Module 20

Hearing


Leland Bobbé/CORBIS

Module Learning Objectives

20-1 Describe the characteristics of air pressure waves, and explain the process by which the ear transforms sound energy into neural messages.

20-2 Discuss the theories that help us understand pitch perception.

20-3 Describe how we locate sounds.

20-1 What are the characteristics of air pressure waves that we hear as sound, and how does the ear transform sound energy into neural messages?

Like our other senses, our **audition,** or hearing, is highly adaptive. We hear a wide range of sounds, but the ones we hear best are those sounds with frequencies in a range corresponding to that of the human voice. Those with normal hearing are acutely sensitive to faint sounds, an obvious boon for our ancestors' survival when hunting or being hunted, or for detecting a child's whimper. (If our ears were much more sensitive, we would hear a constant hiss from the movement of air molecules.)

audition the sense or act of hearing.

We are also remarkably attuned to variations in sounds. We easily detect differences among thousands of possible human voices: Walking between classes, we immediately recognize the voice of a friend behind us. A fraction of a second after a spoken word stimulates the ear's receptors, millions of neurons have simultaneously coordinated in extracting the essential features, comparing them with past experience, and identifying the stimulus (Freeman, 1991).

AP® Exam Tip

Pay attention to how many pages are devoted to each of the senses. Not only does this represent the complexity of the sensory system, it also represents how likely you are to find questions about that system on the AP® exam. More pages are devoted to vision than hearing, and vision questions are somewhat more likely to appear on the exam.

But not everyone has this ability. Some years ago, on a visit to my childhood home, I communicated with my then 80-year-old mother by writing on her erasable "magic pad." Four years earlier she had transitioned from hearing loss to complete deafness by giving up her now useless hearing aids.

"Do you hear anything?" I wrote.

"No," she answered, her voice still strong although she could not hear it. "Last night your Dad came in and found the TV blasting. Someone had left the volume way up; I didn't hear a thing." (Indeed, my father later explained, he recently tested her by sneaking up while she was reading and giving a loud clap just behind her ear. Her eye never wavered from the page.)

What is it like, I wondered. "A silent world?"

"Yes," she replied. "It's a silent world."

And for her, with human connections made difficult, it became a socially isolated world. "Not having understood what was said in a group," she reminisced, "I would chime in and say the same thing someone else had just said—and everyone would laugh. I would be so embarrassed, I wanted to fall through the floor." Increasingly, her way of coping was to avoid getting out onto the floor in the first place. She shied away from public events and found excuses to avoid people who didn't understand.

Our exchange left me wondering: Will I—having inherited her progressive hearing loss—also become socially isolated? Or, aided by today's better technology, can I keep my private vow not to repeat her past? Hearing allows mind-to-mind communication and enables connection. Yet many of us can and do connect despite hearing loss—with help from technology, lip-reading, and signing. For me, it's worth the effort. Communicating with others affirms our humanity as social creatures.

So, how does hearing normally work? How do we harvest meaning from the air pressure waves sent from another's mouth?

The Stimulus Input: Sound Waves


Dennis MacDonald/Photo Edit

The sounds of music A violin's short, fast waves create a high pitch, a cello's longer, slower waves a lower pitch. Differences in the waves' height, or amplitude, also create differing degrees of loudness. (To review the physical properties of light and sound waves, see Figure 18.2 in Module 18.)

Draw a bow across a violin, and you will unleash the energy of sound waves. Jostling molecules of air, each bumping into the next, create waves of compressed and expanded air, like the ripples on a pond circling out from a tossed stone. As we swim in our ocean of moving air molecules, our ears detect these brief air pressure changes. (Exposed to a loud, low bass sound—perhaps from a bass guitar or a cello—we can also *feel* the vibration. We hear by both air and bone conduction.)

Like light waves, sound waves vary in shape. The *amplitude* of sound waves determines their *loudness.* Their length, or **frequency,** determines the **pitch** we experience. Long waves have low frequency—and low pitch. Short waves have high frequency—and high pitch. Sound waves produced by a violin are much shorter and faster than those produced by a cello or a bass guitar.

AP® Exam Tip

Note that both light and sound travel in waves. In each case, the amplitude and length of the waves are important.

We measure sounds in *decibels,* with zero decibels representing the absolute threshold for hearing. Every 10 decibels correspond to a tenfold increase in sound intensity. Thus, normal conversation (60 decibels) is 10,000 times more intense than a 20-decibel whisper. And a temporarily tolerable 100-decibel passing subway train is 10 billion times more intense than the faintest detectable sound.

