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PHYSIOLOGICAL ORGANIZATION OF THE NERVOUS SYSTEM

When male Grayling butterflies are ready to copulate they fly upward toward females passing overhead. The male's response to females is not unerringly accurate, because sometimes they fly toward other passing objects. This fact suggested to the ethologist Tinbergen that the stimulus that is most effective in releasing the male's approach response could be discovered by controlled experiments. Tinbergen made model butterflies, attached them to the line of a fishing rod, and "flew" them to determine which were most effective in attracting males. Although females are brightly colored, and males can see color, color was not an important feature of the stimulus. Males were attracted by dark, large, and irregularly moving stimuli. Furthermore, these characteristics were mutually reinforcing, which suggested to Tinbergen that the nervous system of male butterflies has a "pooling station" that integrates the different features of the stimulating object.

Tinbergen's experiments are an example of excellent behavioral research that, although done with no knowledge or study of the physiology of the butterfly's nervous system, still gives clues about how that system must work. But knowledge of how the process of integration takes place, that is, of how the pooling station works, involves physiology. This is also true of neuropsychology. Much can be learned about people's behavior through careful observations and controlled experiments, but detailed knowledge of how the nervous system controls behavior requires the study of its physiological organization. This requires knowing the structure of cells and how they work. Although an extensive knowledge of electrophysiology (study of neuron activity) and neuropharmacology (study of biochemical activity of neurons) is not essential for understanding neuropsychology, a general understanding of them is helpful. The following sections give a brief description of: (1) the physical features of neurons, (2) the electrical activity of neurons and the techniques used to record their activity, and (3) chemical communication between cells and the phar-

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macological techniques used to manipulate their communication.

NEURON STRUCTURE

Neurons are cells that are the integrating units of the nervous system, and although they share many of the characteristics of other cells in the body, they have special characteristics that make them particularly adaptable to their function.

A broad analogy can be drawn between a neuron and a person. Neurons, once formed, do not regenerate, and unless they suffer lethal damage, they live as long as the person in which they are found. Each neuron is separated from physical contact with every other neuron, but it bridges this separation by communicating with a language that is part electrical and part chemical. Neurons vary enormously in bodily proportions, the differences making each neuron particularly adaptable to its specialized function. Neurons are aggregated into communities, or nuclei, each of which makes a special contribution to behavior. Neurons are modifiable: they change their behavior with experience; they learn; they remember; and they forget. At times neurons can malfunction, causing disruptions in normal behavior. There are similarities in the behavior of neurons, but the full significance of their behavior can only be understood within the context of the community in which they function. In summary, this anthropomorphic analogy serves to caution us that the function of a neuron within the context of a working brain is not as simple as the neuron is small.

Figure 2-1 shows a neuron schematically. The neuron is enclosed in a specialized membrane, and consists of a **cell body**, processes called **dendrites** (from the Greek, meaning tree), a process called an **axon** (from the Greek, meaning axle), and little **end feet** on the terminal branches of the axon. Associated with each of these parts are other specialized structures that are described where appropriate in the following sections. The **dendrites** collect information, which is then integrated at the **axon hillock** close to the cell body; a summary of the input received by the cell is then passed along the axon, through the end feet to other cells. ("Information" is used here loosely to mean any event or events that the cell actively codifies.)

Although neurons have these basic structures, their configurations differ among neurons. For example, a *sensory* cell of the somatosensory system has one very long dendrite coursing from the skin to a point adjacent to its cell body, located near the spinal cord. Here the dendrite connects directly to its axon, which may then travel to the hindbrain. This sensory cell has developed a system of direct information transmission that requires no modification of the signal between receptor and brain. On the other hand, a *motor* cell in the inferior spinal cord has a number of dendrites collecting input and a long axon extending from the cord to muscles. This cell appears specialized to integrate a variety of inputs for a specific action.

Between these sensory and motor cells are many interneurons of various shapes. Some have a densely arborized dendritic system that suggests that their primary function is to collect a great deal of diversified information for integration (for examples of different neuron types see Figure 1-1). Also, although many neurons communicate chemically—and we stress this feature of their function—some probably do communicate electrically.

The Cell Membrane

The cell membrane surrounds the entire cell and consists of a double layer of lipid (fat) molecules. These molecules are polar in structure, each having a head and two tails; the heads face outward, the tails face inward. The

