chapter 10

Somatic and Special Senses

Photo:
Yolanda Santana received a cochlear implant when she was three years old. The device enables her to detect enough sounds to communicate effectively.

GETTING A COCHLEAR IMPLANT. Yolanda Santana, of Rochester, New York, probably lost her hearing when she was only eight weeks old and suffered a high fever. But it wasn't until she was nine months old, when Yolanda didn't babble like her age-mates, that her parents first suspected she might be deaf. She was fitted with hearing aids and did well at a preschool for the deaf. Then Yolanda's parents read about cochlear implants on the Internet and decided to pursue this option for their daughter. They learned that a cochlear implant does not magically restore hearing, but enables a person to hear certain sounds. Teamed with speech therapy and use of sign language, the cochlear implant enables a person to make enough sense of sounds to speak.

At the time Carlos and Beth Santana read about the implants, Yolanda was already approaching three years old. Before age three is the best time to receive a cochlear implant because this is when the brain is rapidly processing speech and hearing as a person masters language. Of the 22,000 people in the United States who have received cochlear implants since they became available in 1984, about half have had them since early childhood.

The implant consists of a part placed under the skin above the ear that leads to two dozen electrodes placed near the auditory nerve in the cochlea, the snail-shaped part of the inner ear. Yolanda wears a headset that includes a microphone lodged at the back of her ear to pick up incoming sounds and a fanny pack containing a speech processor that digitizes the sounds into coded signals. A transmitter on the headset sends the coded signals, as FM radio waves, to the implant, which changes them to electrical signals and delivers them to the cochlea. Here, the auditory nerve is stimulated and sends neural messages to the brain's cerebral cortex, which interprets the input as sound.

Yolanda's audiologist turned on the speech processor a month after the surgery. At first, the youngster heard low sounds and sometimes responded with a low hum. She would grab at the processor, which meant that she realized it was the source of the sound. Still, sounds had no meaning, for she had never heard them before. But, gradually, the little girl learned from context. One day when Carlos signed "father" and said "poppy," Yolanda signed back and tried to say the word! Able to connect mouth movements to sounds to concepts, Yolanda was well on her way to hearing.

Chapter Objectives

After studying this chapter, you should be able to do the following:

10.1 Introduction

1. Distinguish between somatic senses and special senses. (p. 249)

10.2 Receptors and Sensations

2. Name five kinds of receptors, and explain their functions. (p. 249)
3. Explain how a sensation arises. (p. 249)

10.3 Somatic Senses

4. Describe the receptors associated with the senses of touch, pressure, temperature, and pain. (p. 249)
5. Describe how the sense of pain is produced. (p. 251)

10.4 Special Senses

6. Identify the locations of the receptors associated with the special senses. (p. 253)

10.5 Sense of Smell

7. Explain the relationship between the senses of smell and taste. (p. 253)
8. Explain the mechanism for smell. (p. 254)

10.6 Sense of Taste

9. Explain the mechanism for taste. (p. 256)

10.7 Sense of Hearing

10. Name the parts of the ear, and explain the function of each part. (p. 256)

10.8 Sense of Equilibrium

11. Distinguish between static and dynamic equilibrium.(p. 261)

10.9 Sense of Sight

12. Name the parts of the eye, and explain the function of each part. (p. 265)
13. Explain how the eye refracts light. (p. 269)
14. Describe the visual nerve pathway. (p. 271)

Aids to Understanding Words

choroid [skinlike] *choroid* coat: Middle, vascular layer of the eye.
cochlea [snail] *cochlea:* Coiled tube in the inner ear.
iris [rainbow] *iris:* Colored, muscular part of the eye.
labyrinth [maze] *labyrinth:* Complex system of connecting chambers and tubes of the inner ear.
lacri- [tears] *lacri*mal gland: Tear gland.
macula [spot] *macula* lutea: Yellowish spot on the retina.
olfact- [to smell] *olfact*ory: Pertaining to the sense of smell.
scler- [hard] *scler*a: Tough, outer protective layer of the eye.
tympan- [drum] *tympan*ic membrane: Eardrum.
vitre- [glass] *vitre*ous humor: Clear, jellylike substance within the eye.

10.1 Introduction

How dull life would be without sight and sound, smell and taste, touch and balance. Our senses are necessary not only for us to enjoy life, but to survive. *Sensory receptors* detect environmental changes and trigger nerve impulses that travel on sensory pathways into the central nervous system for processing and interpretation. The body reacts with a particular feeling or sensation.

Sensory receptors vary greatly but fall into two major categories. Receptors associated with the *somatic senses* of touch, pressure, temperature, and pain form one group. These receptors are widely distributed throughout the skin and deeper tissues, and are structurally simple. Receptors of the second type are parts of complex, specialized sensory organs that provide the *special senses* of smell, taste, hearing, equilibrium, and vision.

10.2 Receptors and Sensations

The many kinds of sensory receptors share common features. However, each type of receptor is particularly sensitive to a distinct type of environmental change and is much less sensitive to other forms of stimulation. This selective response distinguishes the senses.

Types of Receptors

Sensory receptors are categorized into five types according to their sensitivities: **Chemoreceptors** (ke´´mo-re-sep´torz) are stimulated by changes in the chemical concentration of substances; **pain receptors** (pān re-sep´torz) by tissue damage; **thermoreceptors** (therm´o-re-sep´´torz) by changes in temperature; **mechanoreceptors** (mek´´ah-no-re-sep´torz) by changes in pressure or movement; and **photoreceptors** (fo´´to-re-sep´torz) by light energy.

Sensations

A **sensation** (perception) is a feeling that occurs when the brain interprets sensory impulses. Because all the nerve impulses that travel away from sensory receptors into the central nervous system are alike, the resulting sensation depends on which region of the brain receives the impulse. For example, impulses reaching one region are always interpreted as sounds, and those reaching another are always sensed as touch.

At the same time that a sensation forms, the cerebral cortex causes the feeling to seem to come from the stimulated receptors. This process is called **projection** (pro-jek´shun) because the brain projects the sensation back to its apparent source. Projection allows a person to pinpoint the region of stimulation; thus, the eyes seem to see, and the ears seem to hear.

Sensory Adaptation

The brain must prioritize the sensory input it receives, or it would be overwhelmed by unimportant information. For example, until this sentence prompts you to think about it, you are probably unaware of the pressure of your clothing against your skin, or the background noise in the room. This ability to ignore unimportant stimuli is called **sensory adaptation** (sen´so-re ad´´ap-ta´shun), and it may involve receptors becoming unresponsive (*peripheral adaptation*) or inhibition along the CNS pathways leading to the sensory regions of the cerebral cortex (*central adaptation*).

CHECK YOUR RECALL

1. List five general types of sensory receptors.
2. Explain how a sensation occurs.
3. What is sensory adaptation?

10.3 Somatic Senses

Somatic senses are associated with receptors in the skin, muscles, joints, and viscera. They include the senses of touch and pressure, temperature, and pain.

Touch and Pressure Senses

The senses of touch and pressure derive from three kinds of receptors (fig. 10.1). These receptors sense

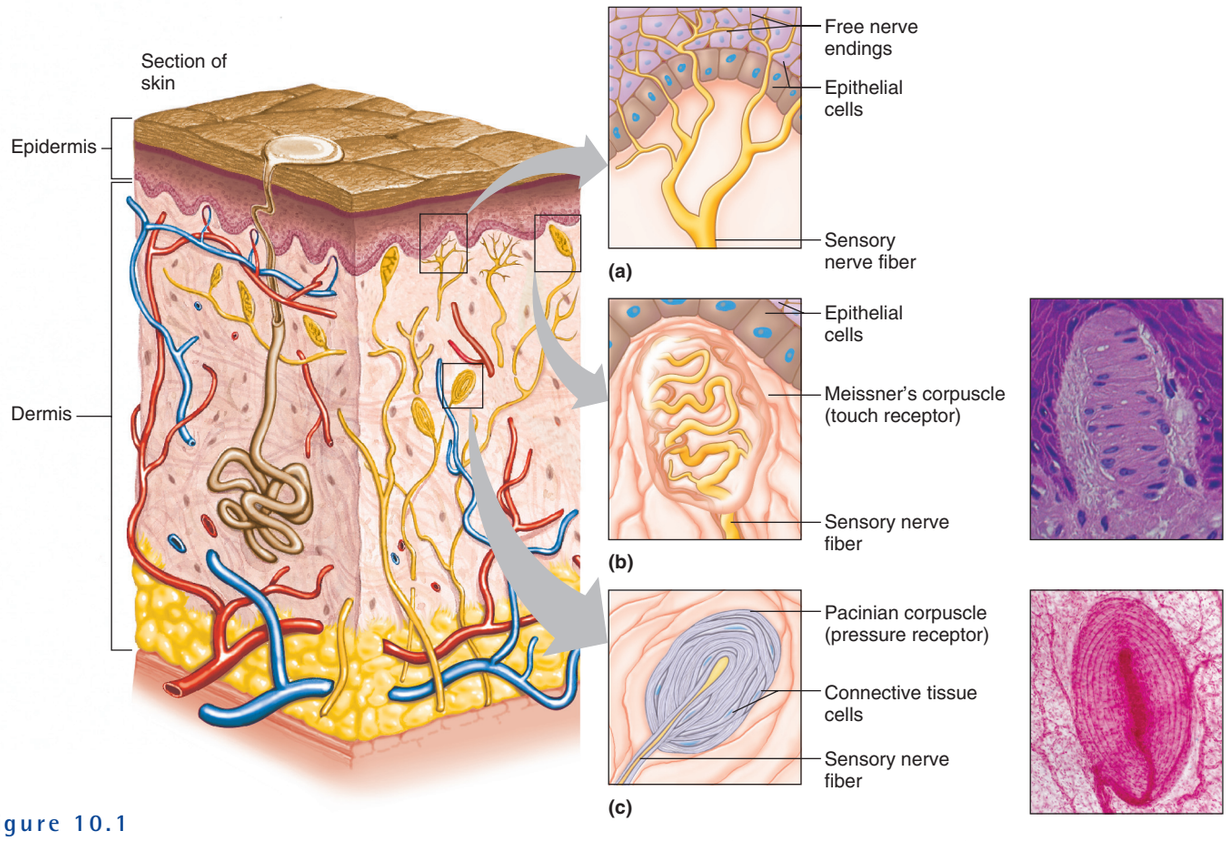


Figure 10.1
Touch and pressure receptors include (*a*) free ends of sensory nerve fibers, (*b*) Meissner's corpuscles (with 225× micrograph), and (*c*) Pacinian corpuscles (with 50× micrograph).

mechanical forces that deform or displace tissues. Touch and pressure receptors include:

1. **Free nerve endings** These receptors are common in epithelial tissues, where their free ends extend between epithelial cells. They are associated with the sensations of touch and pressure.
2. **Meissner's corpuscles** These are small, oval masses of flattened connective tissue cells within connective tissue sheaths. Two or more sensory nerve fibers branch into each corpuscle and end within it as tiny knobs.

   Meissner's corpuscles are abundant in the hairless portions of the skin, such as the lips, fingertips, palms, soles, nipples, and external genital organs. They respond to the motion of objects that barely contact the skin, interpreting impulses from them as the sensation of light touch.
3. **Pacinian corpuscles** These sensory bodies are relatively large structures composed of connective tissue fibers and cells. They are common in the deeper subcutaneous tissues and in muscle tendons and joint ligaments. Pacinian corpuscles respond to heavy pressure and are associated with the sensation of deep pressure.

Temperature Senses

Temperature sensation depends on two types of free nerve endings in the skin. Those that respond to warmer temperatures are called *warm receptors,* and those that respond to colder temperatures are called *cold receptors.*

Warm receptors are most sensitive to temperatures above 25°C (77°F) and become unresponsive at temperatures above 45°C (113°F). Temperatures near and above 45°C stimulate pain receptors, producing a burning sensation.

Cold receptors are most sensitive to temperatures between 10°C (50°F) and 20°C (68°F). Temperatures below 10°C stimulate pain receptors, producing a freezing sensation.

Both warm and cold receptors adapt rapidly. Within about a minute of continuous stimulation, the sensation of warmth or cold begins to fade.

Sense of Pain

Other receptors that consist of free nerve endings sense pain. These receptors are widely distributed throughout the skin and internal tissues, except in the nervous tissue of the brain, which lacks pain receptors.

Pain receptors protect the body because tissue damage stimulates them. Pain sensation is usually perceived as unpleasant, and it signals a person to act to remove the stimulation. Pain receptors adapt poorly, if at all. Once a pain receptor is activated, even by a single stimulus, it may send impulses into the central nervous system for some time. Thus, pain may persist.

The way in which tissue damage stimulates pain receptors is poorly understood. Injuries likely promote the release of certain chemicals that build up and stimulate pain receptors. Deficiency of oxygen-rich blood (ischemia) in a tissue or stimulation of certain mechanoreceptors also triggers pain sensations. For example, the pain elicited during a muscle cramp stems from sustained contraction that squeezes capillaries and interrupts blood flow. Stimulation of mechanical-sensitive pain receptors also contributes to the sensation.

Injuries to bones, tendons, or ligaments stimulate pain receptors that may also contract nearby skeletal muscles. The contracting muscles may become ischemic, which may trigger still other pain receptors within the muscle tissue, further increasing muscular contraction.

Visceral Pain

As a rule, pain receptors are the only receptors in viscera whose stimulation produces sensations. Pain receptors in these organs respond differently to stimulation than those associated with surface tissues. For example, localized damage to intestinal tissue during surgical procedures may not elicit pain sensations, even in a conscious person. However, when visceral tissues are subjected to more widespread stimulation, as when intestinal tissues are stretched or smooth muscles in intestinal walls undergo spasms, a strong pain sensation may follow. Once again, the resulting pain seems to stem from stimulation of mechanoreceptors and from decreased blood flow accompanied by lower tissue oxygen concentration and accumulation of pain-stimulating chemicals via chemoreceptors.