The Ear

The intricate process that transforms vibrating air into nerve impulses, which our brain decodes as sounds, begins when sound waves enter the outer ear. A mechanical chain reaction begins as the visible *outer ear* channels the waves through the auditory canal to the *eardrum,* a tight membrane, causing it to vibrate (**FIGURE 20.1** on the next page). In the **middle ear** three tiny bones (the *hammer, anvil,* and *stirrup*) pick up the vibrations and transmit them to the **cochlea,** a snail-shaped tube in the **inner ear.** The incoming vibrations cause the cochlea's membrane (the *oval window*) to vibrate, jostling the fluid that fills the tube. This motion causes ripples in the *basilar membrane,* bending the *hair cells* lining its surface, not unlike the wind bending a wheat field. Hair cell movement triggers impulses in the adjacent nerve cells. Axons of those cells converge to form the *auditory nerve,* which sends neural messages (via the thalamus) to the *auditory cortex* in the brain's temporal lobe. From vibrating air to fluid waves to electrical impulses to the brain: Voila! We hear.

frequency the number of complete wavelengths that pass a point in a given time (for example, per second).

pitch a tone's experienced highness or lowness; depends on frequency.

middle ear the chamber between the eardrum and cochlea containing three tiny bones (hammer, anvil, and stirrup) that concentrate the vibrations of the eardrum on the cochlea's oval window.

cochlea [KOHK-lee-uh] a coiled, bony, fluid-filled tube in the inner ear; sound waves traveling through the cochlear fluid trigger nerve impulses.

inner ear the innermost part of the ear, containing the cochlea, semicircular canals, and vestibular sacs.

