CHAPTER 2

SOUND AND THE EAR

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KEY TERMS

- **Acceleration**
- **Acoustics**
- **Auditory labyrinth**
- **Basilar membrane**
- **Bel**
- **Boyle's law**
- **Broca's area**
- **Brownian motion**
- **Cochlea**
- **Compression**
- **Condensation**
- **Conductive hearing loss**
- **Decibel (dB)**
- **Decibel hearing level (dB HL)**
- **Decibel sensation level (dB SL)**
- **Decibel sound pressure level (dB SPL)**
- **Displacement**
- **Elastic**
- **Endocochlear electrical potential**
- **Endolymph**
- **Equilibrium**
- **Eustachian tube**
- **External auditory meatus**
- **Force**
- **Helicotrema**
- **Impedance-matching transformer**
- **Incus**
- **Inertia**
- **Inner hair cells**
- **Linear scale**
- **Logarithmic scale**
- **Malleus**
- **Mass**
- **Membranous labyrinth**
- **Mixed hearing loss**
- **Organ of Corti**
- **Osseous labyrinth**
- **Ossicular chain**
- **Ossicles**
- **Outer ear**
- **Outer hair cells**
- **Oval window**
- **Pars flaccida**
- **Pars tensa**
- **Pascal (Pa)**
- **Perilymph**
- **Pinna**
- **Pressure wave**
- **Propagation**
- **Pure tone**
- **Rarefaction**
- **Round window**
- **Saccule**
- **Scala media**
- **Scala tympani**
- **Scala vestibuli**
- **Semicircular canals**
- **Sensorineural hearing loss**
- **Simple harmonic motion (SHM)**
- **Sound**
- **Stapedius muscle**
- **Stapes**
- **Tectorial membrane**
- **Tensor tympani muscle**
- **Tonotopic organization**
- **Transducer**
- **Traveling wave theory**
- **Tympanic membrane**
- **Uniform circular motion**
- **Utricle**
- **Vector**
- **Vestibular labyrinth**
- **Vestibular membrane**
- **Vestibule**
- **Wavelength**
- **Wernicke's area**

OBJECTIVES

- Describe the characteristics of sound.
- Define the concept of simple harmonic motion and its relationship to periodic sounds.
- Summarize the physical characteristics of sound.
- Identify the anatomy of the auditory system and trace the transmission of sound throughout.
- Differentiate the types of hearing loss an abnormality in the auditory system can cause.

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Introduction

For the speech-language pathologist to work within his or her scope of practice with individuals with hearing loss, interpret audiograms, and screen for auditory disorders, one must have a firm understanding of what, how, and why we hear. The intention of this chapter is to provide an overview of the characteristics of sound, sound transmission, and the path sound takes as it is transmitted through the auditory system.

As a supplement to exhaustive coursework required by the American Speech-Language-Hearing Association, the intention of the following information is to provide the reader with a summary of acoustics and anatomy and physiology of the auditory system to reference within this text, rather than to take the place of that coursework.

General Characteristics of Sound

Sound is all around us, although it may be too faint for us to hear or too intense for us to listen to for any length of time. In the 1700s, the British philosopher George Berkeley asked the question, "If a tree falls in the forest and no one is around to hear it, does it make a sound?" Of course it does—unless it falls on another planet with little to no gaseous atmosphere, in which case there is no sound.

The study of sound is a branch of physics called **acoustics**. **Sound** itself is a physical phenomenon that is described as the movement or **propagation** of a disturbance (i.e., a vibration) through an elastic medium (e.g., air molecules) without permanent displacement of the particles.

There are three prerequisites for production of sound: (1) a source of energy (e.g., a force), (2) a vibrating object that generates an audible pressure wave, and (3) a medium of transmission (e.g., air). However, a receiver of these prerequisites of sound production is optional; that is, a listener is not required.

As human beings, we produce sound primarily in air, so let's begin our discussion of the prerequisites with the medium of transmission we call air. Air molecules are not static; in fact, they are moving constantly in random fashion. This random movement at high speeds is called Brownian motion, named for Robert Brown (1773–1858), a Scottish botanist who described this motion, which results from the impact of molecules found within a gas or liquid. **Brownian motion** causes these air molecules to collide with each other and with whatever is in their path—walls, furniture, or people. These molecules are **elastic**—that is, the objects exhibit a tendency to resist deformity and return to their rest position—so there is no change in their shape when they bump into each other and/or other objects. These collisions produce pressure. Although we may not be able to feel that pressure, it is there. You feel this pressure whenever air is set into motion, such as on a windy day or when we speak.

A source of energy, such as a force, is the next prerequisite. **Force** is a push or a pull on an object, and is a **vector** that has both magnitude (some amount greater than zero) and direction. Force is mathematically determined to be the product of mass times acceleration ($\mathbf{F} = ma$). Air molecules have **mass** (the quantity of matter present). Mass is not identical to weight because weight is affected by gravitational forces; however, for our purposes, mass and weight are the same. Because air molecules have mass, they obey laws of motion set forth by the great English scientist Sir Isaac Newton (1643–1727), the first of which states that all bodies remain at rest or in a state of uniform motion unless other forces act in opposition. (This property is called **inertia**.) The amount of inertia an object (e.g., an air molecule) has is directly proportional to its mass: The greater an object's mass, the greater its inertia. An outside force must be applied to change this tendency. **Acceleration** is the speed (distance traveled per unit time) of an object per unit time, which is represented mathematically as $\frac{\text{length}}{(\text{time})^2}$. When a force is applied to the air particles by a moving object, the air particles will travel in the direction of the force. The amount of this distance is proportional to the magnitude of the applied force—a large force will cause the object to travel much further than a small force. Therefore, the greater the force applied to the object, the greater the distance the object travels by that force; in addition, the restoring force is proportional to the displacement (i.e., the object obeys Hooke's law, named for Robert Hooke [1635–1703], an English experimental philosopher who first described this action).