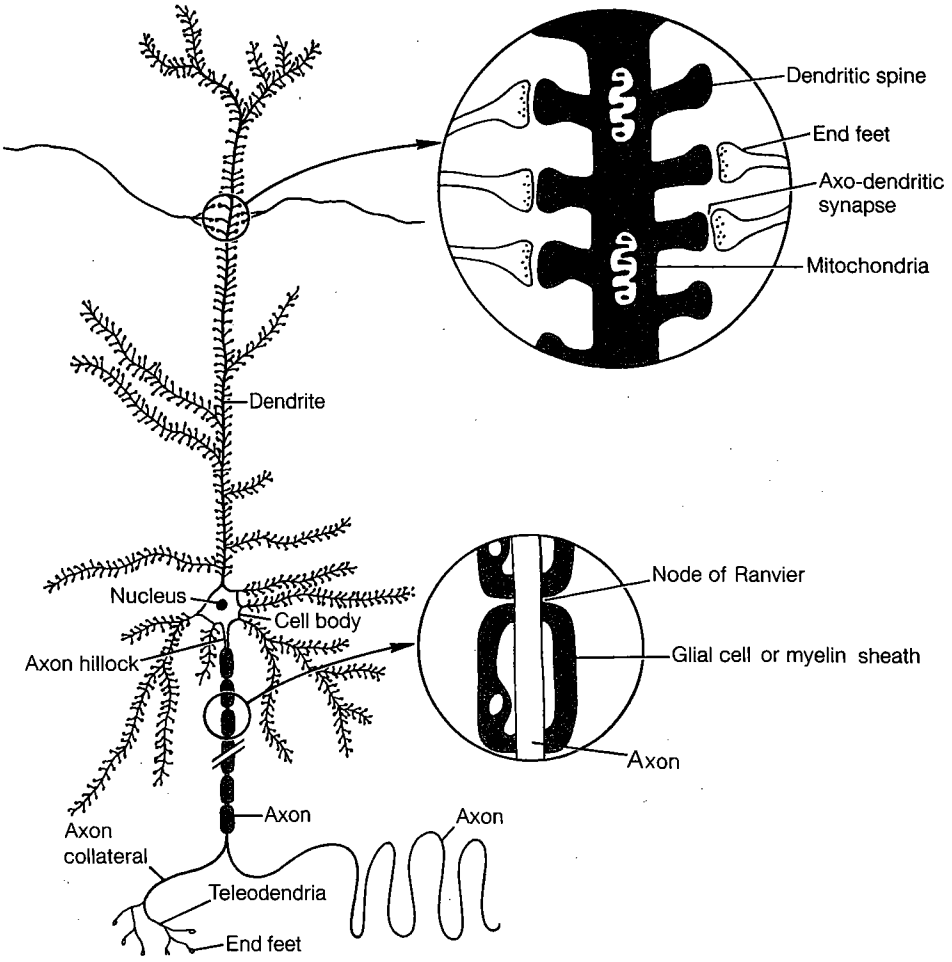

FIGURE 2-1. A typical neuron, showing some of its major physical features.

inner portion made up by the tails is believed to be largely impermeable, thus providing a barrier to free movement of ions through the membrane. Channels exist in the membrane, however, that allow it to be selectively permeable to ions under appropriate conditions. Proteins lie at or near the surface of each layer or penetrate it completely. The proteins provide a structural framework, are involved in the transport of chemicals across the membrane, and act as receptors for various substances that affect the transport mechanism.

The Cell Body

The cell body has a nucleus containing chromosomes that code the cell's genetic information in deoxyribonucleic acid (DNA). Within the nucleus there is also a nucleolus, which is packed with ribonucleic acid (RNA).

Surrounding the nucleus is the cell's cytoplasm, which contains a variety of structures including mitochondria, an endoplasmic reticulum, ribosomes, Golgi complexes, and lysosomes. Mitochondria are believed to have an energy-producing function. The endoplasmic reticulum may provide a transport system between cytoplasm and nucleus and cytoplasm and the cell wall. Ribosomes are believed to be the site of protein synthesis in the cell. The Golgi apparatus may be involved in packaging material to be extruded from the cell, or packaging lysosomes that presumably have digestive functions within the cell.

The Dendrites

The **dendrites** are actually extensions of the cell body that allow the neuron to increase the area of surface upon which it receives information from other cells. The number of dendrites varies from neuron to neuron, some having a few, others over 20; and each dendrite may branch profusely. Dendrites vary from a few microns to millimeters in length and taper as they branch; some have rough projections called dendritic spines upon which they receive end feet from other cells.

The Axon

The **axon** originates in the cell body at a transition point called the axon hillock. Its function is to transmit to other cells information that it receives from the axon hillock. Each cell has only one axon, which varies in length from a few microns to more than a meter in different cells. Most axons have branches called collaterals. At the end of the axon and its collaterals are fine terminations called teleodendria. The teleodendria are covered with little knobs, called end feet, which make junctions with other cells.

The End Feet

The **end feet** terminate in close proximity to other cells. Sherrington coined the term **synapsis** (from the Greek, meaning union) for the "almost" connection between an end foot and another neuron; consequently the end feet became technically known as **synaptic knobs,** abbreviated to *synapses* when speaking functionally or in more general terms. They contain packages of chemical substances that when released will influence the activity of other cells. End feet may synapse with any part of a neuron; they are called axo-dendritic, axo-somatic, axo-axonic, and axo-synaptic, depending upon whether they synapse with, respectively, dendrites, the cell body, axons, or synapses of other cells. Neurons may make other types of contact with each other (for example, somas may touch, or axons may touch), but we will limit our description to the most common, axo-dendritic connections.