Visceral pain may feel as if it is coming from some part of the body other than the part being stimulated, a phenomenon called **referred pain.** For example, pain originating in the heart may be referred to the left shoulder or left upper limb (fig. 10.2). Referred pain may arise from common nerve pathways that carry sensory impulses from skin areas as well as viscera. For example, pain impulses from the heart travel over the

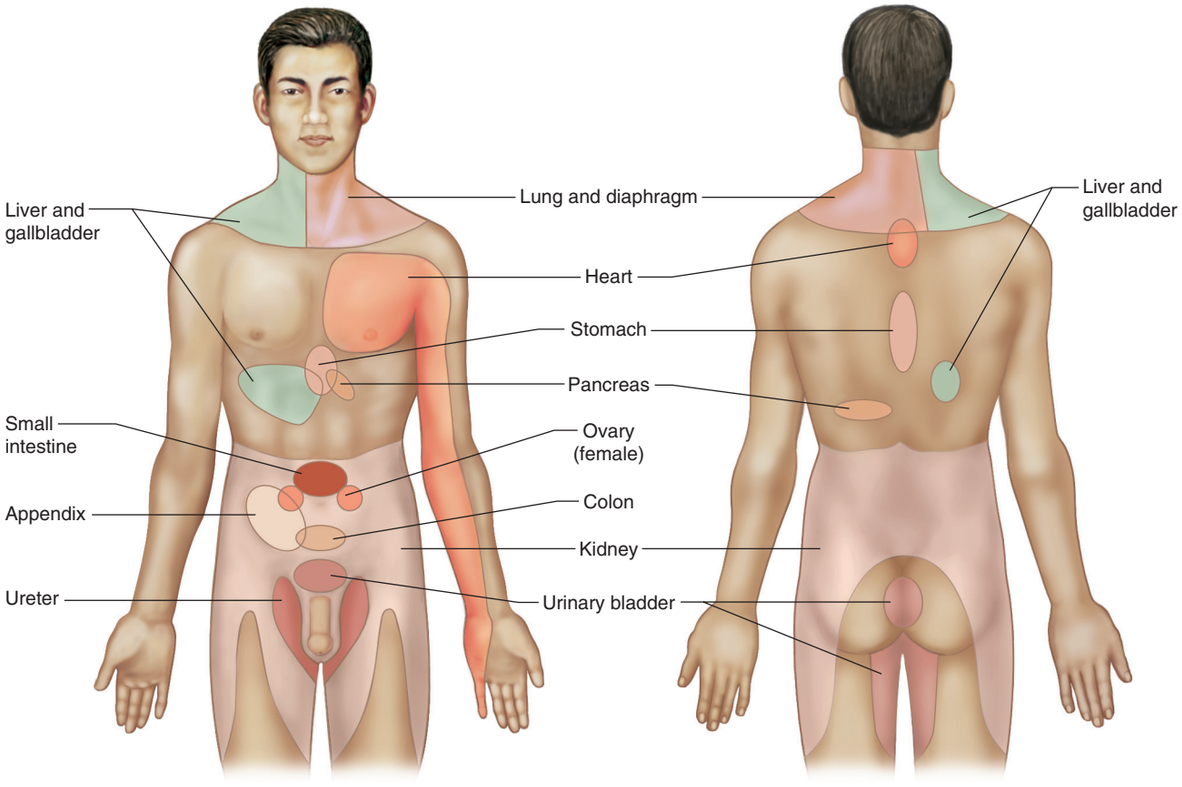


Figure 10.2
Referred pain. Visceral pain may be felt at these surface regions.

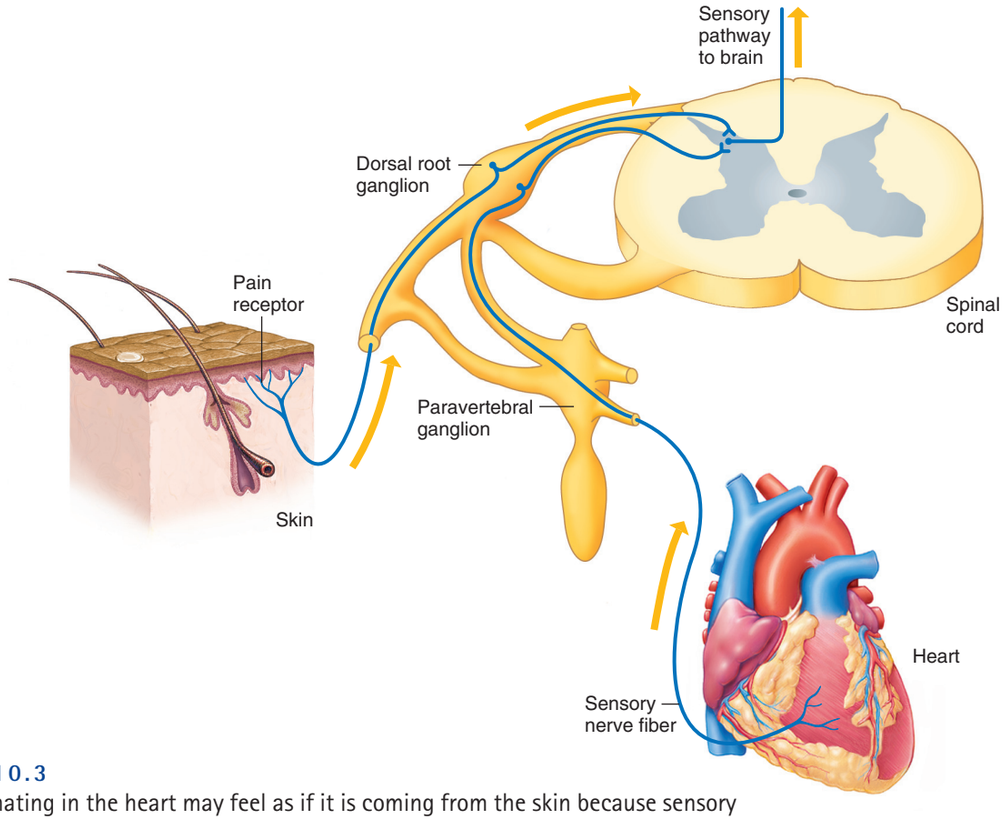


Figure 10.3
Pain originating in the heart may feel as if it is coming from the skin because sensory impulses from the heart and the skin follow common nerve pathways to the brain.

same nerve pathways as those from the skin of the left shoulder and left upper limb (fig. 10.3). Consequently, during a heart attack, the cerebral cortex may incorrectly interpret the source of the pain impulses as the left shoulder or upper limb, rather than the heart.

CHECK YOUR RECALL

1. Describe the three types of touch and pressure receptors.
2. Describe the receptors that sense temperature.
3. What types of stimuli excite pain receptors?
4. What is referred pain?

Pain Nerve Fibers

Nerve fibers that conduct impulses away from pain receptors are of two main types: acute pain fibers and chronic pain fibers. *Acute pain fibers* are relatively thin, myelinated nerve fibers. They conduct nerve impulses rapidly and are associated with the sensation of sharp pain, which typically originates from a restricted area of the skin and seldom continues after the pain-producing stimulus stops. *Chronic pain fibers* are thin, unmyelinated nerve fibers. They conduct impulses more slowly and produce a dull, aching sensation that may be diffuse and difficult to pinpoint. Such pain may continue for some time after the original stimulus ceases. Acute pain is usually sensed as coming only from the skin; chronic pain is felt in deeper tissues as well.

An event that stimulates pain receptors usually triggers impulses on both acute and chronic pain fibers. This causes a dual sensation—a sharp, pricking pain, followed shortly by a dull, aching one. The aching pain is usually more intense and may worsen with time. Chronic pain can cause prolonged suffering.

Pain impulses that originate from the head reach the brain on sensory fibers of cranial nerves. All other pain impulses travel on the sensory fibers of spinal nerves, and they pass into the spinal cord by way of the dorsal roots of these spinal nerves. Within the spinal cord, neurons process pain impulses in the gray matter of the dorsal horn, and the impulses are transmitted to the brain. Here, most pain fibers terminate in the reticular formation (see chapter 9, p. 232). From there, other neurons conduct impulses to the thalamus, hypothalamus, and cerebral cortex.

Regulation of Pain Impulses

Awareness of pain arises when pain impulses reach the thalamus—that is, even before they reach the cerebral

cortex. The cerebral cortex, however, determines pain intensity, locates the pain source, and mediates emotional and motor responses to the pain.

Areas of gray matter in the midbrain, pons, and medulla oblongata regulate movement of pain impulses from the spinal cord. Impulses from special neurons in these brain areas descend in the lateral funiculus (see chapter 9, p. 223) to various levels of the spinal cord. These impulses stimulate the ends of certain nerve fibers to release biochemicals that can block pain signals by inhibiting presynaptic nerve fibers in the posterior horn of the spinal cord.

The inhibiting substances released in the posterior horn include neuropeptides called *enkephalins* and the monoamine *serotonin* (see chapter 9, p. 216). Enkephalins can suppress acute and chronic pain impulses and thus can relieve severe pain, much as morphine and other opiate drugs do. In fact, enkephalins bind to the same receptor sites on neuron membranes as does morphine. Serotonin stimulates other neurons to release enkephalins.

Endorphins are another group of neuropeptides with pain-suppressing, morphinelike actions. Endorphins are found in the pituitary gland and the hypothalamus. Enkephalins and endorphins are released in response to extreme pain and provide natural pain control.

CHECK YOUR RECALL

1. Describe two types of pain fibers.
2. How do acute pain and chronic pain differ?
3. What parts of the brain interpret pain impulses?
4. How do neuropeptides help control pain?

10.4 Special Senses

Special senses are those whose sensory receptors are within large, complex sensory organs in the head. These senses and their respective organs include the following:

- Smell → Olfactory organs
- Taste → Taste buds
- Hearing, Equilibrium → Ears
- Sight → Eyes

10.5 Sense of Smell

The sense of smell is associated with complex sensory structures in the upper region of the nasal cavity.

Olfactory Receptors

Smell (olfactory) receptors and taste receptors are chemoreceptors, which means that chemicals dissolved in liquids stimulate them. Smell and taste function closely together and aid in food selection because we usually smell food at the same time we taste it.

Olfactory Organs

The **olfactory organs,** which contain the olfactory receptors, are yellowish-brown masses of epithelium about the size of postage stamps that cover the upper parts of the nasal cavity, the superior nasal conchae, and a portion of the nasal septum. **Olfactory receptor cells** are bipolar neurons surrounded by columnar epithelial cells (fig. 10.4). Hairlike cilia cover tiny knobs at the distal ends of these neurons' dendrites. The cilia

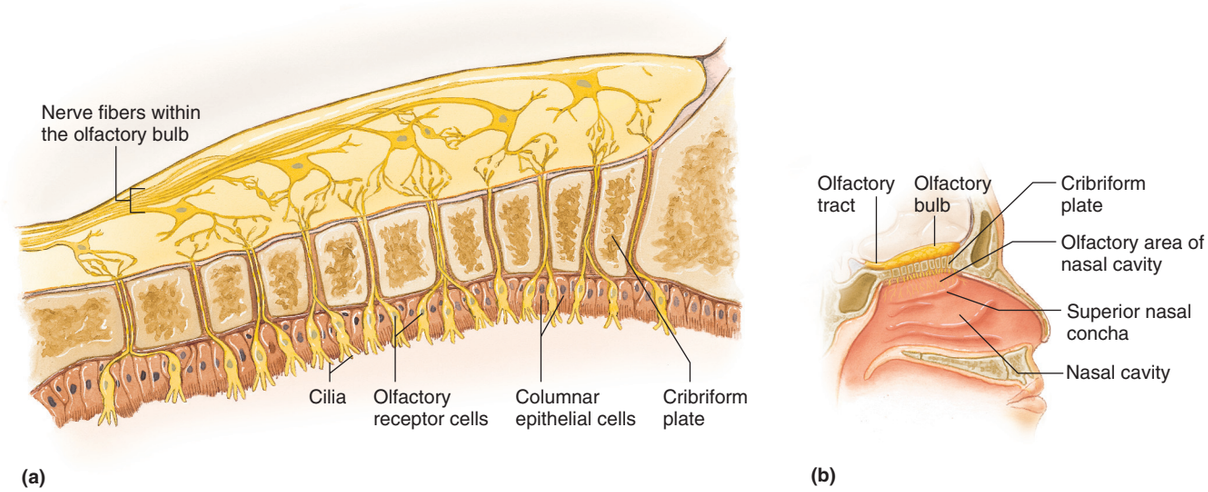


Figure 10.4
Olfactory receptors. (*a*) Columnar epithelial cells support olfactory receptor cells, which have cilia at their distal ends. (*b*) The olfactory area is associated with the superior nasal concha.

Topic of Interest — HEADACHE

Headaches are a common type of pain. Although the nervous tissue of the brain lacks pain receptors, nearly all the other tissues of the head, including the meninges and blood vessels, are richly innervated.

Many headaches are associated with stressful life situations that cause fatigue, emotional tension, anxiety, or frustration. These conditions can trigger various physiological changes, such as prolonged contraction of the skeletal muscles in the forehead, sides of the head, or back of the neck. Such contractions may stimulate pain receptors and produce a *tension headache.* More severe *vascular headaches* accompany constriction or dilation of the cranial blood vessels. For example, the throbbing headache of a "hangover" from drinking too much alcohol may be due to blood pulsating through dilated cranial vessels.

Migraine is another form of vascular headache. In this disorder, certain cranial blood vessels constrict, producing a localized cerebral blood deficiency. This causes a variety of symptoms, such as seeing patterns of bright light that obstruct vision or feeling numbness in the limbs or face. Typically, vasoconstriction subsequently leads to vasodilation of the affected vessels, causing a severe headache, which usually affects one side of the head and may last for several hours. Effective drug treatment is now available for migraines.

Other causes of headaches include sensitivity to food additives, high blood pressure, increased intracranial pressure due to a tumor or to blood escaping from a ruptured vessel, decreased cerebrospinal fluid pressure following a lumbar puncture, or sensitivity to or withdrawal from certain drugs.

project into the nasal cavity and harbor the 400 types of olfactory receptor proteins. Chemicals that stimulate olfactory receptors, called odorant molecules, bind to the receptors in different patterns. Odorant molecules enter the nasal cavity as gases, but they must dissolve at least partially in the watery fluids that surround the cilia before receptors can detect them.

Olfactory Nerve Pathways

Stimulated olfactory receptor cells send nerve impulses along their axons. These fibers (which form the first cranial nerves) synapse with neurons located in enlargements called **olfactory bulbs.** These structures lie on either side of the crista galli of the ethmoid bone (see fig. 7.12, p. 138). Within the olfactory bulbs, the impulses are analyzed, and as a result, additional impulses travel along the **olfactory tracts** to the limbic system (see chapter 9, p. 234). The major interpreting areas for these impulses in the olfactory cortex lie within the temporal lobes and at the bases of the frontal lobes, anterior to the hypothalamus.

Humans smell the world using about 12 million olfactory receptor cells. Bloodhounds have 4 billion such cells—and hence a much better sense of smell. Of the 1,000 or so genes that encode human olfactory receptor proteins, about 600 have mutated into inactivity. In monkeys, apes, dogs, and mice, a much higher proportion of their olfactory receptor genes remain active—and these animals rely more on the sense of smell to identify food than humans do. Evolution has apparently diminished the human sense of smell compared to that of other mammals.

Olfactory Stimulation

When odorant molecules bind to olfactory receptor proteins in olfactory receptor cell membranes, a biochemical pathway is activated that culminates in an influx of sodium ions, which may trigger an action potential if the depolarization reaches threshold. The action potentials from this and other olfactory receptor cells travel to the olfactory bulbs in the brain, where the sensation of smell arises.

A few hundred types of olfactory receptors can detect many thousands of odors when they signal the brain in groups. That is, an odorant molecule stimulates a distinct set of receptor subtypes. Experiments have shown that although an olfactory receptor cell has only one type of olfactory receptor, that receptor can bind several different types of odorant molecules. In addition, any one odorant molecule can bind several different receptors. The brain interprets this binding information as a combinatorial olfactory code. In a simplified example, if there are ten odor receptors, parsley might stimulate receptors 3, 4, and 8, while chocolate might stimulate receptors 1, 5, and 10.

Because the olfactory organs are located high in the nasal cavity above the usual pathway of inhaled air, a person may have to sniff and force air up to the receptor areas to smell a faint odor. The sense of smell adapts rapidly, but adaptation to one scent will not diminish sensitivity to new odors. For example, a person visiting a fish market might at first be acutely aware of the fishy smell, but then that odor seems to fade. But if a second person enters the fish market wearing a strong perfume, that scent will be quite noticeable to the person already present.

Partial or complete loss of smell is called *anosmia*. It may result from a variety of factors, including inflammation of the nasal cavity lining due to a respiratory infection, tobacco smoking, or using certain drugs, such as cocaine.

CHECK YOUR RECALL

1. Where are olfactory receptors located?
2. Trace the pathway of an olfactory impulse from a receptor to the cerebrum.

10.6 Sense of Taste

Taste buds are the special organs of taste (fig. 10.5). The 10,000 or so taste buds are located primarily on the surface of the tongue and are associated with tiny elevations called *papillae*. About 1,000 of the taste buds are scattered in the roof of the mouth and walls of the throat.