Finally, we need an object that is capable of vibrating. Air molecules happen to vibrate quite well, and can be set into vibration easily to produce a **pressure wave**. For example, if we strike a tuning fork on a hard surface to set its tines into vibration, the air molecules surrounding the tuning fork tines are also set into vibration, creating this pressure wave. This initial impact starts movement of the air molecules (**displacement**) in the same direction of the force. This pressure wave displaces air molecules near the tuning fork tines; these displaced air molecules further displace other air molecules adjacent to the pressure wave, which displace adjacent air molecules, and so on. Therefore, the wave motion is propagated, or transferred, through the air to the human ear.

When the air molecules reach the maximum point of displacement, their motion is momentarily halted because of inertia (i.e., air molecules follow Newton's first law of motion, which states that objects at rest will remain at rest unless acted upon by a force). Once the force is removed, the restoring force of elasticity returns the displaced air molecule to a resting state called **equilibrium**. When the air molecules return to their resting state, the void left by their former positions is filled by the adjacent air molecules, which then displace the adjacent air molecules in the opposite direction (i.e., the air molecules follow Newton's third law, which states that for any action there is an equal and opposite reaction). The elastic medium is not displaced over an appreciable distance; rather, the air molecules vibrate to and fro about their average equilibrium positions away from the source of energy.

Elasticity in the tuning fork tine allows for this displacement, but also generates a restoring force that momentarily stops the movement at the point of maximum amplitude away from the rest position. The restoring force pushes the tuning fork tines back to their rest position, but inertia carries the tines past the rest position. By overshooting the rest position, the tines then are pushed toward the opposite maximal position, at which point the restoring force builds up in the other direction and the tuning fork tines return to the rest position once again. The tuning fork tines overshoot the rest position, the restoring force builds up again, and the pattern repeats; this alternating pattern of inertia and elasticity creates one full cycle of vibration. As you can see, inertia and the restoring forces vary continuously during each cycle: Inertia is strong when the restoring force is weak, and vice versa. This interplay between the two forces enables the vibration to persist until other external forces (for example, friction, which causes a gradual decay in vibratory amplitude) overcome the tuning fork tines' mass and elasticity and the energy dissipates. Although the air molecules are displaced from their rest position at various points throughout the cycles of vibration, they continue to vibrate at the same frequency as the tuning fork.

As air molecules vibrate, waves of pressure fluctuations are created and travel through the elastic medium. (However, the molecules themselves move only a short distance.) As this vibratory disturbance (and not the air molecules themselves) propagates through the air, the atmosphere goes through alternating periods of increased and decreased air particle density and, consequently, of high and low pressure. Because air molecules can flow easily, they flow from regions of higher pressure to regions of lower pressure. The density (concentration) of these air particles alternately increases and decreases relative to their conditions at rest (i.e., when there is no vibration and the molecules are in equilibrium). For a fixed volume of vibrating air molecules, increased

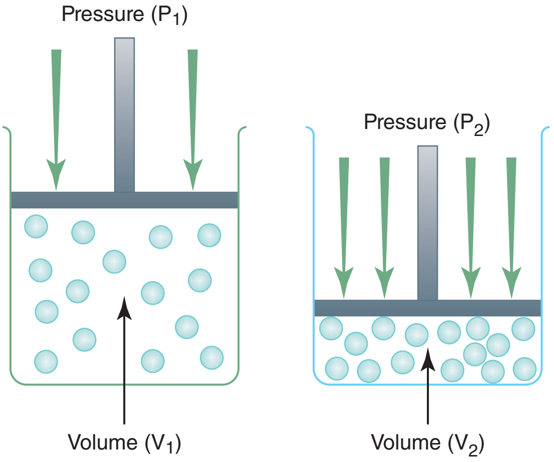

Figure 2.1 Boyle's Law illustrated.

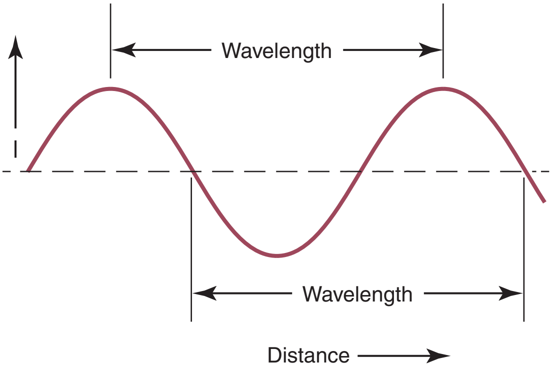

Figure 2.2 Wavelength.

concentration (density) of air particles results in increased air pressure; this is called **Boyle's law** (after Robert Boyle [1627–1691], British physicist and chemist), which states that the pressure and volume of a gas are inversely proportional if kept at a constant temperature (see **Figure 2.1**).