NEURON ELECTRICAL ACTIVITY

Much of the pioneering research on the neuron's electrical activity, such as that done by Hodgkin and Huxley, used the giant axon of the squid, on the recommendation of the biologist Young. This axon measures up to a millimeter in diameter and is a hundred times larger than the axons of human nerve cells. The squid's axon is used to contract muscles that squirt water out the end of the squid's body to propel it through the water. Because effective propulsion requires all of the muscles of the body to contract at the same time, the largest axons, which conduct the fastest, connect to the most distant muscles. Because of its size, the giant axon is easily removed from the squid by dissection, and is easy to use for experiments on how electrical conduction takes place in axons.

Probably everyone knows that if a salt is put into a liquid medium it will dissolve into positive (+) and negative (−) ions that will eventually become distributed equally through the solution. In distributing themselves the ions respond to two forces, concentration and charge, and the equilibrium they obtain represents an equal distribution of both concentration and charge. The membrane of a nerve axon separates two fluid compartments, the intracellular and extracellular fluid, each of which contains many ions. Of these, negatively charged organic ions (An^-) and chlorine ions (Cl^-), and positively charged potassium ions (K^+) and sodium ions (Na^+) are particularly important in electrical conduction. These ions would be equally distributed on both sides of the membrane if it did not act as a barrier to their easy passage. It does this in three ways. First, it provides passive resistance to An^- ions because they are simply too large to pass through it; consequently they are retained in the intracellular fluid. Second, it is semipermeable to the other ions, allowing some of them to pass through more freely than others. Normally, K^+ passes more freely than Na^+ (Na^+, although smaller than K^+, is bound more strongly to water molecules, which add to its bulk). The permeability of the membrane also changes in certain situations, allowing these ions to pass more freely through the membrane at some times than they can at other times. In particular, the membrane contains Na^+ channels and K^+ channels, which close or open to control the flow of these ions. Third, the membrane contains a pumping system, or Na^+–K^+ pump, which exchanges intracellular Na^+ for extracellular K^+. Since the membrane is less permeable to Na^+ than to K^+, Na^+ accumulates on the outside of the membrane. Some K^+ flows back out of the cell when pumped, to equalize the K^+ concentration across the membrane. The unlimited outward flow of K^+ is checked, however, by

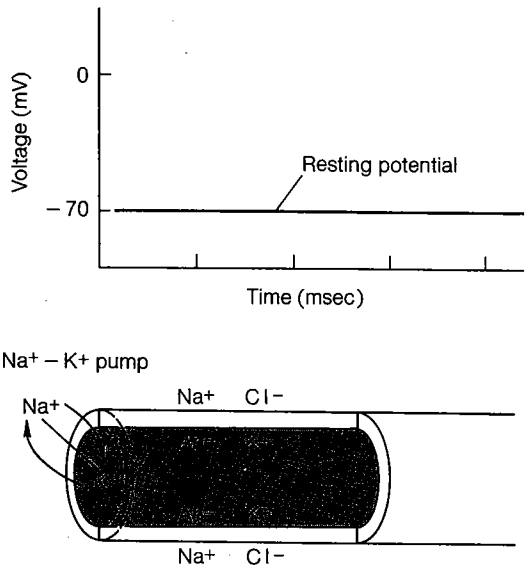

FIGURE 2-2. The nerve membrane, because of its semipermeability and through the action of the Na^+–K^+ pump, accumulates anions (An^-) and potassium (K^+) in its intracellular fluid and sodium (Na^+) and chlorine (Cl^-) in its extracellular fluid. As a result of the charge differences of these ions, the inside of the membrane has a charge of −70 mV compared with the outside. This charge difference is called the *resting potential.*

the accumulating extracellular charge carried by the Na^+ (like charges repel each other). As a result of the action of these three processes there are 350 times as many An^- and 20 times as many K^+ on the inside as are on the outside of the cell membrane, and 9 times as many Cl^- and 20 times as many Na^+ on the outside as are on the inside of the cell membrane.

Figure 2-2 shows the distribution of the various ions on the two sides of the axon. Because the ions are distributed unequally, and because they are charged, there is a voltage across the membrane, produced largely by the high extracellular concentration of Na^+. If this voltage is measured with a voltmeter, with one of its poles placed inside and one placed outside the cell, the voltage is found to be −70 mV

(millivolts) in the squid axon (and −70 to −90 mV in different animals) with the inside of the axon negative with respect to the outside. If this voltage is plotted for a period of time it is found to be relatively stable signifying, presumably, the constant action of the Na^+–K^+ pump. In Figure 2-2 the voltage is plotted on a graph. The voltage across the membrane of the cell is called the **resting potential** of the membrane.

