (from the Greek word for glue). Glial cells do not send or receive nerve impulses, but they surround neurons and hold them in place. The glial cells also manufacture nutrient chemicals that neurons need, and they absorb toxins and waste materials that might damage neurons. During prenatal brain development, as new neurons are being formed through cell division, glial cells send out long fibers that guide newly divided neurons to their targeted place in the brain (Filogamo, 1998). Within the nervous system, glial cells outnumber neurons about ten to one.

Nerve Conduction: An Electrochemical Process

Neurons do two important things: They generate electricity and they release chemicals. Nerve conduction is thus an electrochemical process. The electrical properties of neurons have been known for more than a century, but we have only recently begun to understand the chemical processes involved in neural activity. An understanding of how neurons generate electricity requires a brief excursion into chemistry. Neurons function a bit like batteries in that their own chemical substances are a source of energy. Like other cells, the neuron is surrounded by a cell membrane. This membrane not only protects the inner structures but also operates as a kind of selective filter that allows certain particles in the body fluid around the cell to pass through while refusing passage to other substances.

Neurons are surrounded by a salty liquid environment. This environment's high concentration of sodium carries a positive atomic charge, that is, it has a high concentration of positively charged particles, or ions. Although the inside of the neuron has some positively charged potassium ions, it contains many other ions that carry a negative charge. As a result, the inside of the neuron is electrically negative in relation to the outside, producing an electrical resting potential of about —70 millivolts, or —70/1,000 of a volt, across the membrane. When in this resting state, the neuron is said to be polarized.

All cells in the body have a similar resting voltage. In some animals, specialized organs can combine this tiny voltage to generate very high voltages. For example, electric eels can generate 600 to 700 volts because their muscle tissue cell membranes are arranged so that the small individual cell voltages can be combined to produce one big jolt.

The Action Potential

Neurons, like muscle cells, have a unique property among body cells: Sudden and extreme changes can occur in their resting potential voltage. An action potential, or nerve impulse, is a sudden reversal in the neuron's membrane voltage, during which the membrane voltage momentarily moves from —70 millivolts (inside) to +40 millivolts (Figure 3.4). This shift from negative toward positive voltage is called depolarization.

