34 Neurons, Sense Organs, and Nervous Systems

Chapter Outline

Homeostasis, the dynamic maintenance of optimal conditions, requires sensors and effectors that regulate controlled variables, such as blood pressure. Chemical signaling via hormones is one major signaling route for cellular communication to maintain homeostasis. The other route is the nervous system, discussed here.

While exploring the operations of the brain is a worthy and fun activity, the understanding of individual cells, the neurons, along with the glial cells that support neuronal metabolism, is important to comprehending the overall system. You should find that much of this material is an application of material you have previously learned. You will once again see cellular organelles, membrane structure and function, the sodium-potassium pump, and membrane potentials serving important biological functions. This material is challenging to learn, but spending some time to meet this challenge will open many doors of biological understanding to you.

Chapter 34 includes components of **Big Idea 2, Big Idea 3,** and **Big Idea 4**. The specific parts of the AP Biology curriculum covering **Big Idea 2:** Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis, include:

- **2.B.1**: Cell membranes are selectively permeable due to their structure.
- **2.C.2**: Organisms respond to changes in their external environments.

The specific parts covering **Big Idea 3:** Living systems store, retrieve, transmit, and respond to information essential to life processes, include:

- **3.D.2**: Cells communicate with each other through direct contact with other cells or from a distance via chemical signaling.
- **3.E.2**: Animals have nervous systems that detect external and internal signals, transmit and integrate information, and produce responses.

The specific parts addressing **Big Idea 4:** Biological systems interact, and these systems and their interactions possess complex properties, include:

- **4.B.2**: Cooperative interactions within organisms promote efficiency in the use of energy and matter.

Chapter Review

Concept 34.1 *details the cellular components of the nervous system, starting with cells called neurons. Neurons are similar to one-way roads in that they carry signals in only one direction. An individual neuron has two functional regions. The highly branched, dendritic region is the information-receiving region. It has transmembrane proteins that serve as receptors to bind chemical signals, called neurotransmitters. In response to a signal, the dendritic region of the cell undergoes a small change in membrane potential, called a graded potential. The second functional region of a neuron is called the axon or axonal region. Neurotransmitter signals are released from its terminus in response to action potentials. Neurons that carry information into the central nervous system (spinal cord and brain) are called afferent neurons, as they affect what happens next in the organism. Neurons carrying commands out of the central nervous system are called efferent neurons, because they effect change by controlling effectors in the body. The neurons located between the afferent and efferent neurons are called interneurons.*

1. Describe the difference between a nerve and a neuron.

2. Describe how a neuron's axon hillock acts as the decision point for whether or not the neuron will undergo an action potential to communicate with its target.

3. Discuss the relative abundance of glial cells and neurons in the brain, and describe two functions of glial cells.

Concept 34.2 *reveals details about neuronal function. Whether neuronal activity is as simple as "Me want cookies!" or as sublime as "I finally understand the Nernst equation," it is a matter of understanding that ion movements across neuronal membranes alter membrane potentials.*

The membrane potential describes the separation of charges inside and outside of neuronal membranes, and these potentials are measured in millivolts (mV). The interior of a neuron, its cytosol, has many protein molecules. Most of these are in the anionic (negatively charged) state, so the inside of the "resting" cell is electronegative relative to the outside of the cell, typically between -50 and -70mV. The resting membrane potential of a "quiet" neuron is anything but resting: it depends on a high rate of ATP hydrolysis, driving the sodium-potassium pump (Na^+-K^+-ATPase). The unequal distribution of charge across the membrane means that it is polarized. Changes that reduce the charge difference across the membrane are called depolarizing changes, and changes that increase the charge difference are said to be hyperpolarizing changes.