Because the initial force is a vector, it causes an outward movement of the tuning fork tines toward a positive displacement, which causes the surrounding air molecules to be crowded together. The force of displacement is passed from molecule to molecule; this displacement creates areas of increased pressure and density of air molecules that are called **condensation** (also known as **compression**). When the tines return toward equilibrium because of elasticity, the force on the surrounding medium is relieved, and the air molecules also return toward their position of equilibrium. This "thinning" of air molecules creates areas of decreased air pressure and density (**rarefaction**). The distance between two successive condensations (i.e., from a point on one wave to the same point on the next cycle of the wave) is called the **wavelength** of the sound wave. The wavelength represents the length of the disturbance created by the wave in a medium (see **Figure 2.2**). Wavelength is measured in units of length (e.g., meters) and is represented by the Greek letter lambda (λ).

Sound in air moves in the same (or opposite) direction of the force; in other words, this pressure wave moves longitudinally. In a longitudinal wave, air molecules approach and recede from each other to create variations in pressure so that the wave movement is parallel to the force. The air molecules do not move far from their rest positions; instead, they move a short distance in either direction from rest, but do not move forward with the wave itself. To demonstrate longitudinal waves at home, have a friend hold one end of a Slinky (the metal ones work best) while you hold the other end. Pinch a few of the coils together and then release them. The energy released will travel down the Slinky toward the other end and then return to you until the energy is overcome by friction and dies. In a transverse wave, on the other hand, the air molecules vibrate at right angles to the direction of wave propagation. To demonstrate transverse waves, fill a deep, wide bowl with water, and place a feather (or float a cork) on the water surface. (The fluid tension will keep the feather or the cork floating on the water's surface because the water has greater density than either the feather or the cork.) Drop a small object (e.g., a pebble or a penny) into the bowl; the feather or cork will bob up and down, but not move very far from where it is floating. This movement is perpendicular to the direction of wave propagation.

Simple Harmonic Motion and Sound

In acoustics, when air particles are set into motion by a force to produce changes in pressure, areas of condensation and rarefaction alternate. If these areas of alternating condensation and rarefaction occur at a steady rate of change, the resultant pressure wave is said to be a **pure tone** (e.g., those little beeps you hear during a hearing test), which moves in **simple harmonic motion (SHM)** and is represented graphically by a sine wave. Although pure tones rarely occur in nature, they result when sound waves are propagated through an elastic medium and complete the same number of complete cycles of vibration per unit time. Examples of pure tones include tuning forks and pendulums, both of which produce vibrations that move in SHM (see Figure 2.3).

Characteristics of SHM

The basic attributes of a sound wave—period, frequency, amplitude, and phase—are explained through SHM. When pure tones move in SHM, they take the same amount of time to complete each cycle of vibration. In other words, pure tones are periodic. A period (*p*) is a physical characteristic that describes the amount of time it takes to complete one full cycle of vibration, and is measured in units of time (usually seconds [s] or milliseconds [ms]). Frequency (*f*) is the inverse of the pure tone's period and is a physical characteristic that describes the number of complete cycles of vibration that occur per unit time (Figure 2.4). Frequency is measured in units called Hertz (Hz), in honor of Heinrich Hertz (1857–1894), a German physicist who contributed to the field of electromagnetism through his description of wave movement. Only one frequency is described in a pure tone (e.g., 1000 Hz).

Pitch and frequency are not synonymous. Because frequency is a physical characteristic, it depends on the mass of the vibrating object, its overall size, and so on; in general, the larger the vibrating object, the more slowly that object will vibrate. Pitch, on the other hand, is a percept (a psychological correlate) and is related to the listener's perceptual response to frequency. We might also think of pitch as a relative term; that is, if you ask whether a certain sound is high pitch or low pitch, the question that would arise is: Higher or lower than what? Pitch is measured in Mels. The Mel

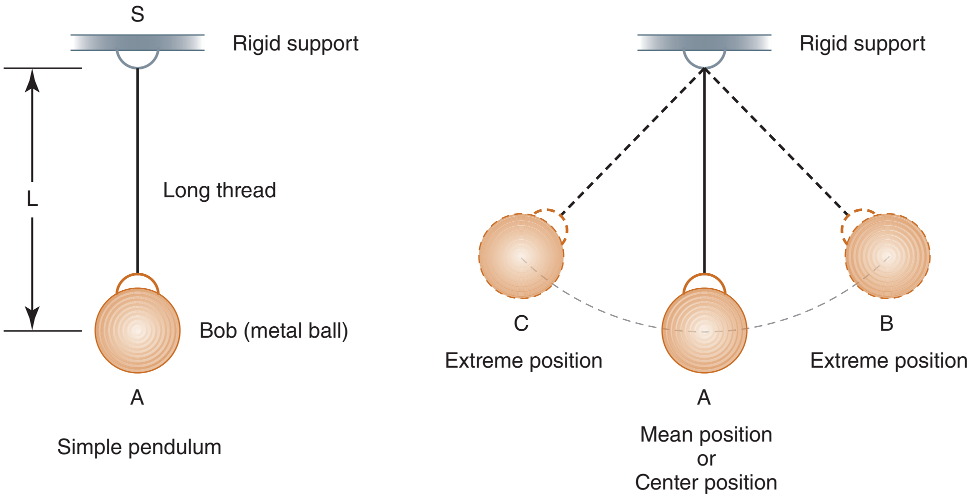

Figure 2.3 Example of simple harmonic motion.