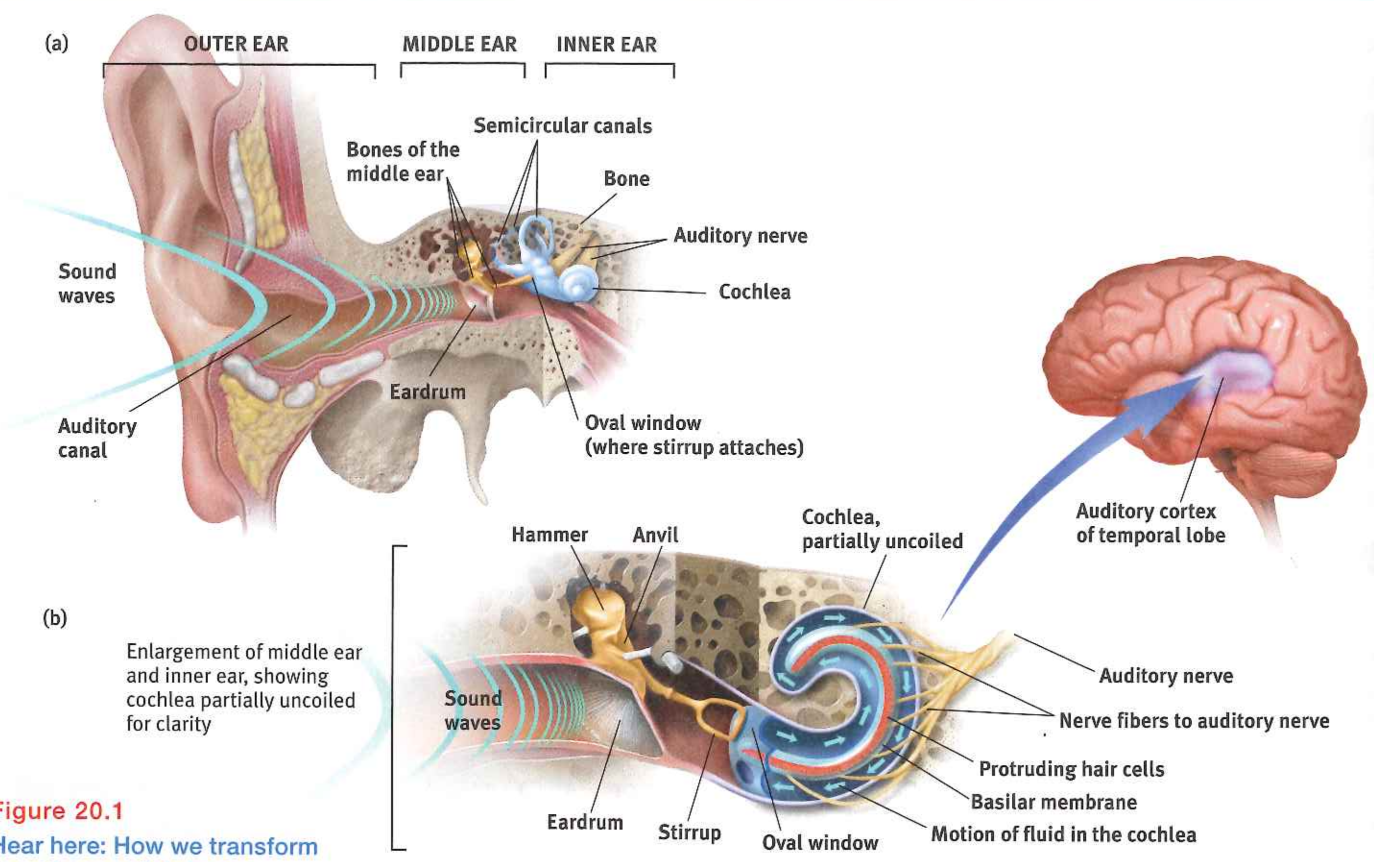


Figure 20.1
Hear here: How we transform sound waves into nerve impulses that our brain interprets (a) The outer ear funnels sound waves to the eardrum. The bones of the middle ear (hammer, anvil, and stirrup) amplify and relay the eardrum's vibrations through the oval window into the fluid-filled cochlea. (b) As shown in this detail of the middle and inner ear, the resulting pressure changes in the cochlear fluid cause the basilar membrane to ripple, bending the hair cells on its surface. Hair cell movements trigger impulses at the base of the nerve cells, whose fibers converge to form the auditory nerve. That nerve sends neural messages to the thalamus and on to the auditory cortex.

My vote for the most intriguing part of the hearing process is the hair cells—"quivering bundles that let us hear" thanks to their "extreme sensitivity and extreme speed" (Goldberg, 2007). A cochlea has 16,000 of them, which sounds like a lot until we compare that with an eye's 130 million or so photoreceptors. But consider their responsiveness. Deflect the tiny bundles of *cilia* on the tip of a hair cell by the width of an atom—the equivalent of displacing the top of the Eiffel Tower by half an inch—and the alert hair cell, thanks to a special protein at its tip, triggers a neural response (Corey et al., 2004).

Susumu Nishinaga/Science Source

Be kind to your inner ear's hair cells When vibrating in response to sound, the hair cells shown here lining the cochlea produce an electrical signal.

Damage to the cochlea's hair cell receptors or their associated nerves can cause **sensorineural hearing loss** (or nerve deafness). (A less common form of hearing loss is **conduction hearing loss,** caused by damage to the mechanical system that conducts sound waves to the cochlea.) Occasionally, disease causes sensorineural hearing loss, but more often the culprits are biological changes linked with heredity, aging, and prolonged exposure to ear-splitting noise or music.

Hair cells have been likened to carpet fibers. Walk around on them and they will spring back with a quick vacuuming. But leave a heavy piece of furniture on them for a long time and they may never rebound. As a general rule, if we cannot talk over a noise, it is potentially harmful, especially if prolonged and repeated (Roesser, 1998). Such experiences are common when sound exceeds 100 decibels, as happens in venues from frenzied sports arenas to bagpipe bands to personal music coming through our earphones near maximum volume (**FIGURE 20.2**). Ringing of the ears after exposure to loud machinery or music indicates that we have been bad to our unhappy hair cells. As pain alerts us to possible bodily harm, ringing of the ears alerts us to possible hearing damage. It is hearing's equivalent of bleeding.

The rate of teen hearing loss, now 1 in 5, has risen by one-third since the early 1990s (Shargorodsky et al., 2010). Teen boys more than teen girls or adults blast themselves with loud volumes for long periods (Zogby, 2006). Males' greater noise exposure may help explain why men's hearing tends to be less acute than women's. But male or female, those who spend many hours in a loud nightclub, behind a power mower, or above a jackhammer should wear earplugs. "Condoms or, safer yet, abstinence," say sex educators. "Earplugs or walk away," say hearing educators.

sensorineural hearing loss hearing loss caused by damage to the cochlea's receptor cells or to the auditory nerves; also called *nerve deafness.*

conduction hearing loss hearing loss caused by damage to the mechanical system that conducts sound waves to the cochlea.