The functions of neurons are based on ion movements (especially sodium and potassium ions) across the cell membrane through transmembrane proteins called ion channels. The channels have two major characteristics: selectivity and gating. Selectivity means that a particular ion-channel protein, when it is open, has a single "best" ion that passes through it. For example, skeletal muscles move toward contraction by first opening sodium (ion) channels. Gating means that the opening or closing of the ion channel is like the operation of a gate that opens or closes in response to particular events. Some of the sodium channels on skeletal muscles open only in response to the binding of the excitatory neurotransmitter acetylcholine, following its release from motor neurons. Overall, the sequence leading to skeletal-muscle contraction begins with the opening of "acetylcholine-gated sodium channels." Some of the other ion channels, including those involved in action potentials, are gated by changes in membrane voltage. Voltage-gated sodium channels and voltage-gated potassium channels have been studied most thoroughly.

Knowing that sodium ions are more abundant outside the neuron than inside, and that the inside of the cell has more negative charges than the outside, one can predict that the opening of sodium channels will result in the inward *movement of sodium ions, which are positively charged, thus depolarizing the neuron. Correspondingly, the opening of potassium channels will allow potassium ions, more abundant inside the cell than outside, to depart from the cell, thus hyperpolarizing the neuron.*

The movement of small numbers of ions across neuronal membranes causes graded potentials, small changes in membrane potential that are most important in the dendritic region of the neuron. Graded potentials spread quickly to nearby areas but decay as they spread. Graded potentials are also summable. In contrast, action potentials are due to large-scale ion movements and to the operation of voltage-gated ion channels. Action potentials are functionally important in the long, thin axonal region of neurons. Action potentials are "all-or-none" events. They do not decay and are not summable.

4. Explain how a "resting" neuron comes to have more sodium ions outside the cell than in the cytosol and to have more potassium ions inside the cell than in the extracellular fluid.

5. Explain what is meant by the term *threshold* in describing neuronal function.

6. The ions considered in studying excitable membranes contribute to the "electrochemical gradient" along the neuronal membrane. Discuss the meanings of "electro-" and "-chemical" gradients.

7. Describe how two or more graded potentials can be added together.

8. Describe how the refractory period makes it impossible for two or more action potentials to be added together.

9. Explain why the concept of threshold does not apply to graded potentials.

10. Explain how the concept of threshold applies to action potentials.

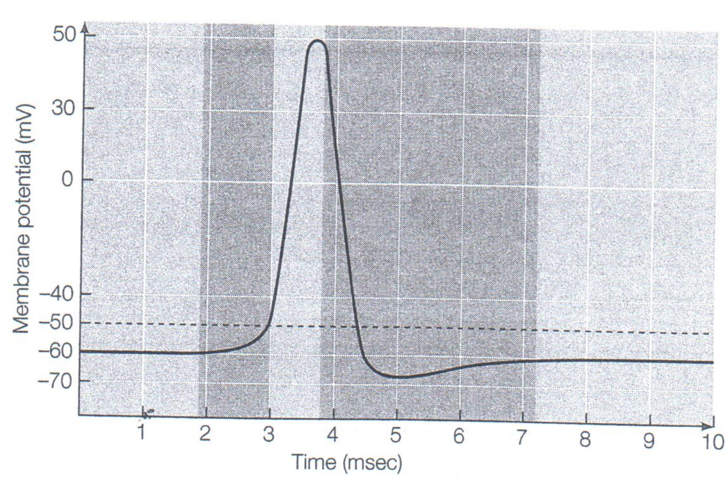
11. Label the graph below with each of the following:

(A) Peak of increased sodium permeability

(B) Threshold for an action potential

(C) Resting membrane potential

(D) Hyperpolarization (undershoot)



12. Certain cells in the heart have a "sodium leak" channel that allows sodium ions to leak into the cytosol. Describe what this leak does to membrane potential. Because these cells can fire action potentials, include the concept of threshold in your answer.

Concept 34.3 *describes the synapse, the point of communication between two neurons or between an efferent neuron and its target cell(s).*

In a small number of adjacent cells with electrical synapses, the opposing membranes are physically connected via gap junctions that allow an immediate and direct spreading of action potentials from cell to cell. Most cells, though, have a physical gap between the cells in communication and are characterized as chemical synapses.