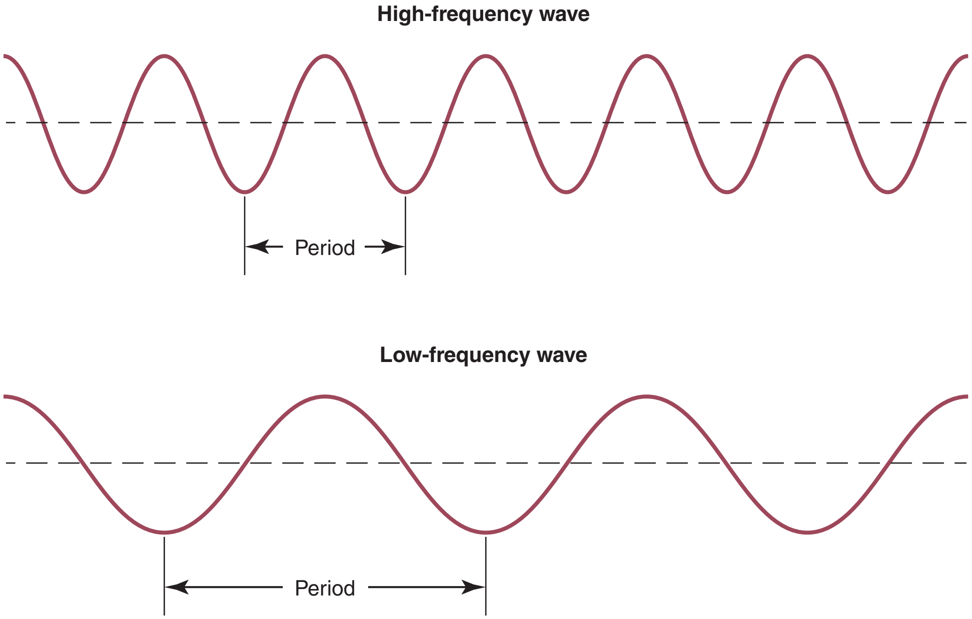

Figure 2.4 High- and low-frequency waves. The waveform at the top has twice as many cycles and its period is half as long as the wave at the bottom; therefore, the upper wave is the octave of the bottom wave.

scale is a psycho-physical scale of pitch perception; 1000 Mels is the pitch equal to a 1000-Hz tone at a specific intensity. Figure 2.5 shows the relationship between pitch and frequency.

As a sound wave travels through an elastic medium like air, we can calculate how far it travels through one complete cycle of vibration. This is called the wavelength (λ), and is measured in units of length (e.g., meters). We can also determine the speed (velocity) of the sound wave if we know how far it travels per unit time. The velocity of air at standard room temperature and pressure (20 degrees Celsius at sea level) is approximately 344 m/s. How fast the sound wave moves depends on the density and elastic properties of the medium through which it is moving, and is independent of pressure as long as air temperature is constant. (In gases like air, temperature plays an important part in how fast sound travels. Sounds travel faster

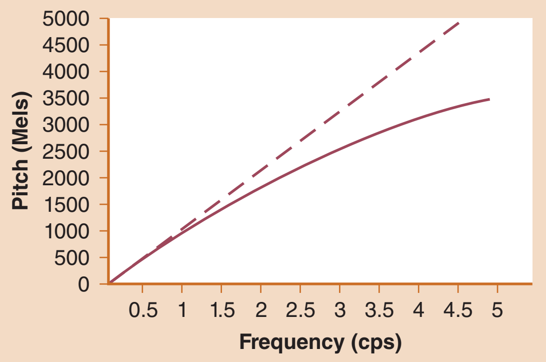

Figure 2.5 This graph shows the relationship between frequency (x-axis, in units of cycles per second [cps]) and pitch (y-axis, in units of Mels). At lower frequencies, frequency (dashed line) and pitch (solid line) have nearly a 1:1 relationship, but at higher frequencies, pitch differs from frequency.

through liquids and fastest along solids because the greater elasticity and density of these media increase the velocity of conduction.) Therefore, a faint sound travels at the same velocity as a loud sound. We can calculate the wavelength l of a 1000-Hz sound wave very easily if we know the velocity of sound; because velocity divided by frequency equals wavelength, $\frac{344 \text{ m/s}}{1000 \text{ cycles/s}} = 0.344$ m (approximately 1 foot). (Note: Do not confuse the velocity of sound wave propagation with the velocity of particle movement; particles vibrating in SHM constantly change velocity, moving with maximum velocity over their rest position.)

Amplitude (**A**) is another vector quantity that describes both magnitude and direction of wave displacement from rest. Amplitude is a derived unit of measurement that describes the distance from an object's rest position by a vibrating body or the magnitude of pressure change that occurs by that object's motion. The greater the distance caused by vibration is from the point of rest, the greater the amplitude. In general, the greater the amplitude, the louder the pure tone sounds to a listener. Amplitude can be described by both physical parameters and psychophysical percepts. Loudness is the percept of intensity and depends on how our inner ears (specifically, the cochlea) interpret how much sound pressure is presented over our tympanic membranes (eardrums). The human ear happens to be very sensitive to changes in sound pressure, so small changes in pressure (i.e., intensity) will result in either an increase or a decrease in loudness sensation. Intensity is a derived unit of measurement that describes the amount of acoustic energy (i.e., sound) that passes through a unit of area in a given time span. A pure tone's intensity is measured by the amplitude of its sine wave, and varies with time. The human ear is capable of hearing a wide range of sound intensities.