Stimulation

There are, of course, normal influences on the cell that change the voltage of the membrane in systematic ways. In addition, a wide variety of external agents such as electrical currents and chemicals and irritation from manual displacement, foreign tissue, etc., can also produce changes in the membrane voltage. The normal processes provide the mechanisms for the normal functioning of the cell; the other processes more generally lead to various types of pathology. Despite these differences, both the normal and abnormal influences act in very much the same way; thus, any influence or irritation which leads to a change in the voltage can be called a **stimulus,** and the process, whether normal or abnormal, can be called **stimulation.** In experimental situations stimulation is usually provided by giving brief pulses of electric shock to the axon through small wires called stimulating electrodes. The response of the axon is then recorded by measuring its voltage change with a voltmeter or oscilloscope attached to the axon by small wires called recording electrodes.

Depolarization, Threshold, and Action Potential

When an axon is stimulated with a very small electric current, its membrane becomes more permeable to Na^+ and K^+, and they move more freely across the membrane. Consequently, Na^+ enters and K^+ leaves the cell, causing the voltage across the membrane to decrease toward 0 mV. (Because K^+ already moves more freely across the membrane than Na^+ the main change is caused by increased inward flow of Na^+.) When this small voltage change occurs the axon is said to undergo **depolarization.** This change in voltage is local—restricted to the area stimulated—and brief, so the resting potential of the membrane is rapidly restored.

Although the neuron membrane responds to weak stimulation by decreasing its permeability to ions in a relatively orderly way, it undergoes a peculiar change of behavior if stimulation is sufficiently intense to cause the transmembrane voltage to depolarize to about −50 mV. At about this voltage the membrane becomes completely permeable to Na^+ and K^+; that is, Na^+ rushes into the cell and K^+ rushes out of it, until the voltage across the membrane falls through 0 mV and reverses to about +50 mV. The depolarizaton of the membrane is largely attributable to Na^+ influx; its repolarization is due to K^+ efflux. The sudden permeability of the membrane occurs independently of any further stimulation once the membrane has depolarized to about −50 mV. The loss of permeability is quite brief, about ½ millisecond, after which normal permeability is regained, the Na^+–K^+ pump resumes its action, and the resting potential of the membrane is restored. The voltage at which the membrane undergoes this autonomous change is called its **threshold.** The sudden reversal of polarity and the restoration of the resting potential are called an **action potential.** These are displayed graphically in Figure 2-3. One can say, therefore, that the threshold for eliciting an action potential is −50 mV.

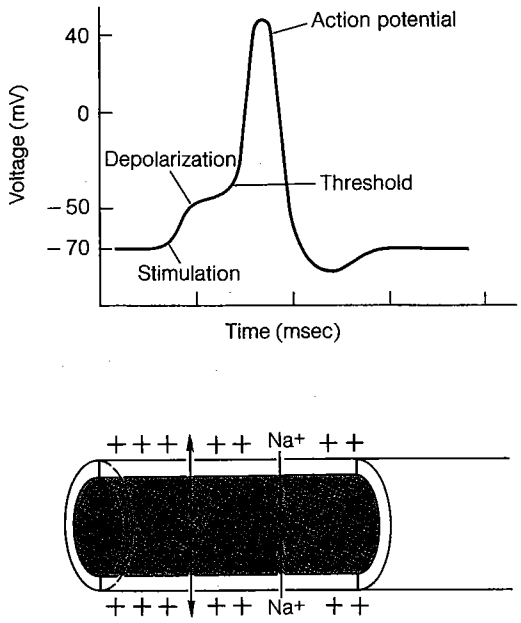

FIGURE 2-3. Stimulation of the membrane causes it to become more permeable to K^+ and Na^+. As a result the transmembrane potential declines or depolarizes. At about −50 mV, its threshold, the membrane becomes completely permeable to Na^+ and K^+ and its charge momentarily reverses. This reversal is called an *action potential.*

Conduction of the Nerve Impulse

When an action potential occurs in a region of the membrane it acts as a stimulus, causing adjacent portions of the membrane to lose their permeability and undergo a similar voltage change. Consequently, an action potential triggered at one end of an axon will be conducted along its length. (Action potentials can travel in either direction, but they normally begin at the cell body and travel away from it.) This movement of the action potential along the length of the axon, shown in Figure 2-4, is called a **nerve impulse** (or, more colorfully and descriptively, *firing* or *discharging*). The rate at which the impulse travels along the axon, varying from 1 to 100 meters per second, is quite slow, but neurons can sustain a wide range of firing rates. Usually they fire fewer than 100 times a second, but they can fire as frequently as 1000 times per second.

The All-or-None Law

A peculiar property of a neuron's behavior is that its threshold is stable, and every action potential, and hence nerve impulse, once it is triggered, has an identical threshold and height. These properties of the neuron's behavior are formulated in the *all-or-none law:* action potentials either occur or they do not; there is no in-between condition.

The Origin of the Nerve Impulse

Graded Potentials. So far we have described the events that occur on an axon when it is stimulated. What happens on dendrites, which are normally the origin of the cell's electrical activity? Dendrites have a membrane similar to the axons', and a similar resting potential, and they also undergo changes in potential when they are stimulated. But unlike the axon, the dendrites do not produce action potentials. If a dendrite is stimulated the voltage changes from resting potential in proportion to the intensity of the stimulation; the change then spreads along the dendrite away from the point of stimulation, getting smaller with distance (as the size of a wave in water decreases with distance from its source). These voltage changes undergone by dendrites are called **graded potentials,** which can occur as a decrease in transmembrane voltage (depolarization) or an increase (hyperpolarization), depending upon the nature of the stimulation. How each of these occurs will be discussed after we have described how graded potentials trigger the nerve impulse on the axon.