AP Photo/Mark J. Terrill

That Baylen may hear When Super Bowl-winning quarterback Drew Brees celebrated New Orleans' 2010 victory amid pandemonium, he used ear muffs to protect the vulnerable hair cells of his son, Baylen.

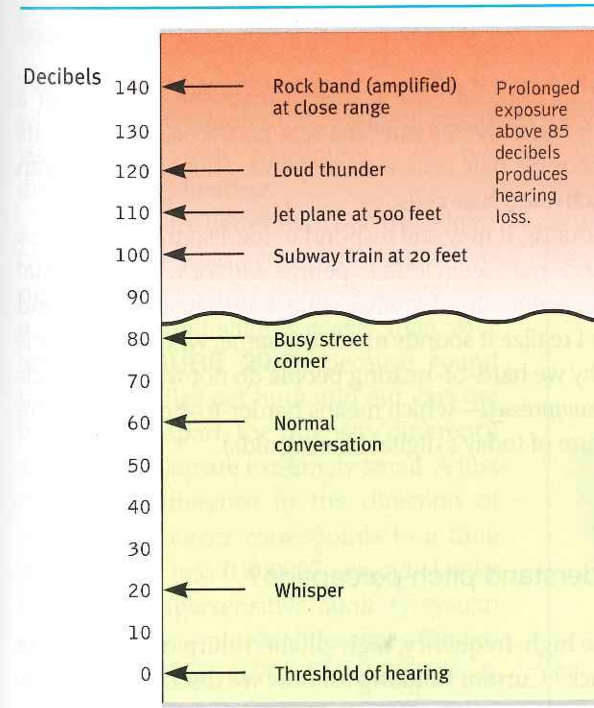
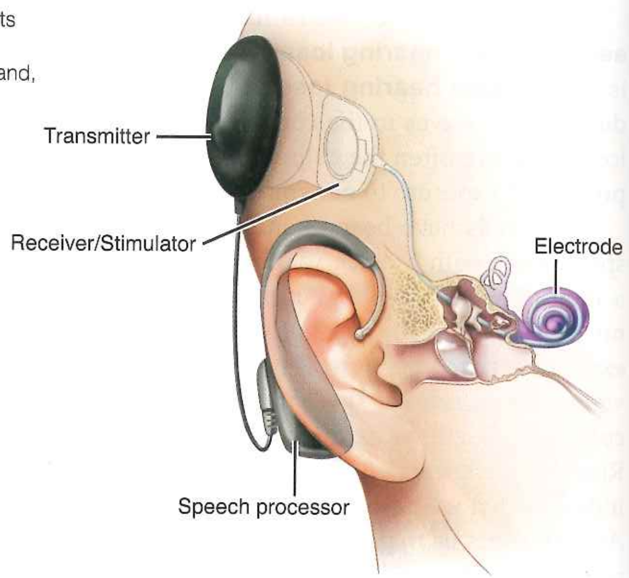


Figure 20.2
The intensity of some common sounds

Mark Holloway/Getty Images



Hardware for hearing Cochlear implants work by translating sounds into electrical signals that are transmitted to the cochlea and, via the auditory nerve, on to the brain.

cochlear implant a device for converting sounds into electrical signals and stimulating the auditory nerve through electrodes threaded into the cochlea.

For now, the only way to restore hearing for people with nerve deafness is a sort of bionic ear—a **cochlear implant**, which, by 2009, had been given to 188,000 people worldwide (NIDCD, 2011). This electronic device translates sounds into electrical signals that, wired into the cochlea's nerves, convey information about sound to the brain. Cochlear implants given to deaf kittens and human infants seem to trigger an "awakening" of the pertinent brain area (Klinke et al., 1999; Sirenteanu, 1999). They can help children become proficient in oral communication (especially if they receive them as preschoolers or even before age 1) (Dettman et al., 2007; Schorr et al., 2005).

The latest cochlear implants also can help restore hearing for most adults. However, the implants will not enable normal hearing in adults if their brain never learned to process sound during childhood. Similarly, cochlear implants did not enable hearing in deaf-from-birth cats that received them when fully grown rather than as 8-week-old kittens (Ryugo et al., 2010).

Perceiving Loudness

How do we detect loudness? It is not, as I would have guessed, from the intensity of a hair cell's response. Rather, a soft, pure tone activates only the few hair cells attuned to its frequency. Given louder sounds, neighboring hair cells also respond. Thus, the brain can interpret loudness from the *number* of activated hair cells.