The signal used in a chemical synapse is often called a neurotransmitter. Neurotransmitters are released from the axon terminal of the neurons sending messages. The released neurotransmitter molecules diffuse across the synaptic space and bind to receptor proteins on the dendritic end of the neurons or cells receiving the message. Upon binding to the neurotransmitter, the dendritic membrane undergoes a change in membrane potential: when the signal is excitatory, the neuron is more likely to "fire" an action potential, but if the signal is inhibitory, it hyperpolarizes and is less likely to fire an action potential. As noted earlier, the key determinant of whether or not the receiving neuron fires an action potential is whether it undergoes enough depolarization to reach the threshold for activating the voltage-gated sodium and potassium channels.

13. For a motor neuron that releases acetylcholine, describe the connection between the arrival of an action potential at the axon terminal and its release of acetylcholine.

14. Speculate on how the "acetylcholine message" is terminated in the neuromuscular junction.

15. Compare the activity of an olfactory neuron, as it samples odorant molecules in the nasal cavity, to chemical communication at a synapse.

16. Assume that learning involves changes in the effectiveness of synaptic communication. Given that assumption, predict how learning may correspond more closely to changes in metabotropic receptors (G protein–linked receptors) than to changes in ionotropic receptors (ligand-gated ion channels). Define the activity of each in your answer.

Concept 34.4 *explores the sensory abilities of animals. In the process of sensory transduction, sense organs convert environmental stimuli to changes in the membrane potentials of sensory neurons, leading to information processing in the nervous system, and possible changes in behavior and physiology.*

Sensory organs, such as the nose, ears, and eyes, allow animals to collect, filter, and magnify the many stimuli encountered from moment to moment. The sensory cells are called chemoreceptors, mechanoreceptors, and photoreceptors. In addition to sensing the outside world, sensory cells monitor the internal environment in key locations, including oxygen concentration in the blood and body temperature.

The arrival of stimuli at sensory cells leads to changes in their membrane potentials, a process called sensory transduction. In this manner, sensory-transducing cells are analogous to dendritic membranes that receive chemical neurotransmitter molecules. Changes in membrane potential are due to the movement of ions across the membranes of the sensory cells/neurons, resulting in graded potentials. To reiterate the focus on sensory reception, these graded potentials are often called receptor potentials. Depending on the sensory modality involved, the receptor potentials can lead to action potentials, which allow for smelling, or graded-potentials that alter neurotransmitter release, which allow for vision and hearing. In both cases, the next neuron in the pathway is altered in its activity, and so on along the pathway into the central nervous system, leading to organismal responses. This contributes to homeostatic regulation.

Mechanoreceptor neurons respond to stretching and deformation of their membranes by altering transmembrane ion traffic, thus generating receptor potentials and initiating transduction. Among their many roles, some mechanoreceptor mechanisms are part of a system that adjusts the strength of muscle contraction so that it can more accurately match load requirements. Mechanoreceptor mechanisms also underlie hearing (audition) and vestibular functions (balance and eye movements).

Vision begins with photosensory transduction. The transducing cells, found in the retina, are the rods and cones, the latter for color vision. In the case of rods, the absorption of photons of light by pigments, such as rhodopsin, is linked to changes in the membrane potential of the photoreceptor cell. In turn, a graded depolarization of the rod changes its secretion of neurotransmitters, altering the activity of the neural pathway leading to visual perception.

The neural signals from different sensory systems are processed in various locations in the brain. (Knowing the specific details of neuroanatomical pathways is beyond the scope of the AP Biology Curriculum Framework.) Organize your studies on the many similarities of sensory receptors in detecting stimuli and then transmitting information via changes in membrane potentials.