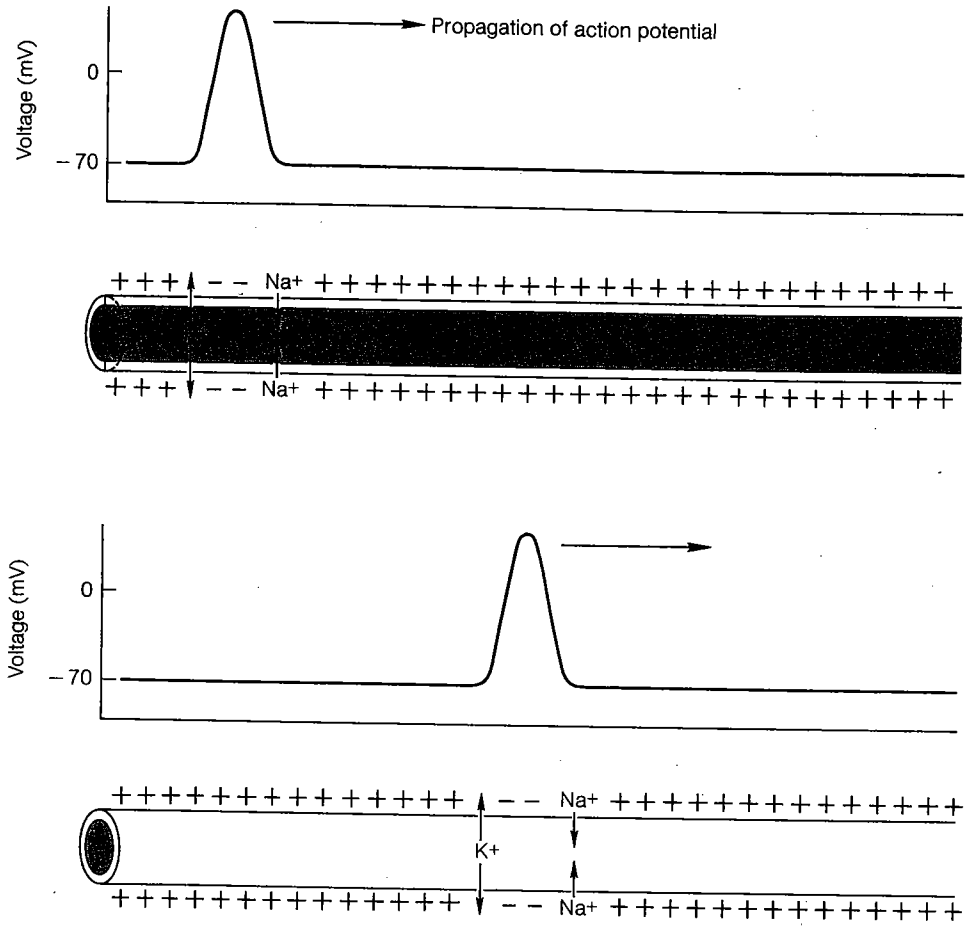

FIGURE 2-4. Because an action potential on one part of the axon stimulates adjacent areas of the axon to produce one, the action potential is propagated along the axon. (After Katz, 1967.)

Spatial and Temporal Summation. Because dendrites respond to stimulation with graded potentials they have some interesting properties. If a dendrite is stimulated at two points in close proximity the graded potentials produced at each point will add. If the two stimuli are identical the graded potential will be twice as large as would occur with only one stimulus. If the two stimuli are given at widely different points on the dendrite the graded potentials will dissipate before they reach each other and will not add. Stimuli given at intermediate distances will produce additive graded potentials, but only at the points that receive the potentials from both sources. Also, the potentials will be smaller because they decay with distance. Similar rules apply when one stimulus hyperpolarizes the mem-

brane and one depolarizes the membrane, with the difference that the graded potentials subtract. This property of adjacent graded potentials to add and subtract is called **spatial summation.**

Another type of change that can occur on dendrites is called **temporal summation.** The graded potential of a stimulated dendrite will decay with time after the stimulus has terminated. A second stimulus given some time later at the same site will produce a similar response. If the second stimulus is given soon after the first, the potentials will add, becoming larger than either is alone. The strength of the graded potential will be determined by the strength of the two stimuli and the interval between them. If one stimulus hyperpolarizes the membrane and the other depolarizes the membrane, then the two will subtract, and the graded potential will accordingly be decreased in size.