Taste Receptors

Each taste bud includes a group of modified epithelial cells, the **taste cells** (gustatory cells), which function as receptors. Each taste bud has 50 to 150 receptor cells, each replaced every three days. The taste bud also includes epithelial supporting cells. The entire structure is somewhat spherical, with an opening, the **taste pore,** on its free surface. Tiny projections called **taste hairs** protrude from the outer ends of the taste cells and extend from the taste pore. These taste hairs are believed to be the sensitive parts of the receptor cells.

Interwoven among the taste cells and wrapped around them is a network of nerve fibers. Stimulation of a receptor cell triggers an impulse on a nearby nerve fiber, and the impulse then travels into the brain.

Cats and dogs may be satisfied with less varied diets than humans because cats have only about 473 taste buds and dogs about 1,700.

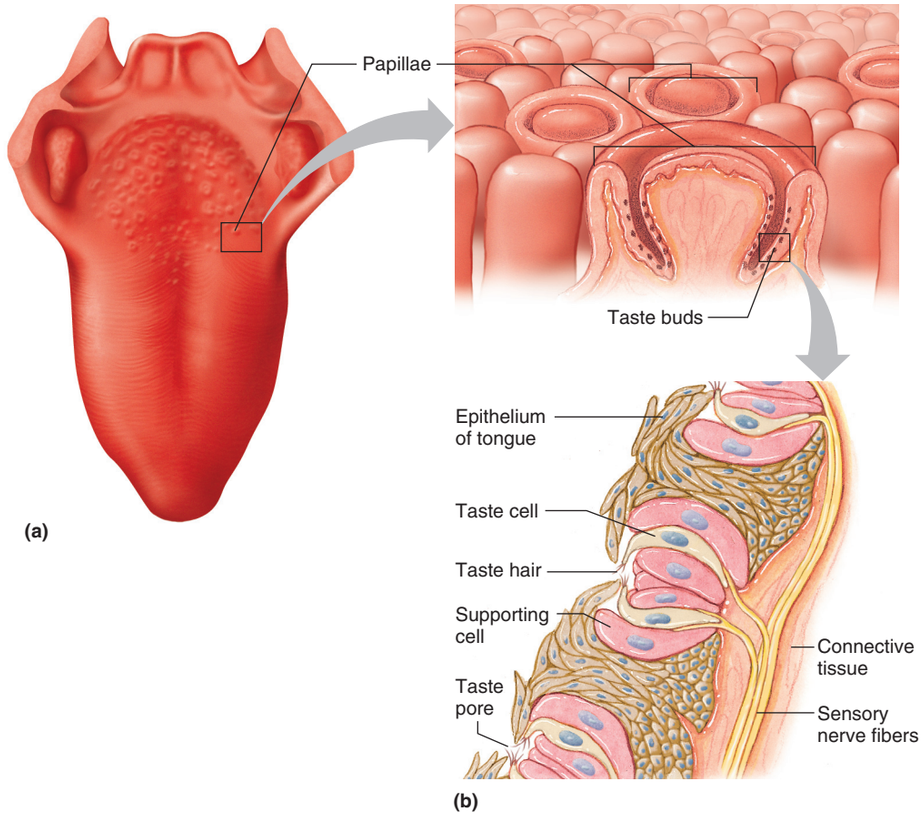


Figure 10.5
Taste receptors. (*a*) Taste buds on the surface of the tongue are associated with nipplelike elevations called papillae. (*b*) A taste bud contains taste cells and has an opening, the taste pore, at its free surface.

Before a particular chemical can be tasted, it must dissolve in the watery fluid surrounding the taste buds. The salivary glands provide this fluid. Food molecules bind to specific receptors embedded in and projecting from taste hairs on the taste cells. The pattern of receptor types that bind food molecules and generate sensory impulses on nearby nerve fibers is interpreted as a particular taste sensation. Therefore, the chemical senses of smell and taste arise from molecules from the environment that bind receptors on neurons specialized as sensory receptors.

The taste cells in all taste buds appear alike microscopically, but are of at least four types. Each type is most sensitive to a particular kind of chemical stimulus, producing at least four primary taste (gustatory) sensations.

Taste Sensations

The four primary taste sensations are:

1. *Sweet,* such as table sugar
2. *Sour,* such as a lemon
3. *Salty,* such as table salt
4. *Bitter,* such as caffeine or quinine

Some investigators recognize other taste sensations—*alkaline, metallic,* and most recently, *umami,* which detects monosodium glutamate (MSG), used as a flavor enhancer in many prepared foods.

A flavor results from one or a combination of the primary sensations. Experiencing flavors involves tasting, which reflects the concentrations of stimulating chemicals, as well as smelling and feeling the texture and temperature of foods. Furthermore, the chemicals in some foods—chili peppers and ginger, for instance—may stimulate pain receptors, which cause a burning sensation. In fact, the chemical in chili peppers that tastes "hot"—capsaicin—actually stimulates heat receptors.

A taste cell can respond to more than one taste sensation, although one taste sensation is likely to predominate. Due to the distribution of taste cells, responsiveness to particular sensations varies from one region of the tongue to another. The tip of the tongue is most sensitive to sweet stimuli, the margins of the tongue most sensitive to sourness, the back of the tongue more likely to detect bitter substances, and responsiveness to salt quite widely distributed. However, because all taste receptor cells sense all of these stimuli to some degree, individual responses vary widely. More importantly, a pattern of these responses from differentially sensitive receptor cells may provide the brain with the information necessary to create what we experience as taste.

Taste sensation, like the sense of smell, undergoes adaptation rapidly. Moving bits of food over the surface of the tongue to stimulate different receptors at different moments keeps us from losing taste due to sensory adaptation.

Taste Nerve Pathways

Sensory impulses from taste receptors in the tongue travel on fibers of the facial, glossopharyngeal, and vagus nerves into the medulla oblongata. From there, the impulses ascend to the thalamus and are directed to the gustatory cortex, which is located in the parietal lobe of the cerebrum, along a deep portion of the lateral sulcus (see fig. 9.26, p. 225).

CHECK YOUR RECALL

1. Why is saliva necessary for the sense of taste?
2. Name the four primary taste sensations.
3. Trace a sensory impulse from a taste receptor to the cerebral cortex.

10.7 Sense of Hearing

The organ of hearing, the ear, has outer, middle, and inner parts. The ear also functions in the sense of equilibrium.

Outer (External) Ear

The outer ear consists of three parts. The first is an outer, funnel-like structure called the **auricle** (pinna). The second is an S-shaped tube called the **external acoustic meatus** (me-a´tus), or external auditory canal, that leads inward through the temporal bone for about 2.5 centimeters (fig. 10.6).

Vibrating objects produce sounds because the vibrations are transmitted through matter in the form of sound waves. For example, vibrating strings or reeds produce the sounds of some musical instruments, and vibrating vocal folds in the larynx produce the voice. The auricle of the ear helps collect sound waves traveling through the air and directs them into the external acoustic meatus. The meatus terminates with the **eardrum** (tympanic membrane).

The eardrum is a semitransparent membrane covered by a thin layer of skin on its outer surface and by mucous membrane on the inside. It has an oval margin and is cone-shaped, with the apex of the cone directed inward. The attachment of one of the auditory ossicles (the malleus) maintains the eardrum's cone shape. Sound waves that enter the external acoustic meatus change the pressure on the eardrum, which moves back and forth in response and thus reproduces the vibrations of the sound wave source.

Middle Ear

The middle ear, or *tympanic cavity,* is an air-filled space in the temporal bone. It contains three small bones

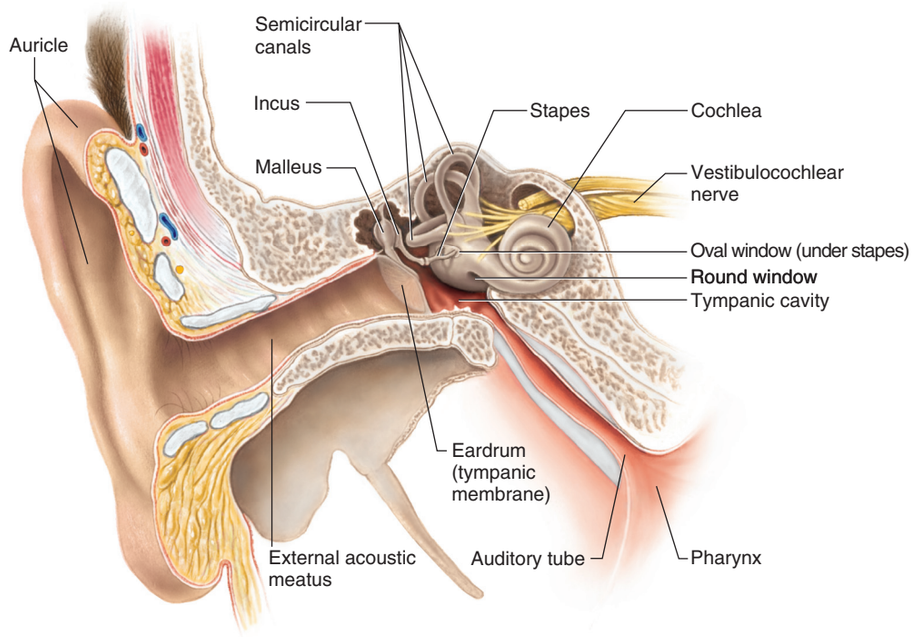


Figure 10.6
Major parts of the ear.

called **auditory ossicles:** the *malleus,* the *incus,* and the *stapes* (fig. 10.7). Tiny ligaments attach them to the wall of the tympanic cavity, and they are covered by mucous membrane. These bones bridge the eardrum and the inner ear, transmitting vibrations between these parts. Specifically, the malleus attaches to the eardrum, and when the eardrum vibrates, the malleus vibrates in unison. The malleus causes the incus to vibrate, and the incus passes the movement on to the stapes. Ligaments hold the stapes to an opening in the wall of the tympanic cavity called the **oval window,** which leads into the inner ear. Vibration of the stapes at the oval window moves a fluid within the inner ear, which stimulates the hearing receptors.

In addition to transmitting vibrations, the auditory ossicles help increase (amplify) the force of vibrations as they pass from the eardrum to the oval window. Because the ossicles transmit vibrations from the relatively large surface of the eardrum to a much smaller area at the oval window, the vibrational force concentrates as it moves from the outer to the inner ear. As a result, the pressure (per square millimeter) that the stapes applies on the oval window is many times greater than the pressure that sound waves exert on the eardrum.

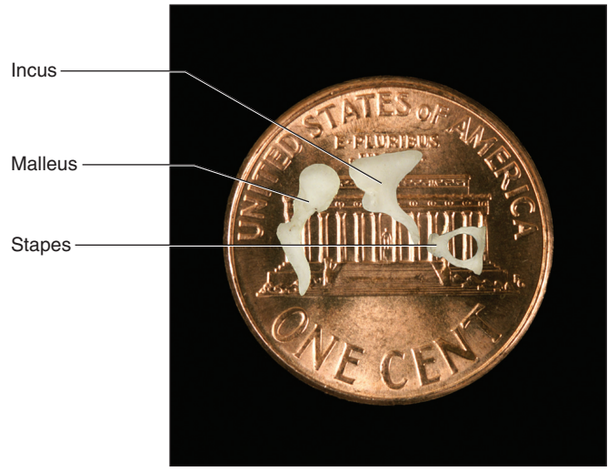


Figure 10.7
Auditory ossicles. The malleus, incus, and stapes are bones that bridge the eardrum and the inner ear (2.5×) (see fig. 10.6).

Auditory Tube

An **auditory tube** (eustachian tube) connects each middle ear to the throat. This tube conducts air between the tympanic cavity and the outside of the body by way of the throat (nasopharynx) and mouth. The auditory tube helps maintain equal air pressure on both sides of the eardrum, which is necessary for normal hearing.

The function of the auditory tube is noticeable during rapid changes in altitude. For example, as a person moves from a high altitude to a lower one, air pressure on the outside of the eardrum increases. This may push the eardrum inward, impairing hearing. When the air pressure difference is great enough, air movement through the auditory tube equalizes the pressure on both sides of the eardrum, and the membrane moves

back into its regular position. This produces a popping sound, which restores normal hearing.

Because auditory tube mucous membranes connect directly with middle ear linings, mucous membrane infections of the throat may spread through these tubes and cause middle ear infection. For this reason, pinching a nostril when blowing the nose is poor practice because the pressure in the nasal cavity may force material from the throat up the auditory tube and into the middle ear.

Inner (Internal) Ear

The inner ear is a complex system of communicating chambers and tubes called a **labyrinth** (lab´i-rinth). Each ear has two parts to the labyrinth—the *osseous labyrinth* and the *membranous labyrinth* (fig. 10.8). The osseous labyrinth is a bony canal in the temporal bone. The membranous labyrinth is a tube that lies within the osseous labyrinth and has a similar shape. Between the osseous and membranous labyrinths is a fluid called *perilymph,* which is secreted by cells in the wall of the bony canal. The membranous labyrinth contains another fluid, called *endolymph.*

The parts of the labyrinths include three **semicircular canals,** which provide a sense of equilibrium (discussed in section 10.8), and a **cochlea** (kok´le-ah), which functions in hearing. The cochlea contains a bony core and a thin, bony shelf that winds around the core like the threads of a screw. The shelf divides the osseous labyrinth of the cochlea into upper and lower compartments. The upper compartment, called the *scala vestibuli,* leads from the oval window to the apex of the spiral. The lower compartment, the *scala tympani,* extends from the apex of the cochlea to a membrane-covered opening in the wall of the inner ear called the **round window** (fig. 10.8).

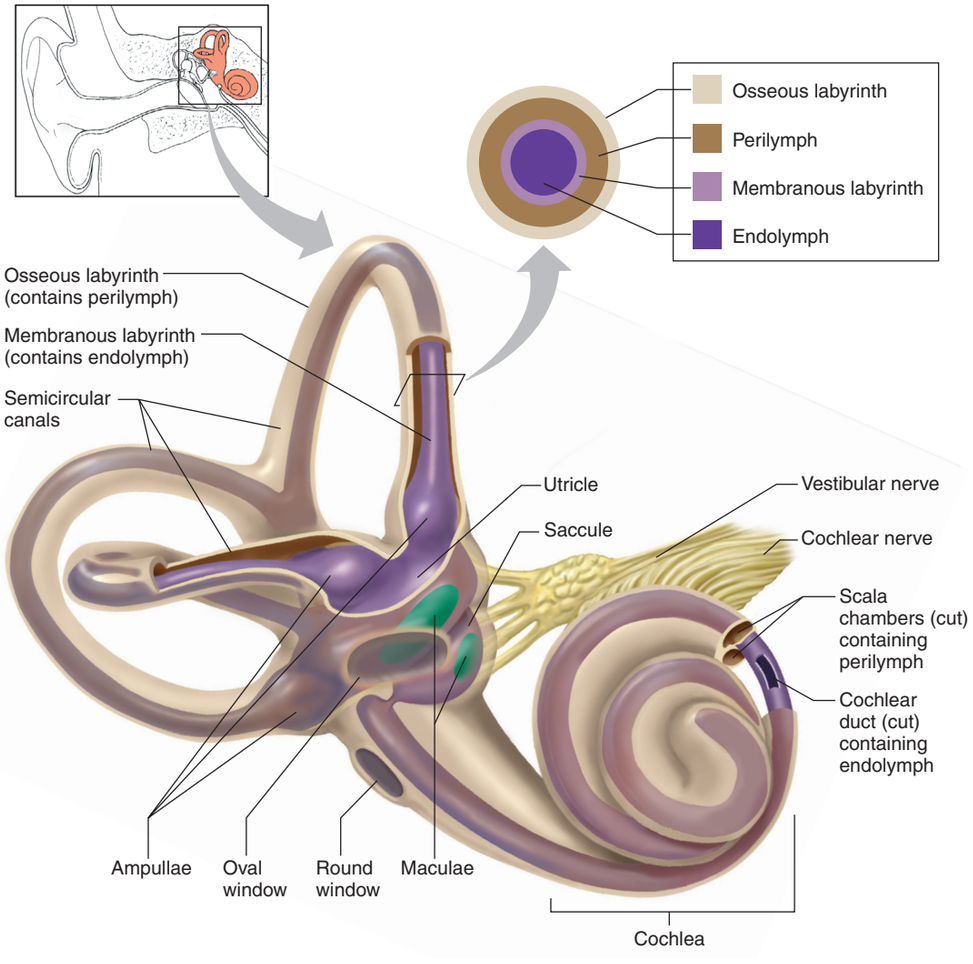


Figure 10.8
Perilymph separates the osseous labyrinth of the inner ear from the membranous labyrinth, which contains endolymph.