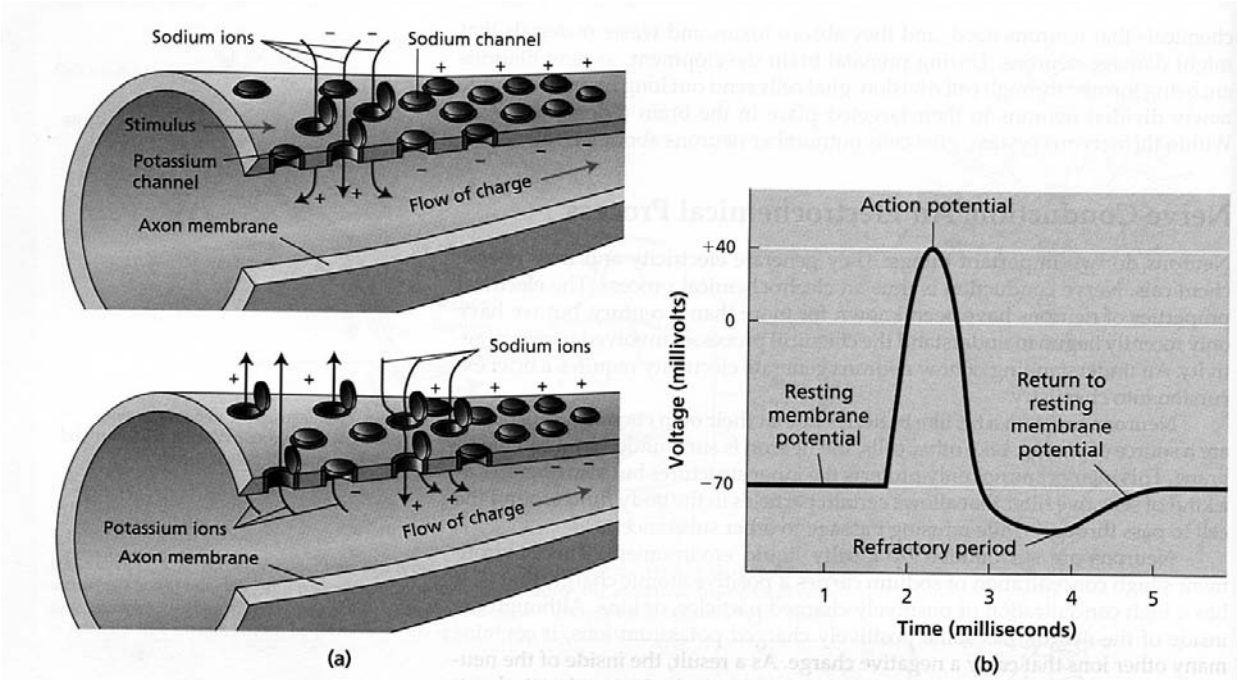

FIGURE 3.4 The nerve impulse is a change in electrical potential resulting from depolarization of the cell membrane. The movement of a nerve impulse along an axon involves the opening of sodium ion channels that allow many positively charged sodium ions to flow into the cell (a) while a smaller number of potassium ions are pumped out (b). The net effect is a reversal of the membrane polarity from about −70 millivolts (resting potential) to about +40 millivolts (action potential). An instant later the sodium ion channels close and the sodium ions are pumped back out of the cell and the potassium ions flow back in, restoring the negative resting potential. After a brief refractory period, another impulse can follow.

To understand how this depolarization process occurs, we might liken the release of an action potential to the firing of a gun. When the dendrites or the cell body of a neuron are stimulated by axons from other neurons, small shifts occur in the cell membrane's electrical potential. These changes, called graded potentials, are proportional to the amount of incoming stimulation. If the graded potential is not strong enough, the neuron will be partially depolarized, but not enough to fire off an action potential. In this sense, a graded potential is like light pressure on the trigger of a gun that is not sufficient to activate its hammer. But if the graded potential is large enough to reach the action potential threshold, the required level of intensity needed to fire the neuron, the neuron discharges with an action potential. Unlike the graded potential, which varies in proportion to the intensity of stimulation, the action potential obeys the all-or-none law; it either occurs with maximum intensity or it does not occur at all. It is in this sense that triggering an action potential is like firing a gun. Unless enough energy is applied to the trigger, the gun will not fire. But once it does fire, the velocity of the bullet bears no relation to how hard the trigger was pulled.

What causes the depolarization of the neuron membrane that may result in an action potential? Through a series of sophisticated experiments that won them the 1963 Nobel Prize, British scientists Alan Hodgkin and Andrew Huxley provided the answer. Recall that when the cell is resting, positively charged sodium ions in the salty liquid environment are kept outside the cell. When a neuron is stimulated, however, tiny protein structures on the cell membrane called ion channels are activated. Each channel can pump specific ions back and forth across the cell membrane. Sodium ion channels in the cell membrane open for an instant and positively charged sodium ions flow into the interior of the cell, attracted by the negative electrical force inside the neuron. The influx of sodium ions causes the interior of the cell to become less negative than it was, creating a state of partial depolarization that may reach the action potential threshold (which is at about —.55 millivolts in most neurons—a decrease of only .15 millivolts from the resting potential). If that occurs, the inside of the neuron responds by becoming more positively charged than the outside for an instant, producing the state of complete depolarization that constitutes the action potential. In a reflex action to restore the resting polarity, the cell quickly closes the sodium ion channels and opens

potassium channels through which positive potassium ions are pumped out of the cell. In this way, the cell's negatively charged resting potential is restored (Fain, 1999). In less than 1/1,000 of a second, the process is over at any given point on the membrane, but the action potential has started a chain reaction "wave" that flows down the membrane as succeeding sodium gates open and the process is repeated. After a brief instant, the sodium ions inside the membrane are pumped back outside and the potassium ions flow back inside the membrane, restoring the normal ion distribution. Figure 3.4 shows this sequence of events.

The wavelike quality of the action potential as it moves down the length of the axon is not unlike the human "wave" that occurs in sports stadiums as fans in adjacent seats successively stand up, cheer, and raise their arms, then sit back down. Nobody actually changes position, but the visual (and auditory) effect is of a "wave" that moves around the stadium.

Immediately after an impulse passes any given point along the axon, there occurs a refractory period, a time period during which the membrane is not excitable and cannot discharge another action potential. This refractory period, lasting one or two thousandths of a second, limits the rate at which action potentials can be triggered in a neuron. In humans the limit seems to be about 300 nerve impulses per second (Roland, 1997).

If action potentials are always identical to one another, how does the nervous system tell the difference between, for example, a dim light and a bright light, or between a light touch and a hard rub? Such information is communicated in a number of ways. For example, a strong stimulus may increase the rate of firing of the individual neuron. Or it may increase the number of neurons that fire by stimulating additional neurons that fire only in response to high-intensity stimulation. In such ways, information is provided concerning the nature of the stimulus.