If the features of spatial and temporal summation of graded potentials are considered, it is possible to see how the nerve impulse is generated. It will be recalled that the threshold for an action potential is −50 mV. If the entire dendritic system is influenced so that it is depolarized to −50 mV, and if this graded potential spreads over the cell body to a point adjacent to the axon, then the necessary conditions for eliciting an action potential will be met. In fact, the point of transition between the cell body and axon, called the **axon hillock** (Figure 2-1), is the site where the nerve impulse originates. As long as this area is depolarized below −50 mV by spread of graded potentials, the cell will fire. However, if graded potentials are not sufficiently strong to depolarize the axon hillock to threshold, the cell will not fire. In summary, therefore, the origin of axonal firing can be traced to the influence of graded potentials from the dendrites of the cell.

The Origin of Graded Potentials: The Synapse, EPSPs, and IPSPs

The idea that chemicals play a role in the transmission of information from one neuron to another, from a neuron to a muscle, or from a neuron to a body organ originated with the experiments of Otto Loewi in 1921. He stimulated the nerves going to a frog heart, collected a fluid perfused through the ventricles of the heart, and transferred it to the heart of another frog. The activity of the second heart was changed by introduction of the fluid in the same way that the activity of the first heart was changed by electrical stimulation. The stimulated nerve had been releasing a chemical, and it was the chemical, not some direct action of the nerve, that was causing the heart's activity to change. It is now widely accepted that neurons communicate chiefly through the agency of the chemicals they release when they fire. These chemicals, each known as a **neurotransmitter,** are released by the end feet of the neuron.

Figure 2-5 shows a diagram of an end foot. The end foot is separated from other neurons by a very small space called the *synaptic space.* The membrane of the end foot is called the **presynaptic membrane,** and the membrane it synapses with is called the **postsynaptic membrane.** Penetrating the end foot from the axon are neurofibrils, which may transport precursor chemicals for the manufacture of neurotransmitters into the end foot. There are *mitochondria* that provide energy for metabolic processes. There are also two types of vesicles in the end foot: **storage granules,** which are presumed to be long-term storage sites for neurotransmitters; and **synaptic vesicles,** which hold neurotransmitters for immediate use. On the postsynaptic membrane there are specialized proteins that act as *receptors* for the neurotransmitter. The synapse functions in the

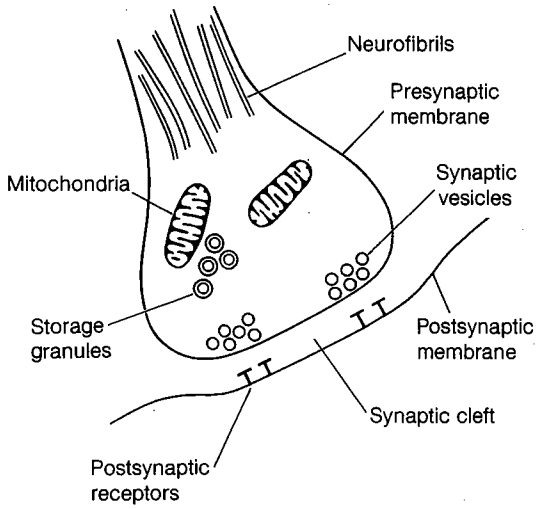

FIGURE 2-5. Diagram of the major features of a synapse.

following way. When a neuron fires, some synaptic vesicles release their neurotransmitter content into the synaptic space. The neurotransmitter binds weakly to the receptors on the postsynaptic membrane, after which it is quickly washed away by extracellular fluid and is destroyed or taken back into the presynaptic membrane for reuse.

How neurotransmitters, released by the firing of a presynaptic neuron, produce graded potentials in a postsynaptic neuron has been clarified in part by Eccles and his coworkers, who stimulated the axons of presynaptic neurons while recording from a postsynaptic cell body. Postsynaptic graded potentials followed each volley of presynaptic stimulation. These postsynaptic potentials, or PSPs, had a very small amplitude, 1 to 3 mV; but depending upon which presynaptic axons were stimulated, they consisted either of depolarization or hyperpolarization of the postsynaptic membrane. Because depolarizing PSPs of course increase the probability of the neuron firing, they are called *excitatory postsynaptic potentials,* or *EPSPs;* and because hyperpolarizing potentials decrease the probability of the neuron firing, they are called *inhibitory postsynaptic potentials,* or *IPSPs.* It is now accepted that the EPSPs and IPSPs are produced by the action of neurotransmitters on the postsynaptic receptors of the cell. Neurotransmitters from certain synapses, called *excitatory neurotransmitters,* are responsible for EPSPs, while other neurotransmitters, called *inhibitory neurotransmitters,* are responsible for IPSPs. Eccles suggests that excitatory neurotransmitters produce EPSPs by making the membrane slightly more permeable to Na^+, which enters the cell, lowering the transmembrane voltage. Inhibitory neurotransmitters, on the other hand, make the membrane more permeable to K^+ and Cl^+ ions; K^+ flows out and Cl^- flows into the cell, raising the transmembrane voltage.