The portion of the membranous labyrinth within the cochlea is called the *cochlear duct*. It lies between the two bony compartments and ends as a closed sac at the apex of the cochlea. The cochlear duct is separated from the scala vestibuli by a *vestibular membrane* (Reissner's membrane) and from the scala tympani by a *basilar membrane* (fig. 10.9).

The basilar membrane contains many thousands of stiff, elastic fibers, which lengthen from the base of the cochlea to its apex. Sound vibrations entering the perilymph at the oval window travel along the scala vestibuli and pass through the vestibular membrane and into the endolymph of the cochlear duct, where they move the basilar membrane.

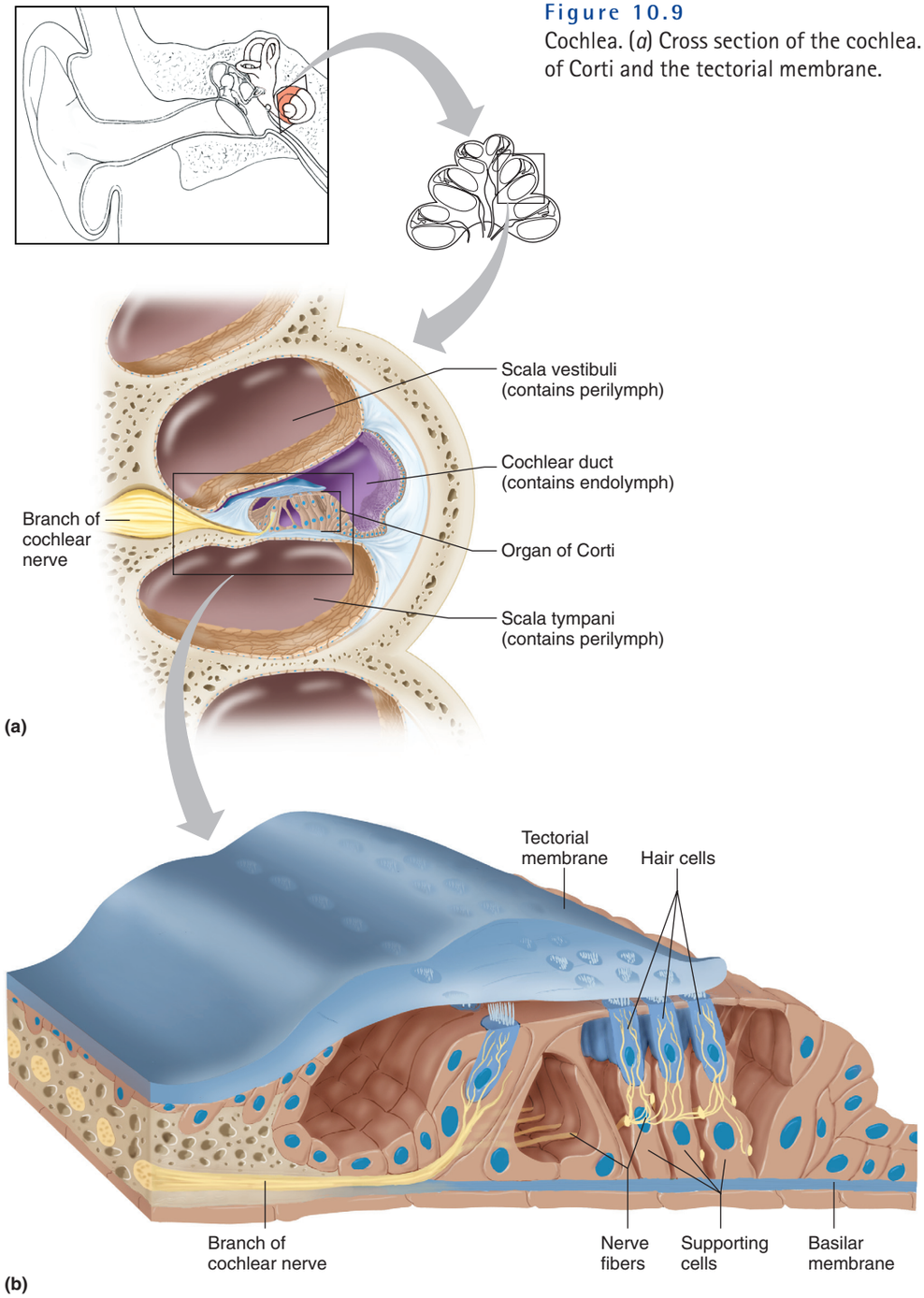


Figure 10.9
Cochlea. (*a*) Cross section of the cochlea. (*b*) Organ of Corti and the tectorial membrane.

After passing through the basilar membrane, the vibrations enter the perilymph of the scala tympani. Movements of the membrane covering the round window dissipate the vibrations into the tympanic cavity.

The **organ of Corti,** which contains the hearing receptors, is located on the upper surface of the basilar membrane and stretches from the apex to the base of the cochlea (fig. 10.9). Its receptor cells, called *hair cells,* are organized in rows and have many hairlike processes that project into the endolymph of the cochlear duct. Above these hair cells is a *tectorial membrane* attached to the bony shelf of the cochlea, passing over the receptor cells and contacting the tips of their hairs.

As sound vibrations pass through the inner ear, the hairs shear back and forth against the tectorial membrane, and the resulting mechanical deformation of the hairs stimulates the hair cells (figs. 10.9 and 10.10). Some of the cells, however, have slightly different sensitivities to deformation. Thus, two frequencies of soundwaves excite different sets of hair cells.

Hair cells are epithelial, but function somewhat like neurons. For example, when a hair cell is at rest, its membrane is polarized. When it is stimulated, selective ion channels open, depolarizing the membrane and making it more permeable to calcium ions. The hair cell has no axon or dendrites, but it has neurotransmitter-containing vesicles near its base. As calcium ions diffuse into the cell, some of these vesicles fuse with the cell membrane and release a neurotransmitter. The neurotransmitter stimulates the ends of nearby sensory nerve fibers, and in response, they transmit impulses along the cochlear branch of the vestibulocochlear nerve to the auditory cortex of the temporal lobe of the brain.

Figure 10.10
Scanning electron micrograph of hair cells in the organ of Corti (3,800×).

The ear of a young person with normal hearing can detect sound waves with frequencies ranging from 20 to 20,000 or more vibrations per second. The range of greatest sensitivity is 2,000-3,000 vibrations per second. Table 10.1 summarizes the steps of hearing.

TABLE 10.1 STEPS IN THE GENERATION OF SENSORY IMPULSES FROM THE EAR

1. Sound waves enter external acoustic meatus.
2. Waves of changing pressures cause eardrum to reproduce vibrations coming from sound wave source.
3. Auditory ossicles amplify and transmit vibrations to end of stapes.
4. Movement of stapes at oval window transmits vibrations to perilymph in scala vestibuli.
5. Vibrations pass through vestibular membrane and enter endolymph of cochlear duct.
6. Different frequencies of vibration in endolymph stimulate different sets of receptor cells.
7. As a receptor cell depolarizes, its membrane becomes more permeable to calcium ions.
8. Inward diffusion of calcium ions causes vesicles at the base of the receptor cell to release neurotransmitter.
9. Neurotransmitter stimulates ends of nearby sensory neurons.
10. Sensory impulses are triggered on fibers of the cochlear branch of vestibulocochlear nerve.
11. Auditory cortex of temporal lobe interprets sensory impulses.

Units called *decibels* (dB) measure sound intensity. The decibel scale begins at 0 dB, which is the intensity of the sound that is least perceptible by a normal human ear. The decibel scale is logarithmic. Thus, a sound of 10 dB is 10 times as intense as the least perceptible sound; a sound of 20 dB is 100 times as intense; and a sound of 30 dB is 1,000 times as intense.

On this scale, a whisper has an intensity of about 40 dB, normal conversation measures 60-70 dB, and heavy traffic or a ringing telephone produces about 80 dB. A sound of 120 dB, common at a rock concert, produces discomfort, and a sound of 140 dB, such as that emitted by a jet plane at takeoff, causes pain. Frequent or prolonged exposure to sounds with intensities above 85 dB can damage hearing receptors and cause permanent hearing loss. Many rock musicians suffer hearing loss due to years of exposure to loud sounds. More common sources of sounds that, if prolonged, damage hearing are boom boxes, car alarms, and leaf blowers.

Auditory Nerve Pathways

The nerve fibers associated with hearing enter the auditory nerve pathways, which pass into the auditory cortices of the temporal lobes of the cerebrum, where they are interpreted. On the way, some of these fibers cross over, so that impulses arising from each ear are interpreted on both sides of the brain. Consequently, damage to a temporal lobe on one side of the brain does not necessarily cause complete hearing loss in the ear on that side.

A variety of factors can cause partial or complete hearing loss, including interference with the transmission of vibrations to the inner ear (*conductive deafness*) or damage to the cochlea, auditory nerve, or auditory nerve pathways (*sensorineural deafness*). Conductive deafness may be due to plugging of the external acoustic meatus or to changes in the eardrum or auditory ossicles. For example, the eardrum may harden as a result of disease and thus be less responsive to sound waves, or disease or injury may tear or perforate the eardrum. Sensorineural deafness can be caused by loud sounds, tumors in the central nervous system, brain damage as a result of vascular accidents, or use of certain drugs.

CHECK YOUR RECALL

1. How are sound waves transmitted through the outer, middle, and inner ears?
2. Distinguish between the osseous and membranous labyrinths.
3. Describe the organ of Corti.

10.8 Sense of Equilibrium

The sense of equilibrium is really two senses—static equilibrium and dynamic equilibrium—that come from different sensory organs. The organs of **static** (stat´ik) **equilibrium** sense the position of the head, maintaining stability and posture when the head and body are still. When the head and body suddenly move or rotate, the organs of **dynamic** (di-nam´ik) **equilibrium** detect such motion and aid in maintaining balance.

Static Equilibrium

The organs of static equilibrium are located within the **vestibule,** a bony chamber between the semicircular canals and the cochlea. The membranous labyrinth inside the vestibule consists of two expanded chambers—a **utricle** and a **saccule** (see fig. 10.8).

Each of these chambers has a tiny structure called a **macula** (mak´u-lah). Maculae contain numerous hair cells, which serve as sensory receptors. When the head is upright, the hairs of the hair cells project upward into a mass of gelatinous material, which has grains of calcium carbonate (otoliths) embedded in it. These particles add weight to the gelatinous structure.

The head bending forward, backward, or to one side stimulates hair cells. Such movements tilt the gelatinous masses of the maculae, and as they sag in response to gravity, the hairs projecting into them bend. This action stimulates the hair cells, and they signal the nerve fibers associated with them in a manner similar to that of hearing receptors. The resulting nerve impulses travel into the central nervous system on the vestibular branch of the vestibulocochlear nerve. These impulses inform the brain of the head's new position. The brain responds by sending motor impulses to skeletal muscles, which contract or relax to maintain balance (fig. 10.11).

Dynamic Equilibrium

The organs of dynamic equilibrium are the three semicircular canals located in the labyrinth. They detect motion of the head and aid in balancing the head and body during sudden movement. These canals lie at right angles to each other, and each corresponds to a different anatomical plane (see fig. 10.8).

Suspended in the perilymph of the osseous portion of each semicircular canal is a membranous canal that ends in a swelling called an **ampulla** (am-pul´lah), which contains the sensory organs of the semicircular canals. Each of these organs, called a **crista ampullaris,** contains a number of sensory hair cells and supporting cells (fig. 10.12). Like the hairs of the maculae, the hair cells extend upward into a dome-shaped, gelatinous mass called the *cupula*.

Rapid turns of the head or body stimulate the hair cells of the crista ampullaris (fig. 10.13). At such times, the semicircular canals move with the head or body, but the fluid inside the membranous canals remains stationary. This bends the cupula in one or more of the canals in a direction opposite that of the head or body movement, and the hairs embedded in it also bend. The stimulated hair cells signal their associated nerve fibers, sending impulses to the brain.

Parts of the cerebellum are particularly important in interpreting impulses from the semicircular canals. Analysis of such information allows the brain to predict the consequences of rapid body movements, and by modifying signals to appropriate skeletal muscles, the cerebellum can maintain balance.

Other sensory structures aid in maintaining equilibrium. For example, certain mechanoreceptors (proprioceptors), particularly those associated with the joints of the neck, inform the brain about the position of body parts. In addition, the eyes detect changes in posture that result from body movements. Such visual information is so important that even if the organs of equilibrium are damaged, a person may be able to maintain normal balance by keeping the eyes open and moving slowly.

The nausea, vomiting, dizziness, and headache of *motion sickness* arise from senses that don't make sense. The eyes of a person reading in a moving car, for example, signal the brain that the person is stationary, because the print doesn't move. However, receptors in the skin detect bouncing, swaying, starting and stopping, as the inner ear detects movement. The contradiction triggers the symptoms. Similarly, in a passenger of an airplane flying through heavy turbulence, skin receptors register the chaos outside, but the eyes focus on the immobile seats and surroundings.

To prevent or lessen the misery of motion sickness, focus on the horizon or an object in the distance ahead. Medications are available by pill (diphenhydramine and meclizine) and, for longer excursions, in a skin patch (scopalamine). Ginger root may ease nausea too—try ginger ale.