The Myelin Sheath

Many axons that transmit information throughout the brain and spinal cord are covered by a tubelike myelin sheath, a fatty whitish insulation layer derived from glial cells during development. The myelin sheath is interrupted at regular intervals by the nodes of Ranvier, where the myelin is either extremely thin or absent). The nodes make the myelin sheath look a bit like sausages placed end to end (see Figure 3.2). In un-myelinated axons, the action potential travels down the axon length like a burning fuse. In myelinated axons, electrical conduction can skip from node to node, and these "great leaps" from one gap to another account for high conduction speeds of more than 200 miles per hour. But even these high-speed fibers are 3 million times slower than the speed at which electricity courses through an electric wire. This is why your brain, though vastly more complex than any computer, cannot begin to match it in speed of operation.

The myelin sheath is most commonly found in the nervous systems of higher animals. In many nerve fibers, the myelin sheath is not completely formed until some time after birth. The increased efficiency of neural transmission that results is partly responsible for the gains that infants exhibit in muscular coordination as they grow older (Weyhenmeyer et al., 2000).

The tragic effects of damage to the myelin coating can be seen in people who suffer from multiple sclerosis. This progressive disease occurs when the person's own immune system attacks the myelin sheath. Damage to the myelin sheath disrupts the delicate timing of nerve impulses, resulting in jerky, uncoordinated movements and, in the final stages, paralysis.

How Neurons Communicate: Synaptic Transmission

The nervous system operates as a giant communications network, and its action requires the transmission of nerve impulses from one neuron to another. Early in the history of brain research, scientists thought that the tip of the axon made physical contact with the dendrites or cell bodies of other neurons, passing electricity directly from one neuron to the next. With the advent of the electron microscope, however, researchers discovered that there is actually a synapse, a tiny gap between the axon terminal and the next neuron. This discovery raised new and perplexing questions: If neurons do not physically touch the other neurons to which they send signals, how does communication occur? If the action potential does not cross the synapse, what does? What carries the message?

Neurotransmitters

We now know that in addition to generating electricity, neurons produce neurotransmitters, chemical substances that carry messages across the synapse to either excite other neurons or inhibit their firing. This process of chemical communication involves five steps: synthesis, storage, release, binding, and deactivation. In the synthesis stage, the chemical molecules are formed inside the neuron. The molecules are then stored in chambers called synaptic vesicles within the axon terminals. When an action potential comes down the axon, these vesicles move to the surface of the axon terminal and the molecules are released into the fluid-filled space between the axon of the sending (pre-synaptic) neuron and the membrane of the receiving (post-synaptic) neuron. The molecules cross the synaptic space and bind (attach themselves) to receptor sites—large protein molecules embedded in the receiving neuron's cell membrane. These receptor sites, which look a bit like lily pads when viewed through an electron microscope, have a specially shaped surface that fits a specific transmitter molecule much like a lock accommodates a single key.

Excitation, Inhibition, and Deactivation

The binding of transmitter molecule to the receptor site produces a chemical reaction that can have one of two effects on the post-synaptic neuron. In some cases, the reaction will depolarize (excite) the post-synaptic cell membrane by stimulating the inflow of sodium ions. Neurotransmitters that create depolarization are called excitatory transmitters. This stimulation, alone or in combination with activity at other excitatory synapses on the dendrites or cell body, may exceed the action potential threshold and cause the post-synaptic neuron to fire an action potential.

In other cases, the chemical reaction created by the docking of a neurotransmitter at its receptor site will hyper-polarize the post-synaptic membrane by stimulating ion channels that allow positively charged potassium ions to flow out of the neuron and thereby make its resting potential even more negative (e.g., increasing it from —70 millivolts to —72 millivolts). Hyperpolarization makes it more difficult for excitatory transmitters at other receptor sites to depolarize the neuron to its action potential threshold of —.65. Transmitters that create hyperpolarization are thus inhibitory in their function. A given neurotransmitter can have an excitatory effect on some neurons and an inhibitory influence — on others.

Every neuron is constantly bombarded with excitatory and inhibitory neurotransmitters from other neurons, and the interplay of these influences determines whether or not the cell fires an action potential. The action of an inhibitory transmitter from one pre-synaptic neuron may prevent the post-synaptic neuron from reaching the action potential threshold even if it is receiving excitatory stimulation from several other neurons at the same time. An exquisite balance between excitatory and inhibitory processes must be maintained if the nervous system is to function properly The process of inhibition allows a fine-tuning of neural activity and prevents an uncoordinated discharge of the nervous system, as occurs in a seizure, when large numbers of neurons fire off action potentials in a runaway fashion.

Once a neurotransmitter molecule binds to its receptor, it continues to activate or inhibit the neuron until it is shut off, or deactivated. This occurs in two major ways (Fain, 1999). Some transmitter molecules are deactivated by other chemicals located in the synaptic space that break them down into their chemical components. In other instances, the deactivation mechanism is reuptake, in which the transmitter molecules are reabsorbed into the prsynaptic axon terminal. When the receptor molecule is vacant, the post-synaptic neuron returns to its former resting state, awaiting the next chemical stimulation.

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