It can now be seen that the origin of the graded potentials of dendrites can be traced to the release and action of neurotransmitters from the end feet of other neurons. It will be remembered that there are thousands of end feet synapsing with the dendrites and cell body of any one neuron; thus, the summed graded potential of the cell is produced by the action of all of these inputs. The integration of these inputs by spatial and temporal summation determines whether the neuron will fire or not. If EPSPs predominate, and if there are enough of them to produce depolarization to threshold at the axon hillock, the neuron will fire. If IPSPs predominate the neuron will not fire.

Factors Determining Nerve Impulse Speed

The nerve impulse does not travel at exactly the same speed in all neurons. At least two factors affect speed. One factor is resistance to current along the axon. Impulse speed is increased as resistance is decreased; and resistance is most

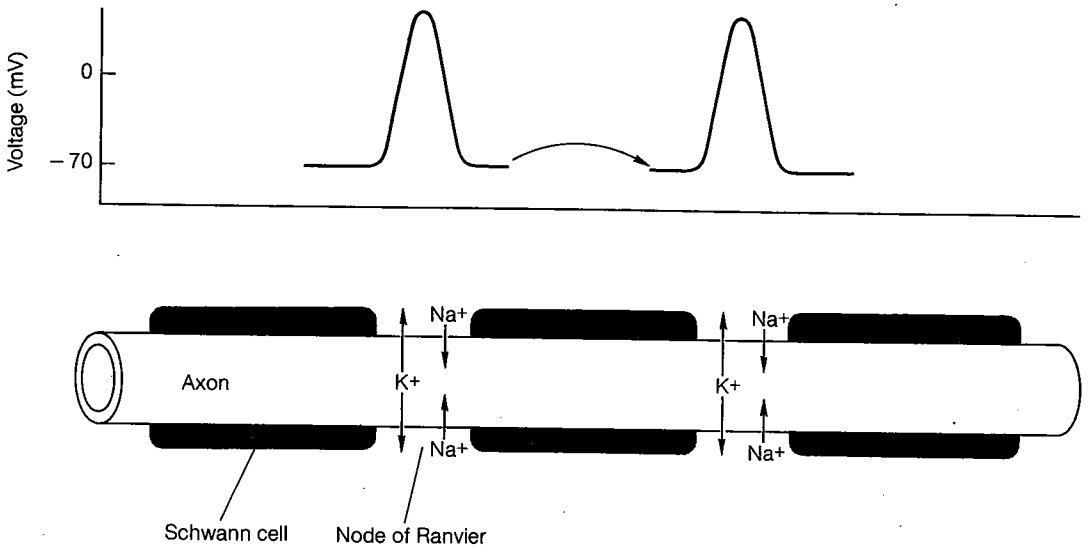

FIGURE 2-6. The nerve impulse jumps from one inter-Schwann cell space, called a *node of Ranvier*, to the next. This process, *saltatory conduction*, greatly speeds impulse transmission.

effectively decreased by increase of the axon size. Thus, large axons conduct at a faster rate than small axons. Were the nervous system to rely only on this procedure, axons would have to be cumbersomely large. An alternative procedure has evolved that uses the glial cells to aid in speeding propagation. Schwann cells in the peripheral nervous system and oligodendroglia in the central nervous system wrap around some axons, forming a compact sheath of **myelin** (from the Greek, meaning marrow) against the cell membrane, as shown in Figure 2-6. Between each glial cell the membrane of the axon is exposed by a gap called a **node of Ranvier.** In these myelinated axons the nerve impulse jumps along the axon from node to node, a type of conduction called **saltatory conduction** (from the Latin, meaning skip). Saltatory conduction is an extremely effective way of speeding the impulse because a small myelinated axon can conduct as rapidly as an unmyelinated axon 30 times as large.

The Integration of Neural Activity and Information Processing

It can be seen from the preceding sections that the dendritic system of the neuron sums the activity from many other neurons by producing graded potentials that will determine whether or not the neuron fires. The firing of the neuron is an all-or-none response, which will continue for as long as the firing threshold of the axon hillock is maintained. But how do these series of activities code information?

It is now thought that the nervous system works by a combination of analogue (how much) and digital, or binary (yes–no), principles. Analogue functions are the property of the dendritic system, and digital functions are the property of the axons. We can see how these principles determine behavior if we return to the opening description of the male Grayling butterfly's behavior. Recall Tinbergen's suggestion that in the male butterfly's

nervous system there is a pooling station that integrates the different features (dark, large, and irregular) of a stimulus object to determine whether or not the male will approach the stimulus. Theoretically, all of the male butterfly's behavior could be accounted for by the activity of one central neuron. The dendrites of that neuron would serve as the pooling station and the axon would be the system that initiates an approach response. If three channels of input converged upon the dendrites (one signalling darkness, one size, and one movement), simultaneous activity in the separate channels signalling dark, large, and irregular would produce EPSPs that when summed would trigger axonal firing and thus approach by the butterfly. Activity in only one channel might not be sufficient to fire the neuron; activity in two channels might be sufficient to produce a response, if input in each were particularly intense. At any rate, it can be seen that the analogue function of the dendrites will integrate the various sources of input, while the digital activity of the axon will determine whether or not approach is to occur. Of course, the analogue feature of dendritic integration can be put to many types of use, and the digital properties of the axon can be expressed in many codes (frequency, pattern of firing, etc.).