SHM is usually depicted as a sine wave, with peaks (i.e., compressions) and troughs (i.e., rarefactions). If we were to cut that sine wave in half and move the trough directly beneath the peak, we would form a circle. If an air molecule were to move around the circumference of that circle at a constant rate, we could describe that movement as projected **uniform circular motion**. The air molecule's displacement along that circumference varies with the passage of time in the same way during a cycle of movement if the frequency of the sine wave is constant. This brings us to our last characteristic of SHM: phase. Phase is that portion of a cycle that has elapsed at any instant in time, relative to some arbitrary starting point—that is, the relative timing of compressions and rarefactions of an object moving in SHM. Because of this relationship between SHM and projected uniform circular motion, phase is measured in degrees (from 0° to 360°). **Figure 2.6** and **Figure 2.7** depict the relationship between these concepts.

Why is phase important? If two sound waves of the exact same frequency are exactly in phase, their amplitudes add together and result in a doubling of intensity; if these sound waves are slightly out of phase, their amplitudes add together, but the resultant intensity ranges from not quite doubled to almost zero. If two sound waves are exactly out of phase, their amplitudes add together to cancel; no sound is produced because there is no change in sound pressure. This is how noise-cancellation headphones work: A sound wave exactly opposite in phase from the generating wave is produced so that their amplitudes cancel.

The Decibel: Measure of Relative Intensity

What Is a Decibel?

Earlier we noted that intensity is the physical measure of what we perceive as the loudness of a sound. A sound's intensity is measured in acoustic (sound) pressure. Pressure is created when a force is distributed over an area; mathematically, pressure $= \frac{\text{force}}{\text{area}}$. (Force is the product of mass and acceleration; its unit of measurement is the dyne.) When we measure sound intensity, we are measuring the force of that sound wave's vibration over a given unit of area: The greater the change in air pressure, the greater

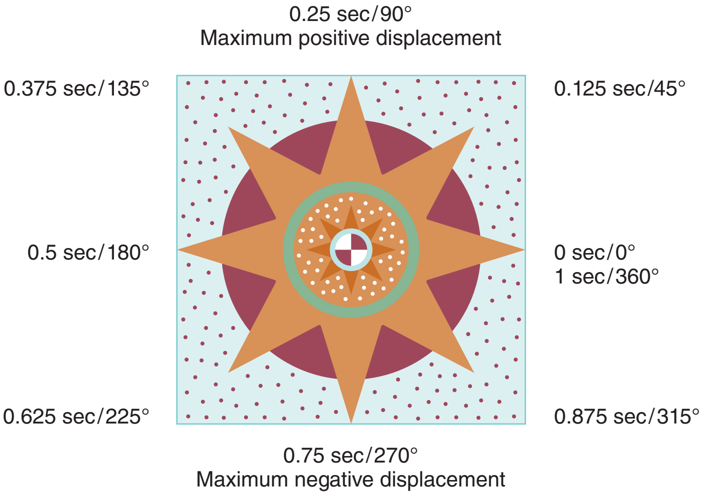

Figure 2.6 Relationship among simple harmonic motion, projected uniform circular motion, phase, and degrees in a sine wave.

the intensity of sound. The unit of measurement that describes sound pressure is the **Pascal (Pa)**, named in honor of Blaise Pascal (1623–1662), a French mathematician; 1 Pa = 10 dynes/cm^2. Normal human-hearing sensitivity ranges from 0.0002 dynes/cm^2 to 2000 dynes/cm^2. Although it is possible to measure sound pressure in units of dynes/cm^2, it would force us to use very large numbers to describe a person's hearing sensitivity (e.g., an intensity range of 10,000,000,000,000 between softest sounds and threshold of pain).

When we describe sound pressure using Pa, we are using what is called a linear (or integral) measuring scale (also known as an absolute scale)—there is a true zero point, each increment on the scale is equal to every other increment, and you can sum incremental units by addition. An example of a **linear scale** is a ruler like a yardstick; you cannot have a negative distance, and each increment (e.g., 1 inch) is equivalent. A better measurement scale to use for intensity, however, is a logarithmic (ratio) scale. A **logarithmic scale** is a relative scale where

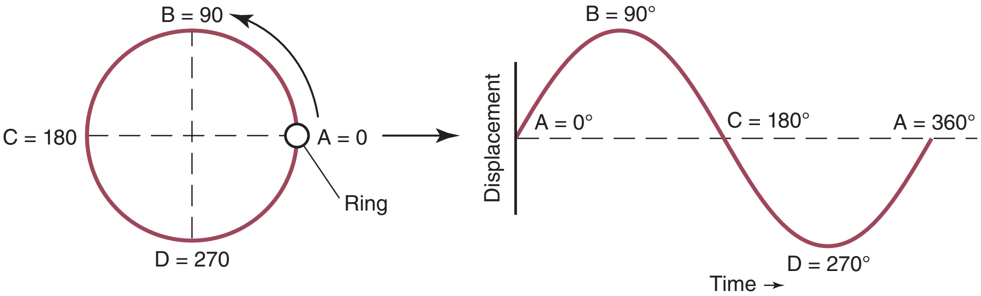

Figure 2.7 Relationship among simple harmonic motion, phase, and projected uniform circular motion.