FYI

Experiments are also under way to restore vision—with a bionic retina (a 2-millimeter-diameter microchip with photoreceptors that stimulate damaged retinal cells), and with a video camera and computer that stimulate the visual cortex. In test trials, both devices have enabled blind people to gain partial sight (Boahen, 2005; Steenhuysen, 2002).

If a hair cell loses sensitivity to soft sounds, it may still respond to loud sounds. This helps explain another surprise: Really loud sounds may seem loud to people with or without normal hearing. As a person with hearing loss, I used to wonder what really loud music must sound like to people with normal hearing. Now I realize it sounds much the same; where we differ is in our sensation of soft sounds. This is why we hard-of-hearing people do not want *all* sounds (loud and soft) amplified. We like sound *compressed*—which means harder-to-hear sounds are amplified more than loud sounds (a feature of today's digital hearing aids).

Perceiving Pitch

20-2 What theories help us understand pitch perception?

How do we know whether a sound is the high-frequency, high-pitched chirp of a bird or the low-frequency, low-pitched roar of a truck? Current thinking on how we discriminate pitch, like current thinking on how we discriminate color, combines two theories.

- Hermann von Helmholtz's **place theory** presumes that we hear different pitches because different sound waves trigger activity at different places along the cochlea's basilar membrane. Thus, the brain determines a sound's pitch by recognizing the specific place (on the membrane) that is generating the neural signal. When Nobel laureate-to-be Georg von Békésy (1957) cut holes in the cochleas of guinea pigs and human cadavers and looked inside with a microscope, he discovered that the cochlea vibrated, rather like a shaken bedsheet, in response to sound. High frequencies produced large vibrations near the beginning of the cochlea's membrane. Low frequencies vibrate more of the membrane, including near the end. But a problem remains: Place theory can explain how we hear high-pitched sounds but not low-pitched sounds. The neural signals generated by low-pitched sounds are not so neatly localized on the basilar membrane.
- **Frequency theory** suggests an alternative: The brain reads pitch by monitoring the frequency of neural impulses traveling up the auditory nerve. The whole basilar membrane vibrates with the incoming sound wave, triggering neural impulses to the brain at the same rate as the sound wave. If the sound wave has a frequency of 100 waves per second, then 100 pulses per second travel up the auditory nerve. But again, a problem remains: An individual neuron cannot fire faster than 1000 times per second. How, then, can we sense sounds with frequencies above 1000 waves per second (roughly the upper third of a piano keyboard)?
- Enter the *volley principle:* Like soldiers who alternate firing so that some can shoot while others reload, neural cells can alternate firing. By firing in rapid succession, they can achieve a *combined frequency* above 1000 waves per second. Thus, place theory best explains how we sense *high pitches,* frequency theory best explains how we sense *low pitches,* and some combination of place and frequency seems to handle the *pitches in the intermediate range.*

place theory in hearing, the theory that links the pitch we hear with the place where the cochlea's membrane is stimulated.

frequency theory in hearing, the theory that the rate of nerve impulses traveling up the auditory nerve matches the frequency of a tone, thus enabling us to sense its pitch.

Locating Sounds

20-3 How do we locate sounds?

Why don't we have one big ear—perhaps above our one nose? "All the better to hear you with," as the wolf said to Red Riding Hood. As the placement of our eyes allows us to sense visual depth, so the placement of our two ears allows us to enjoy stereophonic ("three-dimensional") hearing.

Two ears are better than one for at least two reasons. If a car to the right honks, your right ear receives a more *intense* sound, and it receives sound slightly *sooner* than your left ear (**FIGURE 20.3**). Because sound travels 750 miles per hour and our ears are but 6 inches apart, the intensity difference and the time lag are extremely small. A just noticeable difference in the direction of two sound sources corresponds to a time difference of just 0.000027 second! Lucky for us, our supersensitive auditory system can detect such minute differences (Brown & Deffenbacher, 1979; Middlebrooks & Green, 1991).