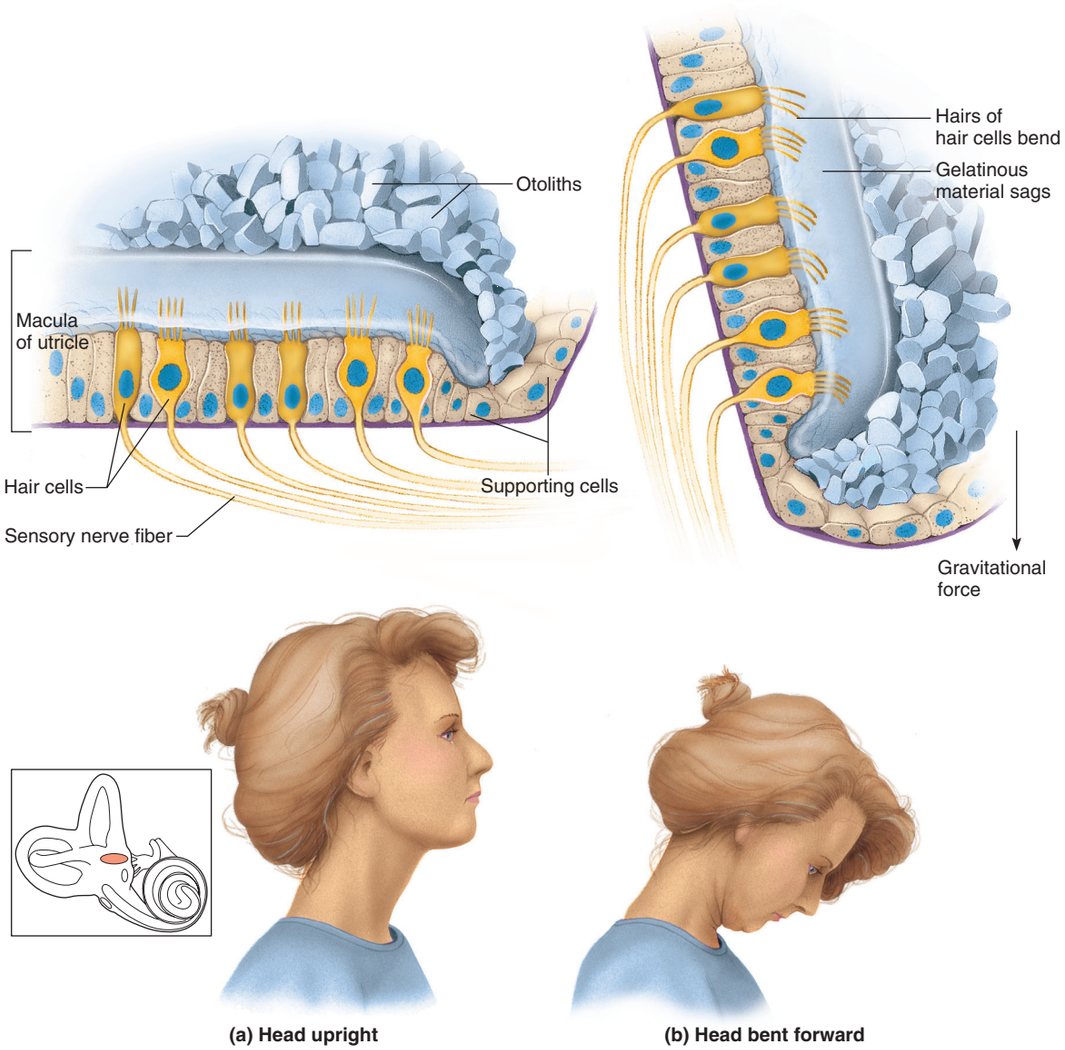


Figure 10.11
The maculae respond to changes in head position. (*a*) Macula of the utricle with the head in an upright position. (*b*) Macula of the utricle with the head bent forward.

CHECK YOUR RECALL

1. Distinguish between static and dynamic equilibrium.
2. Which structures provide the sense of static equilibrium? Of dynamic equilibrium?
3. How does sensory information from other receptors help maintain equilibrium?

10.9 Sense of Sight

The eye, the organ containing visual receptors, provides vision, with the assistance of *accessory organs*. These accessory organs include the eyelids and lacrimal apparatus, which protect the eye, and a set of extrinsic muscles, which move the eye.

Visual Accessory Organs

The eye, lacrimal gland, and associated extrinsic muscles are housed within the pear-shaped orbital cavity, or orbit, of the skull. Each orbit is lined with the periosteum of various bones, and also contains fat, blood vessels, nerves, and connective tissues.

Each **eyelid** has four layers—skin, muscle, connective tissue, and conjunctiva. The skin of the eyelid, which is the thinnest skin of the body, covers the lid's outer surface and fuses with its inner lining near the margin of the lid. The eyelids are moved by the *orbicularis oculi* muscle (see fig. 8.17*a*, p. 186), which acts as a sphincter and closes the lids when it contracts, and by the *levator palpebrae superioris* muscle, which raises the upper lid and thus helps open the eye

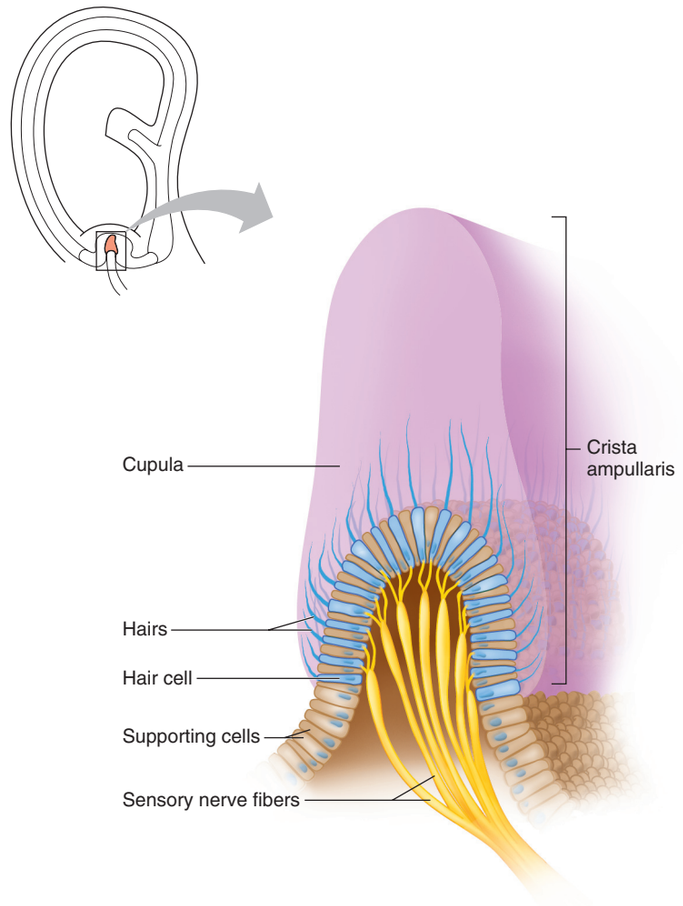


Figure 10.12
A crista ampullaris is located within the ampulla of each semicircular canal.

(fig. 10.14). The **conjunctiva** is a mucous membrane that lines the inner surfaces of the eyelids and folds back to cover the anterior surface of the eyeball, except for its central portion (cornea).

The *lacrimal apparatus* consists of the **lacrimal gland,** which secretes tears, and a series of ducts that carry tears into the nasal cavity (fig. 10.15). The gland is located in the orbit and secretes tears continuously. The tears exit through tiny tubules and flow downward and medially across the eye.

Two small ducts (the superior and inferior canaliculi) collect tears, which flow into the *lacrimal sac,* located in a deep groove of the lacrimal bone, and then into the *nasolacrimal duct,* which empties into the nasal cavity. Secretion by the lacrimal gland moistens and lubricates the surface of the eye and the lining of the lids. Tears also contain an enzyme (*lysozyme*) that is an antibacterial agent, reducing the risk of eye infections.

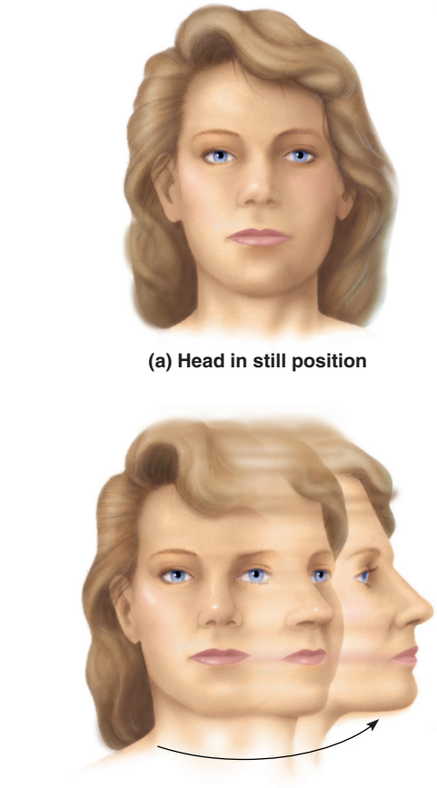


Figure 10.13
Equilibrium. (*a*) When the head is stationary, the cupula of the crista ampullaris remains upright. (*b*) and (*c*) When the head is moving rapidly, the cupula bends opposite the motion of the head, stimulating sensory receptors.

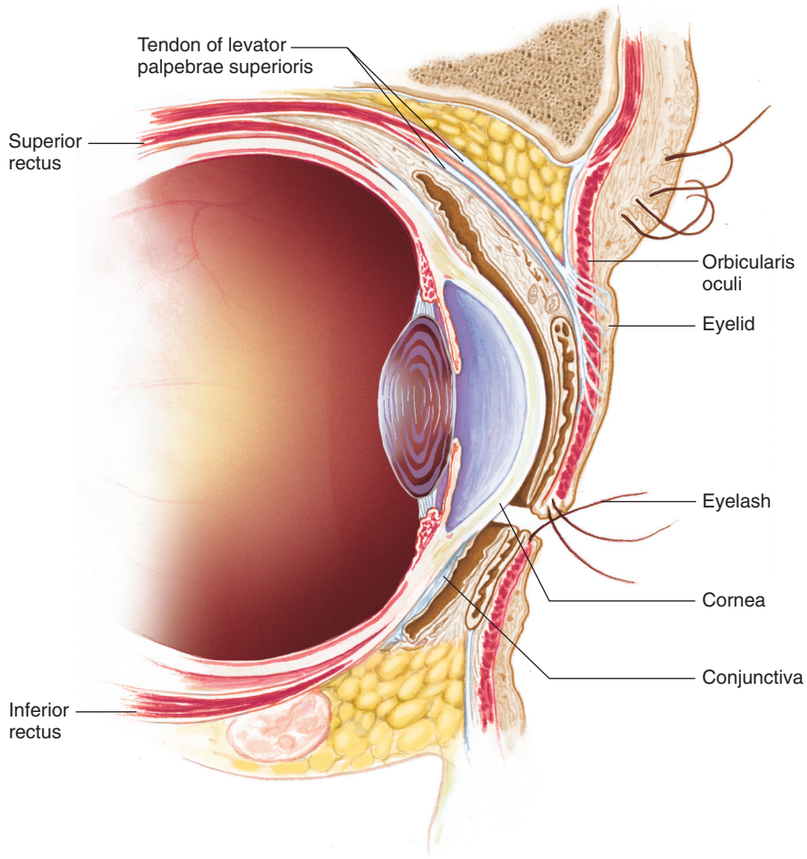


Figure 10.14
Sagittal section of the closed eyelids and anterior portion of the eye.

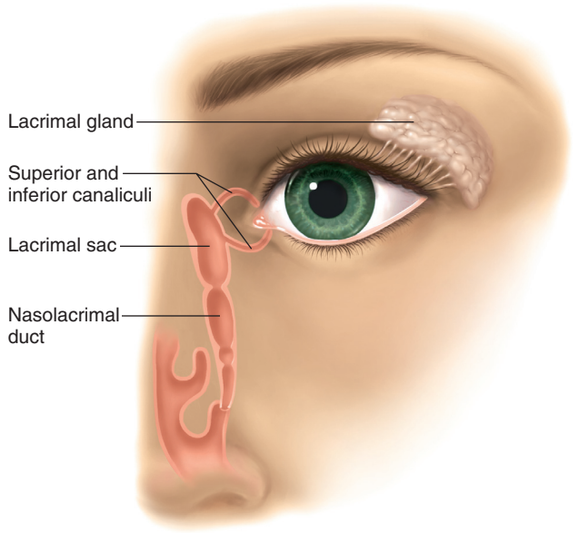


Figure 10.15
The lacrimal apparatus consists of a tear-secreting gland and a series of ducts.

The **extrinsic muscles** arise from the bones of the orbit and insert by broad tendons on the eye's tough outer surface. Six extrinsic muscles move the eye in various directions. Any given eye movement may utilize more than one extrinsic muscle, but each muscle is associated with one primary action. Figure 10.16 illustrates the locations of these extrinsic muscles, and table 10.2 lists their functions, as well as the functions of the eyelid muscles.

One eye deviating from the line of vision may result in double vision (diplopia). If this condition persists, the brain may suppress the image from the deviated eye. As a result, the turning eye may become blind (suppression amblyopia). Treating eye deviation early in life with exercises, eyeglasses, and surgery can prevent such monocular (one eye) blindness.

CHECK YOUR RECALL

1. Explain how the eyelid moves.
2. Describe the conjunctiva.
3. What is the function of the lacrimal apparatus?

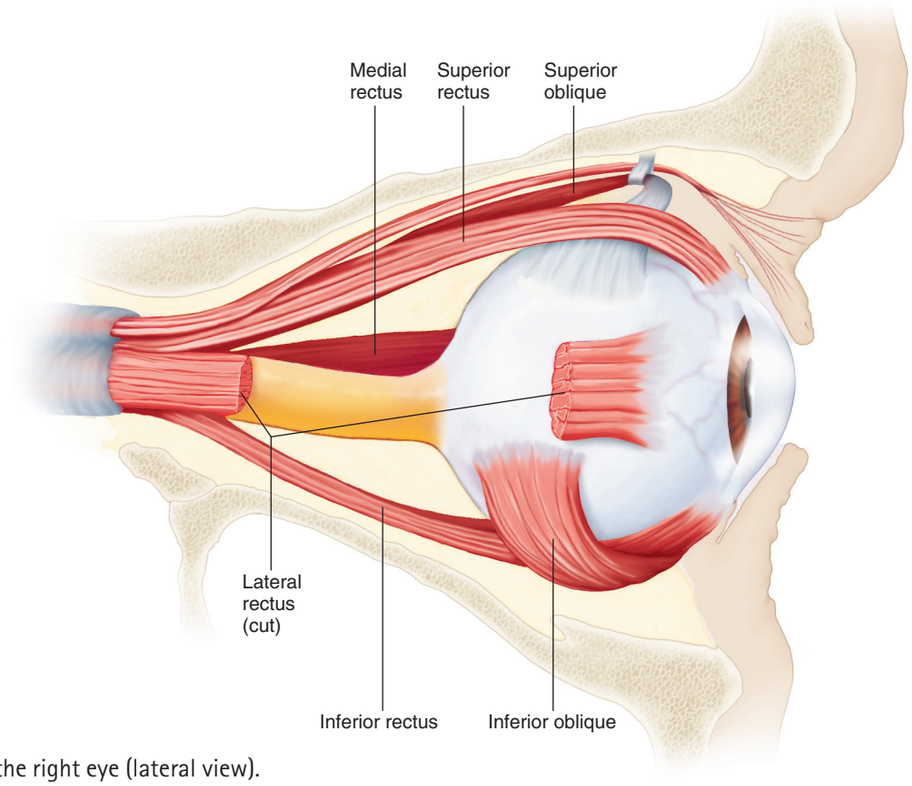


Figure 10.16
Extrinsic muscles of the right eye (lateral view).

TABLE 10.2 MUSCLES ASSOCIATED WITH THE EYELIDS AND EYES

NAME	INNERVATION	FUNCTION
Muscles of the Eyelids		
Orbicularis oculi	Facial nerve (VII)	Closes eye
Levator palpebrae superioris	Oculomotor nerve (III)	Opens eye
Extrinsic Muscles of the Eyes		
Superior rectus	Oculomotor nerve (III)	Rotates eye upward and toward midline
Inferior rectus	Oculomotor nerve (III)	Rotates eye downward and toward midline
Medial rectus	Oculomotor nerve (III)	Rotates eye toward midline
Lateral rectus	Abducens nerve (VI)	Rotates eye away from midline
Superior oblique	Trochlear nerve (IV)	Rotates eye downward and away from midline
Inferior oblique	Oculomotor nerve (III)	Rotates eye upward and away from midline

Structure of the Eye

The eye is a hollow, spherical structure about 2.5 centimeters in diameter. Its wall has three distinct layers—an outer (fibrous) layer, a middle (vascular) layer, and an inner (nervous) layer. The spaces within the eye are filled with fluids that support its wall and internal parts and help maintain its shape. Figure 10.17 shows the major parts of the eye.