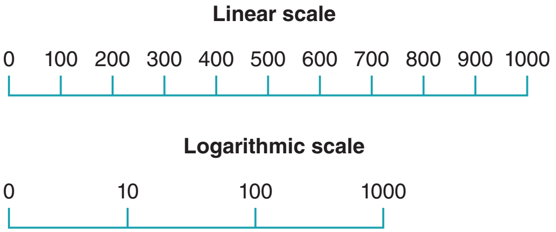

Figure 2.8 Relationship between linear and logarithmic scales.

there is no zero point (you must define what zero is), the zero point does not represent the absence of what is being measured, and each successive unit is larger than the one preceding it; therefore, each increment is not equal and represents increasingly large numerical differences. A logarithmic scale compresses the potentially very large numbers used in a linear scale into much more manageable increments to use. See Figure 2.8, which illustrates the incremental differences between linear and logarithmic scales.

Why do we use a logarithmic scale for intensity? It has been known since the 19th century that the logarithmic scale corresponds nicely to how intensity differences are perceived in the human ear. Equal increases in sensation (in this case, loudness) are obtained by multiplying the stimulus by a constant factor. Although this doesn't work for all intensities to which the ear is sensitive, it is accurate enough to be practical.

The unit of measurement used to describe human intensity differences is the **Bel** (named in honor of Alexander Graham Bell [1847–1922], the Scottish-American inventor and teacher of oral speech to individuals who are deaf). The Bel is a relative measurement of intensity that expresses the ratio of a measured sound intensity to a relative sound intensity. In other words, this very large range of human hearing (on the order of 10^{14} dynes/cm^2) is compressed so that smaller numbers are used. By using the Bel we bring the range of intensities heard from 10^{14} units to a range of 0 to 14. However, this is so far to the other extreme that it is absurd! The scale of the Bel has been compressed so much that fractions must be used to reflect the desired accuracy of measurement of intensity (e.g., an intensity of 4.5 Bels). To minimize the use of fractions and decimals, we can use a smaller unit of measurement, the decibel (literally, one-tenth of a Bel). The **decibel (dB)** is a much more user-friendly unit of measurement of intensity, and the range of human hearing on the decibel scale becomes whole numbers that range between 0 dB and 140 dB.

The decibel expresses a logarithmic ratio between the measured sound pressure and a relative sound pressure (defined at 0.0002 dynes/cm^2, which happens to be the softest sound a person with normal hearing sensitivity can hear). In its simplest form, a logarithm is the same as an exponent, which indicates how many times a number is multiplied by itself. Take the equation $10 \times 10 = 100$; the number 10 is multiplied by itself. We can also express this equation as $10^2 = 100$; in this case, the number 10 is the base and the number 2 is the exponent. If we wanted to express the second equation logarithmically, we can also say $\log_{10} 100 = 2$. The number 10 is still the base, the number 2 is still the exponent, and the number 100 is still the product of the multiplication of 10×10, but we just rearranged how we expressed the multiplication problem using logarithms. To multiply logarithms with the same base number, you add their exponents; to divide logarithms with the same base number, you subtract their exponents.

We also use decibels to denote intensity for another reason: We can describe intensity either in units of power (used in acoustics) or sound pressure (**decibel sound pressure level [dB SPL]**, used in the measurement of hearing sensitivity). (Because we are primarily interested in changes in sound pressure—e.g., running speech—this discussion will be limited to audiometric applications.) In audiology, intensity level refers to the changes in sound pressure level, as measured in dynes/cm^2. Because decibels are based on relative differences in intensities, a reference value (standard) must be provided, which is the threshold of human hearing (equal to 0.0002 dynes/cm^2 in units of sound pressure). We can calculate sound intensity in decibels using the following formula:

$$\text{dB SPL} = 20 \log_{10} (P_o/P_r)$$

where P_o = measured sound pressure and P_r = recognized reference point (0.0002 dynes/cm^2).

To illustrate how we use this equation, let's say that our measured sound pressure (P_o) is equivalent to our reference pressure (P_r = 0.0002 dynes/cm^2). We can then substitute these values into the equation to get:

$$\text{dB SPL} = 20 \log_{10} (0.0002 \text{ dynes/cm}^2 \div 0.0002 \text{ dynes/cm}^2) = 20 \log_{10} (1) = 0$$

To what power do we raise 10 to equal 1? The answer is zero (0) because $10^0 = 1$, and anything multiplied by 0 is equal to 0. Therefore, a sound stimulus that is minimally audible has an intensity of 0 dB SPL.

As you can see from **Table 2.1**, a tenfold increase in sound pressure (a linear measure) yields a 20-dB increase in intensity (a logarithmic measure).

Intensity versus Loudness

Intensity, like frequency, is a physical property of an acoustic signal. The loudness—the subjective, psychological sensation of intensity—of a signal is related to its intensity; however, this relationship between loudness and intensity is not linear. At a given intensity, loudness perception varies with sound frequency because the human auditory system is designed to receive the middle frequencies with much less intensity than is needed for extremely high and low frequencies. Just as frequency has a perceptual correlate (pitch), intensity also has perceptual correlates: the phon (a unit of equal loudness) and the sone (an arbitrary unit of loudness). The phon level roughly matches intensity (in dB SPL) at a frequency of 1000 Hz. Frequencies in the range of 1000 Hz to 6000 Hz are detected at the lowest sound pressure levels, whereas very low and very high frequencies require greater sound pressure levels to pass the threshold of hearing. **Figure 2.9** shows how equal loudness changes over a range of frequencies—that is, the minimum audibility needed at each frequency. (However, lower frequencies span the range of