17. Ligand-gated channels open or close when a chemical signal binds to the receptor protein associated with the channel. Another class of channels opens or closes in response to mechanical stimulation, such as the physical deformation of the cell in response to external pressure. Propose the transduction mechanism for a sensory process that is due to the operation of mechanically gated ion channels, and identify the type of sensory information provided by that sense.

18. An individual olfactory neuron in a dog's nasal cavity will likely express only one of more than 1,000 odorant-receptor genes, yet it seems dogs are capable of distinguish hundreds of thousands of different odorants. Discuss some possible mechanisms by which this diverse sampling capability might occur.

19. "The world is one gigantic synapse," wrote one olfactory biologist. Describe the meaning of this statement using principles of synaptic communication.

20. Describe the anatomical and functional relationships between the tympanic membrane; the incus, malleus, and stapes; and the cochlear fluid.

21. "Ringing" noises in the ears are not uncommon after a blow to the head. Describe how physical jostling of the hearing apparatus can lead to the perception of sound that does not really exist.

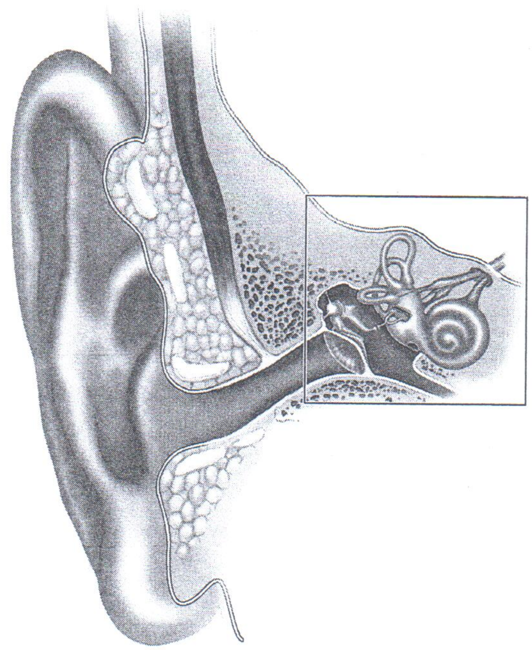
22. As you fill a pail with water, you manage to hold it steady under the faucet even as the mass of the filling pail becomes greater and greater. Describe the sensory feedback system that adjusts the strength of skeletal muscle contraction to match the load of the filling bucket.

23. Describe how the exposure of a rod to a brief flash of light affects its membrane potential and the release of its neurotransmitter.

24. Explain how and why colors are vivid in daylight but dull and grayish at night.

25. Describe what you would expect to see in examining the rods and cones in nocturnal owls compared to birds that are diurnal in behavioral activity.

26. A tumor damaged the bones in a patient's middle ear on the left side of her head, impairing her sense of hearing. After the tumor was removed, the audiologist tested the patient's ability to hear by placing a tuning fork near the left pinna, and then again while touching the vibrating tuning fork to the left side of the patient's forehead. The patient could hear the tuning fork better when it was touching her forehead. When the unaffected right ear was tested, the tuning fork was heard more clearly when it was placed near the right pinna than when it was placed on the right side of the forehead. Refer to the diagram to the right to explain these observations.



Concept 34.5 *describes the vertebrate nervous system. The brain and the spinal cord make up the central nervous system and are organized in a predictable manner. The spinal cord includes neuronal tracts to the brain (afferent pathways) and from the brain (efferent pathways), as well as synaptic contacts and interneurons required for reflexes. An example is the knee-jerk reflex, wherein sensory afferent inputs about muscle and tendon stretch modify the amount of efferent motor outputs on associated muscles.*

The autonomic nervous system controls involuntary physiological functions in the body. It is subdivided into two opposing sections: the sympathetic (exercise and emergency) and the parasympathetic (resting and fed) systems. For example, heart rate is under autonomic influence, with sympathetic signals (epinephrine from the adrenal gland and norepinephrine from sympathetic terminals) accelerating heart rate as appropriate during exercise or emergency, whereas parasympathetic signals (acetylcholine from parasympathetic neurons) slow your heart rate during other times.