Outer Layer

The anterior sixth of the outer layer bulges forward as the transparent **cornea** (kor´ne-ah), which is the window of the eye and helps focus entering light rays. The cornea is composed largely of connective tissue with a thin surface layer of epithelium. It is transparent because it contains few cells and no blood vessels, and the cells and collagenous fibers form unusually regular patterns.

Along its circumference, the cornea is continuous with the **sclera** (skle´rah), the white portion of the eye. The sclera makes up the posterior five-sixths of the outer layer and is opaque due to many large, disorganized, collagenous and elastic fibers. The sclera protects the eye and is an attachment for the extrinsic muscles. In the back of the eye, the **optic nerve** and certain blood vessels pierce the sclera.

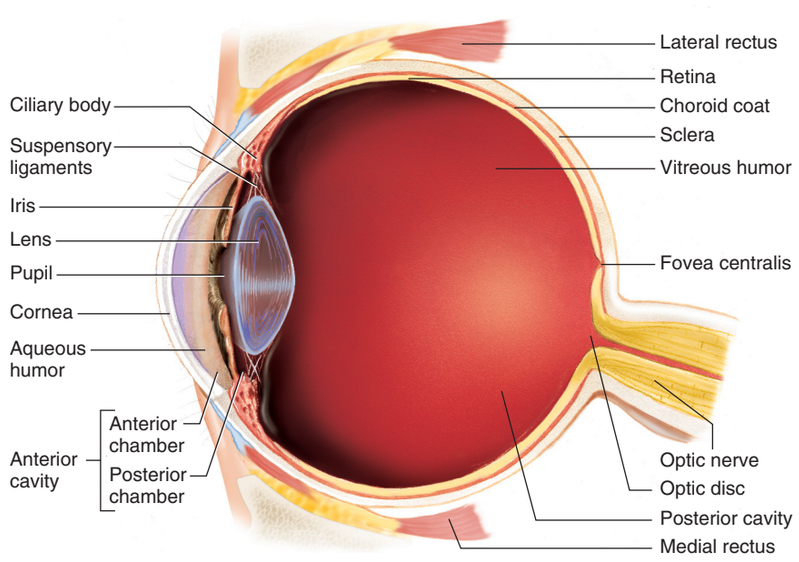


Figure 10.17
Transverse section of the right eye (superior view).

Worldwide, the most common cause of blindness is loss of transparency of the cornea. A corneal transplant (penetrating keratoplasty) can treat this condition by replacing the central two-thirds of the defective cornea with a similar-sized portion of cornea from a donor eye. Because corneal tissues lack blood vessels, transplanted tissue is usually not rejected. The success rate of the procedure is very high.

Middle Layer

The middle layer includes the choroid coat, ciliary body, and iris (fig. 10.17). The **choroid coat,** in the posterior five-sixths of the globe of the eye, is loosely joined to the sclera and is honeycombed with blood vessels, which nourish surrounding tissues. The choroid coat also contains many pigment-producing melanocytes. The melanin that these cells produce absorbs excess light and thus helps keep the inside of the eye dark.

The **ciliary body,** which is the thickest part of the middle layer, extends forward from the choroid coat and forms an internal ring around the front of the eye. Within the ciliary body are many radiating folds called *ciliary processes* and groups of muscle fibers that constitute the *ciliary muscles.*

Many strong but delicate fibers, called *suspensory ligaments,* extend inward from the ciliary processes and hold the transparent **lens** in position (fig. 10.18). The distal ends of these fibers attach along the margin of a thin capsule that surrounds the lens. The body of the lens lies directly behind the iris and pupil and is composed of differentiated epithelial cells called *lens fibers.* The cytoplasm of these cells is the transparent substance of the lens.

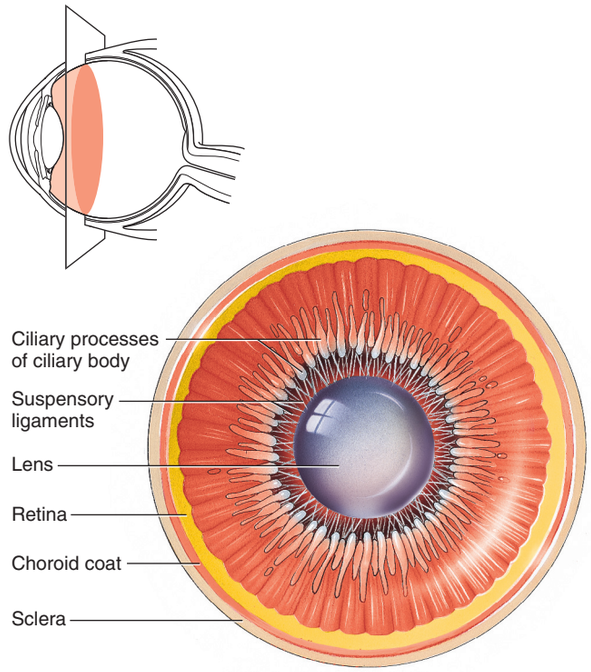


Figure 10.18
Lens and ciliary body viewed from behind.

The ciliary muscles and suspensory ligaments, along with the structure of the lens itself, enable the lens to adjust shape to facilitate focusing, a phenome-

non called **accommodation** (ah-kom´´o-da´shun). The lens is enclosed by a clear capsule composed largely of elastic fibers. This elastic nature keeps the lens under constant tension, and enables it to assume a globular shape. The suspensory ligaments attached to the margin of the capsule are also under tension. When they pull outward, flattening the capsule and the lens inside, the lens focuses on distant objects (fig. 10.19*a*). However, if the tension on the suspensory ligaments relaxes, the elastic lens capsule rebounds, and the lens surface becomes more convex—focused for viewing closer objects (fig. 10.19*b*).

The ciliary muscles control the actions of the suspensory ligaments in accommodation. For example, one set of these muscle fibers extends back from fixed points in the sclera to the choroid coat. When the fibers contract, the choroid coat is pulled forward, and the ciliary body shortens. This relaxes the suspensory ligaments, and the lens thickens in response. When the ciliary muscles relax, tension on the suspensory ligaments increases, and the lens becomes thinner and less convex again.

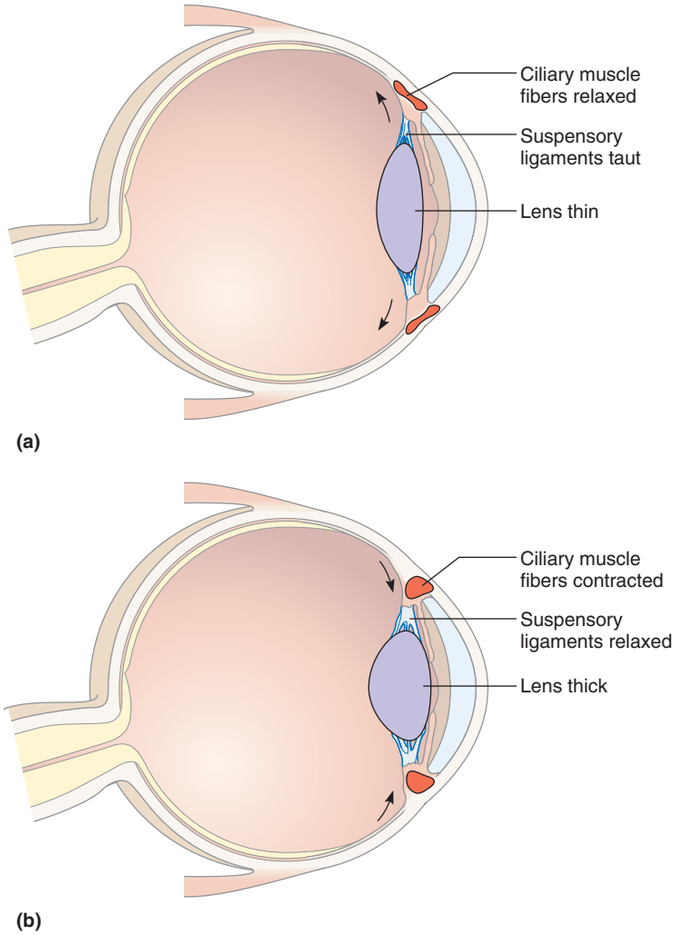


Figure 10.19
Accommodation. (*a*) The lens thins as the ciliary muscle fibers relax. (*b*) The lens thickens as the ciliary muscle fibers contract.

A common eye disorder, particularly in older people, is *cataract.* The lens or its capsule slowly becomes cloudy and opaque. Without treatment, cataracts eventually cause blindness. In the past, cataracts were treated surgically, with a two-week recovery period. Today, cataracts are treated on an outpatient basis with a laser.

CHECK YOUR RECALL

1. Describe the outer and middle layers of the eye.
2. What factors contribute to the transparency of the cornea?
3. How does the shape of the lens change during accommodation?

The **iris** is a thin diaphragm composed mostly of connective tissue and smooth muscle fibers. From the outside, the iris is the colored portion of the eye. The iris extends forward from the periphery of the ciliary body and lies between the cornea and lens (see fig. 10.17). The iris divides the space (anterior cavity) separating these parts into an *anterior chamber* (between the cornea and the iris) and a *posterior chamber* containing the lens (between the iris and the vitreous body).

The epithelium on the inner surface of the ciliary body secretes a watery fluid called **aqueous humor** into the posterior chamber. The fluid circulates from this chamber through the **pupil,** a circular opening in the center of the iris, and into the anterior chamber. Aqueous humor fills the space between the cornea and lens, helps nourish these parts, and aids in maintaining the shape of the front of the eye. It subsequently leaves the anterior chamber through veins and a special drainage canal, the scleral venous sinus (canal of Schlemm) located in its wall at the junction of the cornea and the sclera.

The smooth muscle fibers of the iris are organized into two groups, a *circular set* and a *radial set*. These muscles control the size of the pupil, through which light passes as it enters the eye. The circular set of muscle fibers acts as a sphincter. When it contracts, the pupil gets smaller, and less light enters. Bright light stimulates the circular muscles to contract, which decreases the intensity of light entering the eye. Conversely, when the radial muscle fibers contract, the pupil's diameter increases, and more light enters (fig. 10.20). Dim light stimulates the radial muscles to contract, which dilates the pupil, allowing more light to enter the eye.

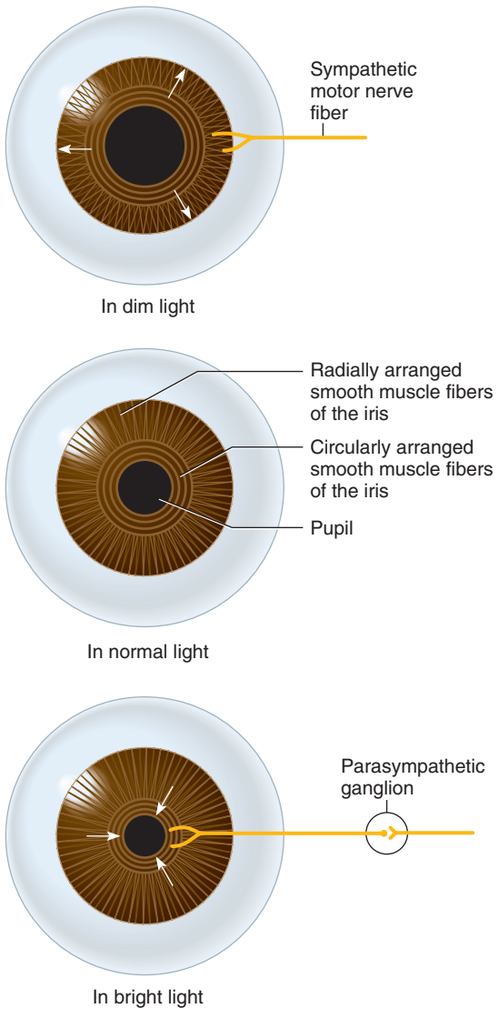


Figure 10.20
Dim light stimulates the radial muscles of the iris to contract, and the pupil dilates. Bright light stimulates the circular muscles of the iris to contract, and the pupil constricts.

An eye disorder called *glaucoma* develops when the rate of aqueous humor formation exceeds the rate of its removal. As fluid accumulates in the anterior chamber of the eye, fluid pressure rises and is transmitted to all parts of the eye. In time, the building pressure squeezes shut blood vessels that supply the receptor cells of the retina. Cells that are robbed of nutrients and oxygen in this way may die, and permanent blindness can result.

When diagnosed early, glaucoma can usually be treated successfully with drugs, laser therapy, or surgery, all of which promote the outflow of aqueous humor. Since glaucoma in its early stages typically produces no symptoms, discovery of the condition usually depends on measuring intraocular pressure, using an instrument called a *tonometer.*

Inner Layer

The inner layer consists of the **retina** (ret˜ĭ-nah), which contains the visual receptor cells (photoreceptors). This nearly transparent sheet of tissue is continuous with the optic nerve in the back of the eye and extends forward as the inner lining of the eyeball. It ends just behind the margin of the ciliary body.

The retina is thin and delicate, but its structure is quite complex. It has a number of distinct layers, as figures 10.21 and 10.22 illustrate.

In the central region of the retina is a yellowish spot called the *macula lutea.* A depression in its center, called the **fovea centralis,** is in the region of the retina that produces the sharpest vision (see figs. 10.17 and 10.23).

The fovea centralis of the human eye has 150,000 cones per square millimeter. In contrast, a bird of prey's eye has about a million cones per square millimeter.

Just medial to the fovea centralis is an area called the **optic disc** (fig. 10.23). Here, nerve fibers from the retina leave the eye and join the optic nerve. A central artery and vein also pass through the optic disc. These vessels are continuous with the capillary networks of the retina, and along with vessels in the underlying choroid coat, they supply blood to the cells of the inner layer. Because the optic disc region lacks receptor cells, it is commonly known as the *blind spot* of the eye.

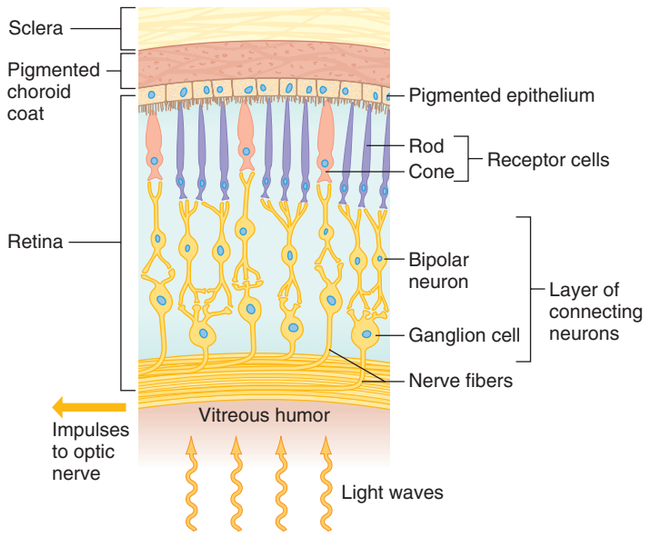


Figure 10.21
The retina consists of several cell layers.