Table 2.1 Relationship of Measured Pressure to Intensity

Measured Pressure (dynes/cm^2)	Intensity (dB SPL)
0.0002	0 (minimum audible sound)
0.002	20
0.02	40
0.2	60
2.0	80
20.0	100
200.0	120
2000.0	140

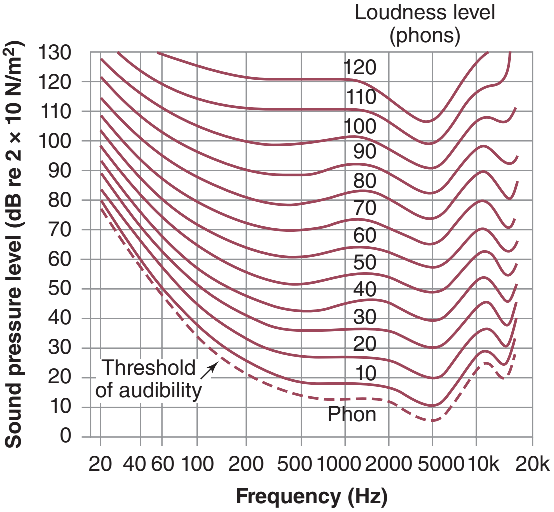

Figure 2.9 The heavy line on a phon curve also represents the 0 dB HL line on an audiogram. This is also known as a Fletcher–Munson curve, named for the researchers (H. Fletcher and W.A. Munson) who developed the scale.

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Table 2.2 Relative Scales Used in Acoustics

	Name	Unit
Physical Properties	Frequency	Hertz (Hz)
	Intensity	Decibel (dB)
Psychological Properties	Pitch	Mel (scaling)
	Loudness	Sone (scaling) Phon (equal)

loudness with a smaller range of perceptual intensities than do the higher frequencies.) The sone, on the other hand, is defined as the loudness of a 1000-Hz tone set at 40 dB above threshold. The sensation of loudness increases more slowly than the actual increase in intensity for normal auditory systems; in pathologic systems, the abnormally rapid growth of loudness is called recruitment. This phenomenon usually occurs in those individuals who have sensorineural (especially cochlear) hearing loss. The scales used in acoustics are shown in Table 2.2.

Which Decibel Should I Use?

The decibel symbol is often qualified with a suffix that indicates which reference quantity has been used. We have seen how the decibel (in units of sound pressure level, dB SPL) expresses a ratio of measured sound pressure to a reference sound pressure. Indeed, we use dB SPL to indicate the intensity of a sound stimulus. However, when we measure an individual's auditory sensitivity, it is more useful to compare that threshold intensity to the softest intensity the average person with normal hearing sensitivity can hear. Therefore, we use a different decibel—in terms of hearing level—to show this deviation from what is considered to be "normal hearing." The **decibel hearing level (dB HL)** is used audiometrically to show the degree of hearing impairment, and its reference level varies with frequency according to a minimum audibility curve (as was shown in the discussion of phon).

Therefore, at each frequency, the average of the softest intensity heard by young adults is denoted as 0 dB HL (also known as audiometric zero), to which we can compare an individual's auditory sensitivity. We denote these comparisons on a graph called an audiogram, which plots the intensity (in units of dB HL) for each test frequency (in units of Hz). Another common reference that is used audiometrically is the individual's auditory threshold for a stimulus. A threshold is defined as the level at which a stimulus (e.g., a pure tone or speech) is so soft that it is perceived 50% of the time it is presented. The intensity in decibels above an individual's threshold is called the sensation level (SL), and is known as the **decibel sensation level (dB SL)**. We often use dB SL when denoting speech audiometric testing; just as we can determine speech intensity (in dB HL), we can also test speech understanding at intensity levels above threshold (in dB SL).

Anatomy and Physiology of Hearing

Sound is audible to us only if we have an auditory system that can utilize the physical characteristics of sound—that is, a sound's frequency (or frequencies), intensity, and phase(s)—to understand the world around us. Our hearing is sensitive enough to hear very faint sounds (e.g., leaves rustling on the ground from a gentle breeze), yet can appreciate and identify the different instruments comprising a symphony orchestra at much higher intensities. This section will describe the different parts of the ear—the outer, middle, and inner ear—to see how sound waves travel from the ambient air into the outer ear and then are funneled through the middle and inner ears up to the brain.

The ear itself is described as a **transducer**—it changes one form of energy (in this case, acoustic energy) to another form (fluid/electrical) via mechanical energy of the middle ear. This transduction of sound enables the ear to analyze the various physical parameters (frequency, intensity, phase, and duration) to perceive in the brain what the ear has heard.

The Outer Ear

We most often think of our ears as just what is visible, the outer ear. The **outer ear** (Figure 2.10) comprises two structures, the **pinna** (or auricle) and the **external auditory meatus** (ear canal). The pinna is the visible part of the auditory system and is shaped like a funnel; it is composed of skin overlaying stiffer cartilage along with a fleshier lobe, and is attached to the cranium by ligaments. The pinna has several landmarks, such as the concha (depression in the lower center of the pinna that forms the external auditory meatus), the helix (auricular rim), the antihelix (ridge just inside the helix), the scaphoid fossa (which lies between the helix and antihelix, at the lateral aspect of the pinna), and the triangular fossa (which lies superior to the scaphoid fossa between the helix and antihelix). Other landmarks include the tragus (small flap of cartilage anterior to the opening of the external auditory meatus), the antitragus (lies just opposite the tragus and forms the inferior boundary of the concha), and the highly vascular lobe, which is inferior to the external auditory meatus. The funnel-like shape of the concha gives rise to the pinna's basic function: to collect and send sound waves through the ear canal. The pinna also assists in sound localization and helps to protect the entrance to the external auditory canal.