27. Describe the anatomical differences between sensory (afferent) and motor (efferent) neurons.

28. Describe the functional differences between sensory and motor neurons. Give an example of the stimulus or organ controlled by each.

29. Describe how the following changes in the activity of the autonomic nervous system affect heart rate. Include as many anatomical and neurochemical details as you can.

a. Increased activity in the sympathetic division:

b. Increased activity in the parasympathetic division:

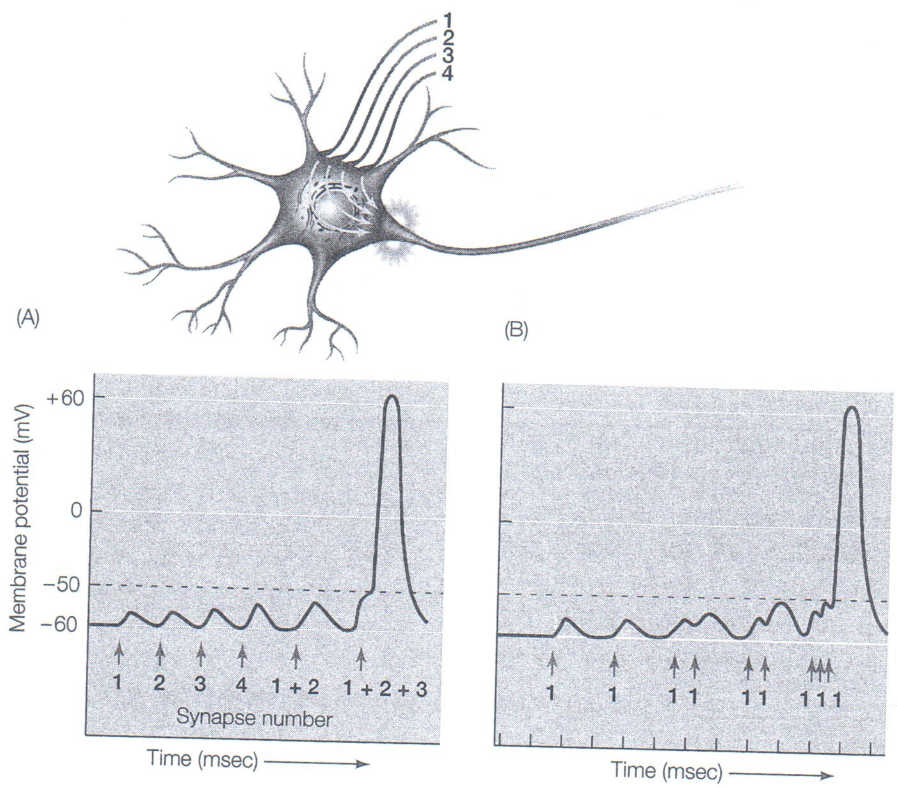
30. Discuss the general principles that speaking uses a different part of the brain than does understanding and responding to words.

Science Practices & Inquiry

In the AP Biology Curriculum Framework, there are seven **Science Practices**. In this chapter, we focus on **Science Practice 1:** The student can use representations and models to communicate scientific phenomena and solve scientific problems. More specifically, we focus on **Science Practice 1.4:** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

In Question 31, you will evaluate a model of a synapse and describe how nervous systems transmit information (**Learning Objective 3.45**).

31. Respond to each of the following prompts, using the following terms: graded potential, threshold, and action potential. Assume that the four axon terminals shown in the drawing represent excitatory synapses.



a. Explain how graph A represents spatial summation.

b. Explain how graph B represents temporal summation.

c. Add a fifth inhibitory axon terminal to the diagram, close to the axon hillock, and discuss the effect of its simultaneous activity with attainment of threshold.