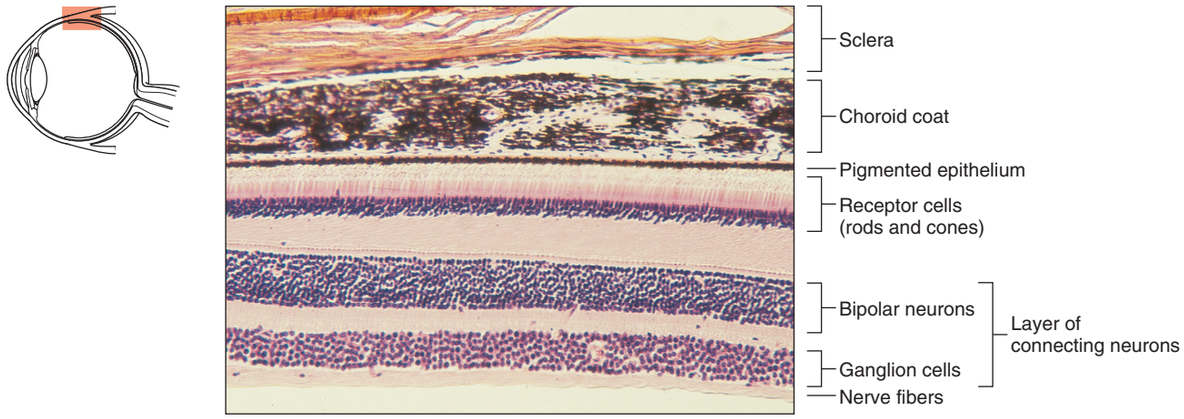
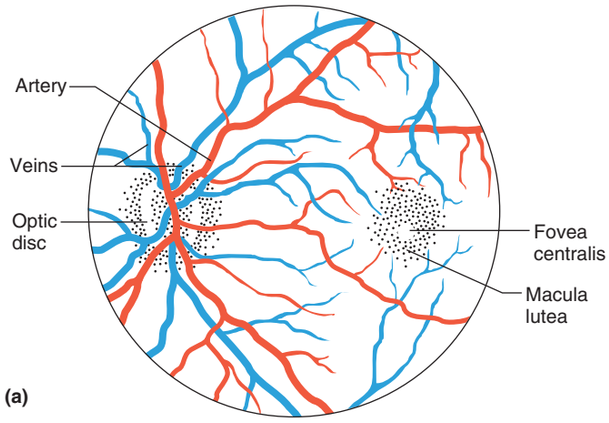
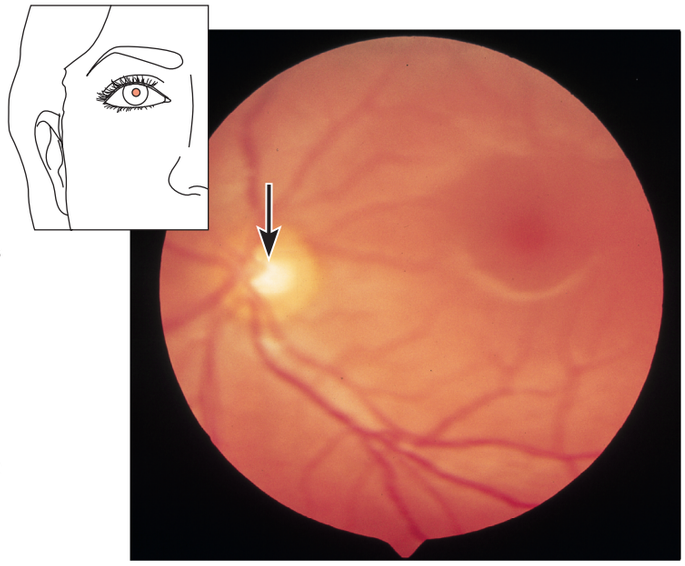


Figure 10.22
Retinal structure. Note the layers of cells and nerve fibers in this light micrograph of the retina (75×).



(a)



(b)

Figure 10.23
Retina. (*a*) Major features of the retina. (*b*) Nerve fibers leave the retina of the eye in the area of the optic disc (arrow) to form the optic nerve in this magnified view of the retina (53×). The fovea centralis can be seen in the upper right portion of the photo as a reddish area.

The space bounded by the lens, ciliary body, and retina is the largest compartment of the eye and is called the *posterior cavity* (see fig. 10.17). It is filled with a transparent, jellylike fluid called **vitreous humor,** which along with collagenous fibers comprises the *vitreous body*. The vitreous body supports the internal parts of the eye and helps maintain its shape.

As a person ages, tiny, dense clumps of gel or deposits of crystal-like substances form in the vitreous humor. When these clumps cast shadows on the retina, the person sees small, moving specks in the field of vision. Such specks, known as *floaters,* are most apparent when looking at a plain background, such as the sky or a wall.

CHECK YOUR RECALL

1. Explain the origin of aqueous humor, and trace its path through the eye.
2. How does light regulate the size of the pupil?
3. Describe the structure of the retina.

Light Refraction

When a person sees something, either the object is giving off light, or light waves are reflected from it. These light waves enter the eye, and an image of the object is focused on the retina. Focusing bends the light waves, a phenomenon called **refraction** (re-frak´shun).

Refraction occurs when light waves pass at an oblique angle from a medium of one optical density into a medium of a different optical density. This occurs at the curved surface between the air and the cornea and at the curved surface of the lens itself. A lens with a *convex* surface (as in the eye) causes light waves to converge (fig. 10.24).

The convex surface of the cornea refracts light waves from outside objects. The convex surface of the lens and, to a lesser extent, the surfaces of the fluids within the chambers of the eye then refract the light again.

If eye shape is normal, light waves focus sharply on the retina, much as a motion picture image is focused on a screen for viewing. Unlike the motion picture image, however, the image that forms on the retina is upside down and reversed from left to right. The visual cortex interprets the image in its proper position.

CHECK YOUR RECALL

1. What is refraction?
2. What parts of the eye provide refracting surfaces?

Visual Receptors

Visual receptor cells are modified neurons of two distinct kinds, as figure 10.21 illustrates. One group, called *rods,* have long, thin projections at their ends, and provide black and white vision. The other group, *cones,* have short, blunt projections, and provide color vision. Rods are of one type, cones of three.

Rods and cones are in a deep portion of the retina, closely associated with a layer of pigmented epithelium (see fig. 10.22). The epithelial pigment absorbs light waves not absorbed by the receptor cells, and together with the pigment of the choroid coat, keeps light from reflecting off surfaces inside the eye. Projections from receptors, which are loaded with light-sensitive visual pigments, extend into this pigmented layer.

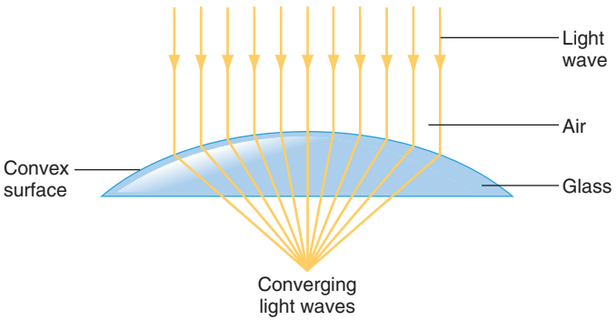


Figure 10.24
A lens with a convex surface causes light waves to converge. The lens of the eye functions the same way.

Visual receptors are stimulated only when light reaches them. A light image focused on an area of the retina stimulates some receptors, and impulses travel from them to the brain. However, the impulse leaving each activated receptor provides only a fragment of the information required for the brain to interpret a complete scene.

Rods and cones provide different aspects of vision. Rods are hundreds of times more sensitive to light than cones and therefore can provide vision in dim light, without color. Cones detect color.

A human eye has 125 million rods and 7 million cones. A cat has three types of cone cells, but sees mostly pastels. A dog has two types of cone cells, and its visual world is much like that of a person with color blindness.

Rods and cones also differ in the sharpness of the perceived images, or visual acuity. Cones provide sharp images, and rods provide more general outlines of objects. Rods give less precise images because nerve fibers from many rods converge, their impulses transmitted to the brain on the same nerve fiber (fig. 10.25*a*). Thus, if a point of light stimulates a rod, the brain cannot tell which one of many receptors has been stimulated. Convergence of impulses is less common among cones. When a cone is stimulated, the brain can pinpoint the stimulation more accurately (fig. 10.25*b*).

The fovea centralis, the area of sharpest vision, lacks rods but contains densely packed cones with few or no converging fibers (see fig. 10.17). Also in the fovea centralis, the overlying layers of the retina and the retinal blood vessels are displaced to the sides, more fully exposing receptors to incoming light. Consequently, to view something in detail, a person moves the eyes so that the important part of an image falls on the fovea centralis.

Visual Pigments

Both rods and cones contain light-sensitive pigments that decompose when they absorb light energy. The light-sensitive biochemical in rods is called **rhodopsin** (ro-dop´sin), or *visual purple*. In the presence of light, rhodopsin molecules are broken down into a colorless protein called *opsin* and a yellowish substance called *retinal* (retinene) that is synthesized from vitamin A.

Poor vision in dim light, called night blindness, results from vitamin A deficiency. Lack of the vitamin reduces the supply of retinal, rhodopsin production falls, and rod sensitivity is low. Supplementing the diet with vitamin A is used to treat night blindness.

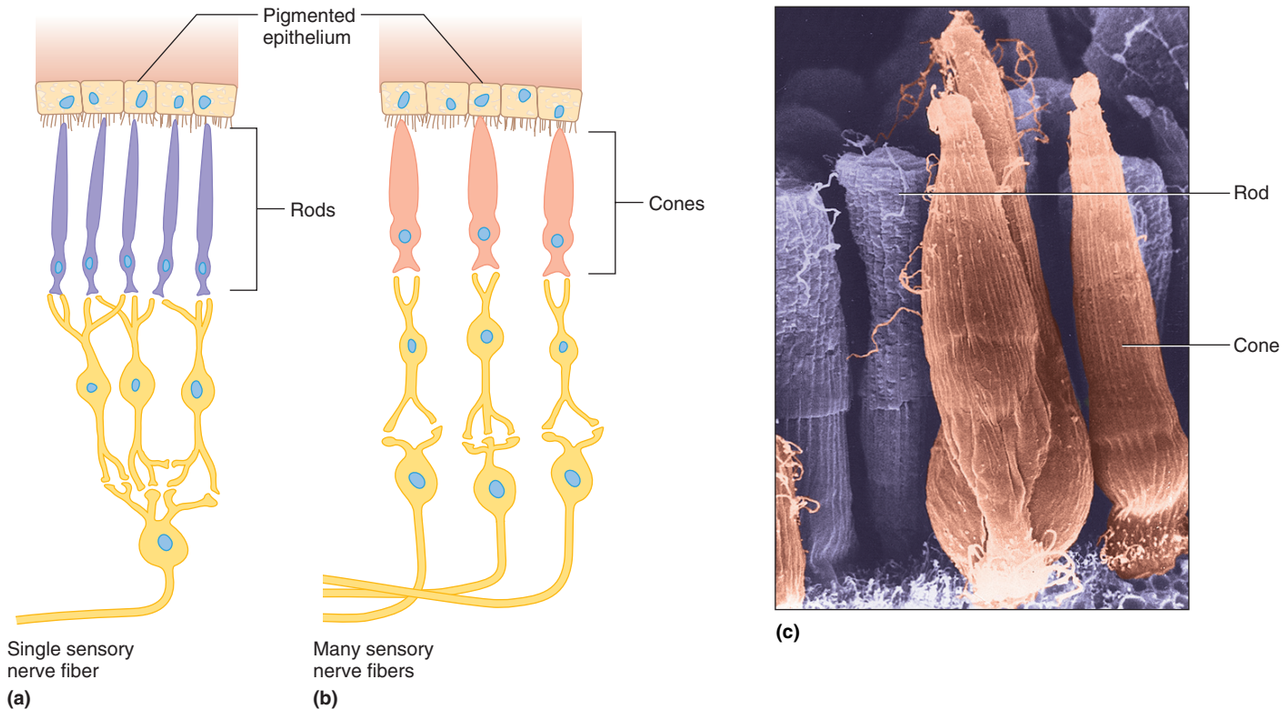


Figure 10.25
Rods and cones. (*a*) A single sensory nerve fiber transmits impulses from several rods to the brain. (*b*) Separate sensory nerve fibers transmit impulses from cones to the brain. (*c*) Scanning electron micrograph of rods and cones (1,350×).

Decomposition of rhodopsin molecules activates an enzyme that initiates a series of reactions altering the permeability of the rod cell membrane. As a result, a complex pattern of nerve impulses originates in the retina. The impulses travel away from the retina along the optic nerve into the brain, where they are interpreted as vision.

In bright light, nearly all of the rhodopsin in the rods of the retina decomposes, greatly reducing rod sensitivity. In dim light, however, regeneration of rhodopsin from opsin and retinal is faster than rhodopsin breakdown. ATP provides the energy required for this regeneration (see chapter 4, p. 78).

As in rods, the light-sensitive pigments in cones are composed of retinal and protein. In cones, however, three different opsin proteins, different from that found in rods, combine with retinal to form the three cone pigments. The three types of cones each contain one of these three visual pigments.

The wavelength of light determines the color that the brain perceives from it. For example, the shortest wavelengths of visible light are perceived as violet, and the longest are perceived as red. One type of cone pigment (erythrolabe) is most sensitive to red light waves, another (chlorolabe) to green light waves, and a third (cyanolabe) to blue light waves. The color a person perceives depends on which set of cones or combination of sets the light in a given image stimulates. If all three sets of cones are stimulated, the person senses the light as white, and if none are stimulated, the person senses black. Different forms of color blindness result from lack of different types of cone pigments.

Visual Nerve Pathways

Visual nerve pathways bring nerve impulses from the retina to the visual cortex, where they are perceived as vision. The pathways begin as the axons of the retinal neurons leave the eyes to form the *optic nerves* (fig. 10.26). Just anterior to the pituitary gland, these nerves give rise to the X-shaped *optic chiasma,* and within the chiasma, some of the fibers cross over. More specifically, the fibers from the nasal (medial) half of each retina cross over, but those from the temporal (lateral) sides do not. Thus, fibers from the nasal half of the left eye and the temporal half of the right eye form the *right optic tract,* and fibers from the nasal half of the right eye and the temporal half of the left eye form the *left optic tract.*

Just before the nerve fibers reach the thalamus, a few of them enter nuclei that function in various visual reflexes. Most of the fibers, however, enter the thalamus and synapse in its posterior portion (lateral geniculate body). From this region, the visual impulses enter nerve

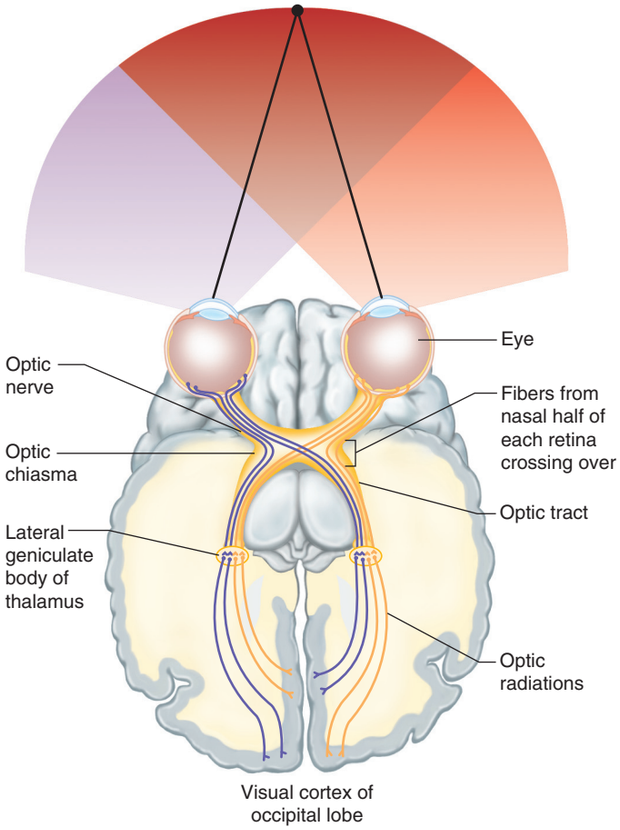


Figure 10.26
A visual pathway includes the optic nerve, optic chiasma, optic tract, and optic radiations.

pathways called *optic radiations,* which lead to the visual cortex of the occipital lobes.