Many other factors contribute to information processing. Synapses proximal to the axon hillock may have special access to influence cell firing. Inhibition or excitation by more distal axosynaptic connections may allow for more subtle control of intercell communication. Some synapses may also change structurally with use or disuse, thus becoming increasingly or decreasingly effective in communicating. These factors, and many others, are beyond the scope of the present discussion, but they do contribute to the brain's incredible synthesizing and storage abilities.

ANALYZING THE BRAIN THROUGH ITS ELECTRICAL ACTIVITY

Because the activity of nerve cells has an electrochemical basis the activity can be recorded with instruments sensitive to small changes in electrical activity. The several techniques for recording the brain's electrical activity include: (1) intracellular unit and extracellular unit recording, (2) electroencephalographic (EEG) recording, and (3) evoked potential (EP) recording. Relating each of these types of activity to behavior can be used as a way of determining the function of particular brain areas, and as a way of determining the normality of function in a given brain area. Because of its electrochemical mode of activity, the brain can also be artificially stimulated with electrical current. This technique has been used as a method of analyzing the function of different areas, as a possible source of therapy, and as a method of producing experimental models of diseases such as epilepsy.

Unit Recording

If small wires or pipettes containing an ionized conducting solution are inserted into the brain so that their tips are placed in or near a nerve cell, the changes in a single cell's electrical potentials, i.e., **unit activity,** can be recorded in relation to some indifferent electrode or ground. *Intracellular* recordings are made from electrodes with very tiny tips, less than $^1/_{1000}$ of a millimeter in diameter, which are placed in the cell, whereas *extracellular* recordings are made when an electrode tip is placed adjacent to one or a number of cells. Both techniques require amplification of the signal and some type of display. The cell's activity is either displayed on an oscilloscope for photographing or recorded on a tape recorder for computer analysis. In many experiments the

signal is played through a loudspeaker so cell firing is heard as a beep or pop. Both recording techniques require considerable skill to perform because it is difficult to place the electrode in or sufficiently close to the cell without killing it, and when a cell is "captured," it is often difficult to hold it for more than a few minutes or hours before the signal is lost.

Unit recording techniques provide a particularly interesting insight into the brain's function. For example, cell records obtained from the visual cortex of cats and monkeys reveal that each cell has a preferred stimulus and a preferred response pattern. Some cells fire to horizontal lines, others to diagonal lines, and still others fire only to lines that are oriented in a special way and that also move in a particular direction. Unit recording techniques have also been used to analyze such abnormal cell activity as occurs in epilepsy. In epilepsy, the activity of cells becomes synchronized in an abnormal pattern, and an understanding of epilepsy depends in part upon analyzing and controlling this feature of the cell's behavior. Much of the information obtained with unit recordings has of necessity come from experiments performed on anesthetized animals. Future research is likely to repeat these tests in freely moving animals to confirm and elaborate upon the findings.

EEG Recording

A simple technique for recording electrical activity of the brain was developed in the early 1930s by Hans Berger. He found that it was possible to record "brain waves" from the scalp. These waves, called **electroencephalograms,** or **EEGs,** have proved to be a valuable tool for studying problems such as sleep-waking, for monitoring depth of anesthesia, and for diagnosing epilepsy and brain damage.

To record a person's EEG a small metal disc is attached to the scalp, and the change in electrical activity in the area of this electrode is compared to some electrically neutral zone such as the ear lobe. The electrical changes recorded on the scalp are rather small, usually much less than a millivolt, so they must be amplified for display on an oscilloscope or on a paper chart recorder called an electroencephalograph, or EEG machine.

The electrical activity recorded from the scalp is the sum of all neural activity, action potentials, graded potentials etc., but it is mostly the measure of the graded potentials of dendrites. As a result, it represents the summed dendritic activity of thousands of nerve cells and can only be considered a rather general measure of the brain's activity. Although it can be used as a crude index of the brain's level of excitation it tells very little about the activity of single cells as such. During a given EEG pattern any particular single cell may be active or inactive.

It was originally thought that each cytoarchitectonic area of the brain had its own pattern of EEG activity, but it is now recognized that variations in patterns do not correlate closely with cytoarchitectonic areas. Figure 2-7 shows the characteristic *resting* rhythms obtained from different parts of the cortex. The patterns are obtained only under optimal conditions, when the person is awake, resting quietly, with eyes closed. The dominant rhythm of the posterior cortex is an 8-to-12 cycles/second waveform called the **alpha rhythm.** The dominant rhythm of the precentral and postcentral sensorimotor area is a 20-to-25 cycles/second **beta rhythm.** The secondary frontal areas have a 17-to-20 cycles/second beta rhythm. And the tertiary frontal area has 8-to-12 cycles/second waves.

The resting EEG patterns desynchronize or flatten into a low-voltage asynchronous activ-