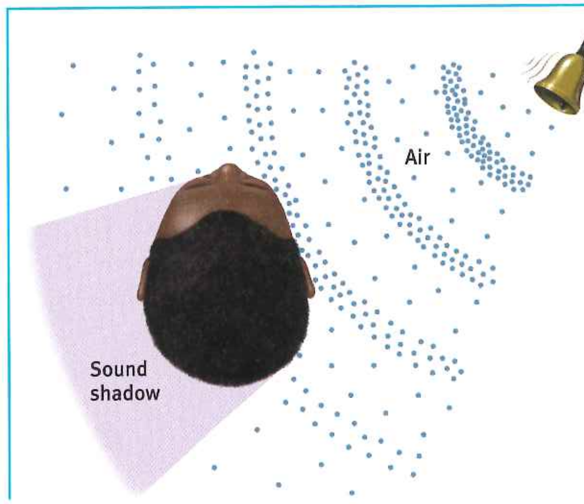


Figure 20.3 **How we locate sounds** Sound waves strike one ear sooner and more intensely than the other. From this information, our nimble brain computes the sound's location. As you might therefore expect, people who lose all hearing in one ear often have difficulty locating sounds.

Before You Move On

▶ ASK YOURSELF

If you are a hearing person, imagine that you had been born deaf. Do you think your life would be different?

▶ TEST YOURSELF

What are the basic steps in transforming sound waves into perceived sound?

Answers to the Test Yourself questions can be found in Appendix E at the end of the book.

Module 20 Review

20-1 What are the characteristics of air pressure waves that we hear as sound, and how does the ear transform sound energy into neural messages?

- Sound waves are bands of compressed and expanded air. Our ears detect these changes in air pressure and transform them into neural impulses, which the brain decodes as sound.
- Sound waves vary in amplitude, which we perceive as differing loudness, and in *frequency*, which we experience as differing *pitch*.
- The outer ear is the visible portion of the ear. The *middle ear* is the chamber between the eardrum and *cochlea*.
- The *inner ear* consists of the cochlea, semicircular canals, and vestibular sacs.
- Through a mechanical chain of events, sound waves traveling through the auditory canal cause tiny vibrations in the eardrum. The bones of the middle ear (the *hammer, anvil,* and *stirrup*) amplify the vibrations and relay them to the fluid-filled cochlea. Rippling of the basilar membrane, caused by pressure changes in the cochlear fluid, causes movement of the tiny hair cells, triggering neural messages to be sent (via the thalamus) to the auditory cortex in the brain.
- *Sensorineural hearing loss* (or nerve deafness) results from damage to the cochlea's hair cells or their associated nerves. *Conduction hearing loss* results from damage to the mechanical system that transmits sound waves to the cochlea. *Cochlear implants* can restore hearing for some people.

20-2 What theories help us understand pitch perception?

- *Place theory* explains how we hear high-pitched sounds, and *frequency theory* explains how we hear low-pitched sounds. (A combination of the two theories (the volley principle) explains how we hear pitches in the middle range.)
  - *Place theory* proposes that our brain interprets a particular pitch by decoding the place where a sound wave stimulates the cochlea's basilar membrane.
  - *Frequency theory* proposes that the brain deciphers the frequency of the neural impulses traveling up the auditory nerve to the brain.

20-3 How do we locate sounds?

- Sound waves strike one ear sooner and more intensely than the other. The brain analyzes the minute differences in the sounds received by the two ears and computes the sound's source.

Multiple-Choice Questions

1. What type of hearing loss is due to damage to the mechanism that transmits sound waves to the cochlea?

a. Sensorineural
b. Window-related
c. Conduction
d. Cochlear
e. Basilar

2. Pitch depends on which of the following?

a. Amplitude of a sound wave
b. Number of hair cells stimulated
c. Strength of nerve impulses traveling up the auditory nerve
d. Number of sound waves that reach the ear in a given time
e. Decibels of a sound wave

3. Which of the following reflects the notion that pitch is related to the number of impulses traveling up the auditory nerve in a unit of time?

a. Place theory
b. Frequency theory
c. Volley principle
d. Sound localization
e. Stereophonic hearing

4. The three small bones of the ear are located in the

a. cochlea.
b. outer ear.
c. inner ear.
d. middle ear.
e. auditory nerve.

Practice FRQs

1. Describe two parts of the ear that transmit sound waves before they reach the hair cells.

Answer

Students may describe any two of the following:

1 point: The eardrum, a tight membrane separating the middle ear from the outer ear.

1 point: The three bones in the middle ear that transmit sound waves between the eardrum and the cochlea.

1 point: The oval window, the point at which vibrations enter the cochlea.

1 point: The cochlea, where the fluid inside vibrates and the hair cells are stimulated.

2. What roles do the outer, middle, and inner ear play in helping a person hear a song on the radio?

(3 points)