CHECK YOUR RECALL

1. Distinguish between the rods and cones of the retina.
2. Explain the roles of visual pigments.
3. Trace a nerve impulse from the retina to the visual cortex.

Clinical Terms Related to the Senses

amblyopia (am´´ble-o´pe-ah) Dim vision not due to a refractive disorder or lesion.
anopia (an-o´pe-ah) Absence of an eye.
audiometry (aw´´de-om´ĕ-tre) Measurement of auditory acuity for various frequencies of sound waves.
blepharitis (blef´´ah-ri´tis) Inflammation of the eyelid margins.
causalgia (kaw-zal´je-ah) Persistent, burning pain usually associated with injury to a limb.
conjunctivitis (kon-junk´´tĭ-vi´tis) Inflammation of the conjunctiva.
diplopia (dĭ-plo´pe-ah) Double vision.
emmetropia (em´´ĕ-tro´pe-ah) Normal condition of the eyes; eyes with no refractive defects.
enucleation (e-nu´´kle-a´shun) Removal of the eyeball.
exophthalmos (ek´´sof-thal´mos) Abnormal protrusion of the eyes.
hemianopsia (hem´´e-an-op´se-ah) Defective vision affecting half of the visual field.
hyperalgesia (hi´´per-al-je´ze-ah) Heightened sensitivity to pain.
iridectomy (ir´´ĭ-dek´to-me) Surgical removal of part of the iris.
iritis (i-ri´tis) Inflammation of the iris.
keratitis (ker´´ah-ti´tis) Inflammation of the cornea.
labyrinthectomy (lab´´ĭ-rin-thek´to-me) Surgical removal of the labyrinth.
labyrinthitis (lab´´ĭ-rin-thi´tis) Inflammation of the labyrinth.
Ménière's disease (men´´e-ārz´ dĭ-zēz´) Inner ear disorder that causes ringing in the ears, increased sensitivity to sounds, dizziness, and hearing loss.
neuralgia (nu-ral´je-ah) Pain resulting from inflammation of a nerve or a group of nerves.
neuritis (nu-ri´tis) Inflammation of a nerve.
nystagmus (nis-tag´mus) Involuntary oscillation of the eyes.
otitis media (o-ti´tis me´de-ah) Inflammation of the middle ear.
otosclerosis (o´´to-skle-ro´sis) Formation of spongy bone in the inner ear, which often causes deafness by fixing the stapes to the oval window.
pterygium (tĕ-rij´e-um) Abnormally thickened patch of conjunctiva that extends over part of the cornea.
retinitis pigmentosa (ret´´ĭ-ni´tis pig´´men-to´sa) Inherited, progressive retinal sclerosis characterized by pigment deposits in the retina and by retinal atrophy.
retinoblastoma (ret´´ĭ-no-blas-to´mah) Inherited, highly malignant tumor arising from immature retinal cells.
tinnitus (tĭ-ni´tus) Ringing or buzzing noise in the ears.
trachoma (trah-ko´mah) Bacterial disease of the eye that causes conjunctivitis, which may lead to blindness.
tympanoplasty (tim´´pah-no-plas´te) Surgical reconstruction of the middle ear bones and the establishment of continuity from the eardrum to the oval window.
uveitis (u´´ve-i´tis) Inflammation of the uvea, the region of the eye that includes the iris, ciliary body, and choroid coat.
vertigo (ver´tĭ-go) Sensation of dizziness.

Clinical Connection

"The song was full of glittering orange diamonds."
"The paint smelled blue."
"The sunset was salty."
"The pickle tasted like a rectangle."

To 1 in 500,000 people with a condition called synesthesia, sensation and perception mix, so that the brain perceives a stimulus to one sense as coming from another. Most commonly, letters, numbers, or periods of time evoke specific colors. These associations are involuntary, are very specific, and persist over a lifetime. For example, a person might report that 3 is always mustard yellow, or Thursday a very dark brown.

Synesthesia seems to be inherited and is more common in women and among creative individuals, such as artists and writers. One of the authors of this book (R. L.) has it—to her, days and months are specific colors. People have reported the condition to psychologists and physicians for at least 200 years.

PET (positron emission tomography) scanning reveals a physical basis to synesthesia. Brain scans of six nonsynesthetes were compared with those of six synesthetes who associate words with colors. The researchers monitored blood flow in the cerebral cortex while a list of words was read aloud to both groups. While blood flow was increased in word-processing areas for both groups, the scans revealed that areas important in vision and color processing were also lit up in those with synesthesia.

SUMMARY OUTLINE

10.1 Introduction (p. 249)

Sensory receptors sense changes in their surroundings.

10.2 Receptors and Sensations (p. 249)

1. Types of receptors
   a. Each type of receptor is most sensitive to a distinct type of stimulus.
   b. The major types of receptors are chemoreceptors, pain receptors, thermoreceptors, mechanoreceptors, and photoreceptors.
2. Sensations
   a. Sensations are feelings resulting from sensory stimulation.
   b. A particular part of the sensory cortex interprets every impulse reaching it in the same way.
   c. The cerebral cortex projects a sensation back to the region of stimulation.
3. Sensory adaptation
   Sensory adaptation may involve receptors becoming unresponsive or inhibition along the CNS pathways leading to the sensory regions of the cerebral cortex.

10.3 Somatic Senses (p. 249)

Somatic senses are associated with receptors in the skin, muscles, joints, and viscera.

1. Touch and pressure senses
   a. Free ends of sensory nerve fibers are receptors for the sensations of touch and pressure.
   b. Meissner's corpuscles are receptors for the sensation of light touch.
   c. Pacinian corpuscles are receptors for the sensation of heavy pressure.
2. Temperature senses
   Temperature receptors include two sets of free nerve endings that are warm and cold receptors.
3. Sense of pain
   a. Pain receptors are free nerve endings that tissue damage stimulates.
   b. Visceral pain
      (1) Pain receptors are the only receptors in viscera that provide sensations.
      (2) Sensations produced from visceral receptors may feel as if they are coming from some other body part.
      (3) Visceral pain may be referred because sensory impulses from the skin and viscera travel on common nerve pathways.
   c. Pain nerve fibers
      (1) The two main types of pain fibers are acute pain fibers and chronic pain fibers.
      (2) Acute pain fibers conduct nerve impulses rapidly. Chronic pain fibers conduct impulses more slowly.
      (3) Pain impulses are processed in the gray matter of the spinal cord and ascend to the brain.
      (4) Within the brain, pain impulses pass through the reticular formation before being conducted to the cerebral cortex.
   d. Regulation of pain impulses
      (1) Awareness of pain occurs when pain impulses reach the thalamus.
      (2) The cerebral cortex determines pain intensity and locates its source.
      (3) Impulses descending from the brain stimulate neurons to release pain-relieving neuropeptides, such as enkephalins.

10.4 Special Senses (p. 253)

Special senses are those whose receptors are within relatively large, complex sensory organs of the head.

10.5 Sense of Smell (p. 253)

1. Olfactory receptors
   a. Olfactory receptors are chemoreceptors that are stimulated by chemicals dissolved in liquid.
   b. Olfactory receptors function with taste receptors and aid in food selection.
2. Olfactory organs
   a. Olfactory organs consist of receptors and supporting cells in the nasal cavity.
   b. Olfactory receptor cells are bipolar neurons with cilia.
3. Olfactory nerve pathways
   Nerve impulses travel from the olfactory receptor cells through the olfactory nerves, olfactory bulbs, and olfactory tracts to interpreting centers in the temporal and frontal lobes of the cerebrum.
4. Olfactory stimulation
   a. Olfactory impulses may result when odorant molecules bind cell surface olfactory receptors on cilia of receptor cells. The binding pattern encodes a specific odor, which is interpreted in the brain.
   b. The sense of smell adapts rapidly.

10.6 Sense of Taste (p. 255)

1. Taste receptors
   a. Taste buds consist of taste (receptor) cells and supporting cells.
   b. Taste cells have taste hairs.
   c. Taste hair surfaces have receptors to which chemicals bind, stimulating nerve impulses.
2. Taste sensations
   a. The four primary taste sensations are sweet, sour, salty, and bitter.
   b. Various taste sensations result from the stimulation of at least two sets of taste receptors.
3. Taste nerve pathways
   a. Sensory impulses from taste receptors travel on fibers of the facial, glossopharyngeal, and vagus nerves.
   b. These impulses are carried to the medulla oblongata and then ascend to the thalamus, from which they travel to the gustatory cortex in the parietal lobes.

10.7 Sense of Hearing (p. 256)

1. Outer ear
   The outer ear collects sound waves of vibrating objects.
2. Middle ear
   Auditory ossicles of the middle ear conduct sound waves from the eardrum to the oval window of the inner ear.
3. Auditory tube
   Auditory tubes connect the middle ears to the throat and help maintain equal air pressure on both sides of the eardrums.
4. Inner ear
   a. The inner ear is a complex system of connected tubes and chambers—the osseous and membranous labyrinths.
   b. The organ of Corti contains hearing receptors that are stimulated by vibrations in the fluids of the inner ear.
   c. Different frequencies of vibrations stimulate different sets of receptor cells.
5. Auditory nerve pathways
   a. Auditory nerves carry impulses to the auditory cortices of the temporal lobes.
   b. Some auditory nerve fibers cross over, so that impulses arising from each ear are interpreted on both sides of the brain.

10.8 Sense of Equilibrium (p. 261)

1. Static equilibrium
   Static equilibrium maintains the stability of the head and body when they are motionless.
2. Dynamic equilibrium
   a. Dynamic equilibrium balances the head and body when they are moved or rotated suddenly.
   b. Other structures that help maintain equilibrium include the eyes and mechanoreceptors associated with certain joints.

10.9 Sense of Sight (p. 262)

1. Visual accessory organs
   Visual accessory organs include the eyelids, lacrimal apparatus, and extrinsic muscles of the eyes.
2. Structure of the eye
   a. The wall of the eye has an outer (fibrous), a middle (vascular), and an inner (nervous) layer.
      (1) The outer layer is protective, and its transparent anterior portion (cornea) refracts light entering the eye.
      (2) The middle layer is vascular and contains pigments that keep the inside of the eye dark.
      (3) The inner layer contains the visual receptor cells.
   b. The lens is a transparent, elastic structure. Ciliary muscles control its shape.
   c. The lens must thicken to focus on close objects.
   d. The iris is a muscular diaphragm that controls the amount of light entering the eye.
   e. Spaces within the eye are filled with fluids that help maintain its shape.
3. Light refraction
   The cornea and lens refract light waves to focus an image on the retina.
4. Visual receptors
   a. Visual receptors are rods and cones.
   b. Rods are responsible for colorless vision in dim light, and cones provide color vision.
5. Visual pigments
   a. A light-sensitive pigment in rods decomposes in the presence of light and triggers a complex series of reactions that initiate nerve impulses.
   b. Color vision comes from three sets of cones containing different light-sensitive pigments.
6. Visual nerve pathways
   a. Nerve fibers from the retina form the optic nerves.
   b. Some fibers cross over in the optic chiasma.
   c. Most of the fibers enter the thalamus and synapse with others that continue to the visual cortex in the occipital lobes.

REVIEW EXERCISES

1. List five groups of sensory receptors, and name the kind of change to which each is sensitive. (p. 249)
2. Define *sensation.* (p. 249)
3. Explain projection of a sensation. (p. 249)
4. Define *sensory adaptation,* and provide an example. (p. 249)
5. Describe the functions of free nerve endings, Meissner's corpuscles, and Pacinian corpuscles. (p. 250)
6. Define *referred pain,* and provide an example. (p. 251)
7. Explain why pain may be referred. (p. 251)
8. Describe the olfactory organs and their functions. (p. 253)
9. Trace a nerve impulse from an olfactory receptor to the interpreting center of the cerebrum. (p. 254)
10. Explain how salivary glands aid the function of taste receptors. (p. 256)
11. Name the four primary taste sensations. (p. 256)
12. Trace the pathway of a taste impulse from a taste receptor to the cerebral cortex. (p. 256)
13. Distinguish among the outer, middle, and inner ears. (p. 256)
14. Trace the path of a sound wave from the eardrum to the hearing receptors. (p. 256)
15. Describe the functions of the auditory ossicles. (p. 257)
16. Explain the function of the auditory tube. (p. 257)
17. Distinguish between the osseous and membranous labyrinths. (p. 258)
18. Describe the cochlea and its function. (p. 258)
19. Describe a hearing receptor. (p. 260)
20. Explain how a hearing receptor stimulates a sensory neuron. (p. 260)
21. Trace a nerve impulse from the organ of Corti to the interpreting centers of the cerebrum. (p. 260)

22. Describe the organs of static and dynamic equilibrium and their functions. (p. 261)
23. List the visual accessory organs, and describe the functions of each organ. (p. 262)
24. Name the three layers of the eye wall, and describe the functions of each layer. (p. 265)
25. Describe how accommodation is accomplished. (p. 267)
26. Explain how the iris functions. (p. 267)
27. Distinguish between the aqueous humor and the vitreous humor. (p. 267)
28. Distinguish between the fovea centralis and the optic disc. (p. 268)
29. Explain how light waves are focused on the retina. (p. 269)
30. Distinguish between rods and cones. (p. 270)
31. Explain why cone vision is generally more acute than rod vision. (p. 270)
32. Describe the function of rhodopsin. (p. 270)
33. Describe the relationship between light wavelengths and color vision. (p. 271)
34. Trace a nerve impulse from the retina to the visual cortex. (p. 271)

CRITICAL THINKING

1. Loss of the sense of smell often precedes the major symptoms of Alzheimer disease and Parkinson disease. What additional information is needed to use this association to prevent or treat these diseases?
2. Why is dietary vitamin A good for eyesight?
3. PET (positron emission tomography) scans of the brains of people who have been blind since birth reveal high neural activity in the visual centers of the cerebral cortex when these people read Braille. However, when sighted individuals run their fingers over the raised letters of Braille, the visual centers do not show increased activity. Explain these experimental results.
4. People who are deaf due to cochlear damage do not suffer from motion sickness. Why not?
5. We have relatively few sensory systems. How, then, do we experience such a huge and diverse number of sensory perceptions?
6. We humans love sucrose (table sugar), but armadillos, hedgehogs, lions, and seagulls do not respond to it. Opossums love lactose (milk sugar), but rats avoid it. Chickens hate the sugar xylose, while cattle love it, and humans are indifferent. In what way might these diverse tastes in the animal kingdom help an organism survive?
7. Why are astronauts unable to taste their food while eating in zero-gravity conditions?
8. Why does a fish market at first seem to have a strong odor that in time becomes less offensive?
9. Why are some serious injuries, such as a bullet entering the abdomen, relatively painless, but others, such as a burn, considerably more painful?
10. Labyrinthitis is an inflammation of the inner ear. What symptoms would you expect in a patient with this disorder?
11. A patient with heart disease experiences pain at the base of the neck and in the left shoulder and upper limb during exercise. How would you explain the probable origin of this pain to the patient?

WEB CONNECTIONS

Visit the website for additional study questions and more information about this chapter at:

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