The external auditory meatus is a somewhat irregularly S-shaped tube that runs from the pinna to the eardrum (**tympanic membrane**). It is approximately 6 mm in diameter and about 23–29 mm long in adults, is lined with epithelium (skin) and tiny hairs (cilia), and contains glands in the cartilaginous portion that produce earwax (cerumen). Cerumen is waxy and somewhat sticky, which helps to keep the ear canal moisturized and clean of debris that could accumulate. The external auditory canal has two main functions: to protect the delicate middle and inner ears from foreign bodies that could damage these structures and, with the concha, to boost (that is, increase) the amplitude of high-frequency sounds. The concha and external auditory meatus each have a natural resonant frequency to which they respond best, and each structure increases the sound pressure at its resonant frequency by approximately 10 to 15 dB for frequencies ranging from 2000 Hz through 5000 Hz. This increase in amplitude is helpful in discriminating fricative consonants such as s, z, f, and sh, all of which have acoustic energy above 2000 Hz. This boost of high-frequency sounds also enables us to localize the source of sounds, because high-frequency sounds have short wavelengths that cannot travel around the head. (In contrast, low-frequency sounds have longer wavelengths, which enable them to travel around the head.) Differences in sound wavelengths help to create timing differences between the ears and give us cues to where sounds are located.

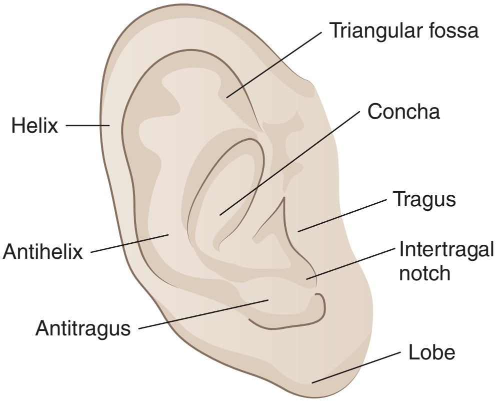

Figure 2.10 The outer ear.

The Middle Ear

The external auditory meatus terminates medially at the tympanic membrane, which acts as the anatomic boundary between the outer and middle ear. The tympanic membrane is a thin, concave, elastic, pearly gray to whitish translucent membrane that is made up of multiple layers of tissue—epithelial tissue (lateral layer), fibrous middle layer, and medial membranous layer—that are both concentric and radial, i.e., they fan out from a central point in a circular fashion. The membranous layer of the tympanic membrane is contiguous with the membranous lining of the external auditory meatus. The fibrous layer maintains compliance of the membrane itself so that it can vibrate. The inner, membranous layer is contiguous with the mucous membrane lining of the middle ear space, a small cavity that links the outer ear to the fluid-filled inner ear. The tympanic membrane has a more compliant, smaller section called the **pars flaccida**, which is located superiorly, and a stiffer, larger section called the **pars tensa**, located inferiorly.

It is within the petrous portion of the temporal bone that we find the middle ear cavity, which houses the **ossicles**, muscles, and ligaments of the middle ear. This air-filled cavity is medial to the tympanic membrane and contains three very tiny bones (in fact, the smallest and hardest-working bones in the body)—the malleus, incus, and stapes—all of which can fit easily on a dime with room to spare. The ossicles are suspended in the middle ear cavity by ligaments, which permit the ossicular chain to move like a piston to push the sound waves through the middle ear to the inner ear fluids, and help the inner ear from being overdriven by excessively strong sound vibrations. The **malleus**, less than a centimeter in length, is embedded slightly into the fibrous and mucous membrane layers of the tympanic membrane at its manubrium (handle); as the tympanic membrane vibrates from sound energy impinging on it, the malleus (and incus, with which it articulates and with which forms a unit) moves at the same vibratory speed. The **incus** is the middle bone, attaching to both the malleus head (at the incudomalleolar articulation) and the stapes. It is less than a centimeter in length and has two processes: the short crus, which fits into a recess in the wall of the tympanic membrane, and the long crus, which is parallel to the manubrium of the malleus and attaches to the head of the stapes at the incudostapedial joint. The smallest of the three bones, the **stapes** looks like a stirrup, with two crura (arms) and a footplate, which fits very neatly over the oval window of the cochlear wall. The stapedial footplate helps to push the acoustic energy into the inner ear. The ossicles are suspended in the middle ear cavity by five ligaments, which permit movement of the ossicles.

The **ossicular chain** acts like an **impedance-matching transformer**. The middle ear compensates for loss of sound energy when going from low-impedance, air-filled medium to a high-impedance, fluid-filled medium through three primary mechanisms: the difference in area between the tympanic membrane and the oval window (the tympanic membrane is about 17 times the size of the oval window); the incudomalleolar joint between the malleus and long process of the incus, which forms a complex lever system that helps to amplify sounds traveling through the middle ear space to the inner ear; and the tympanic membrane buckling effect (**Figure 2.11**). Sound vibrations hitting the proportionally larger surface of the tympanic membrane must be communicated to the much smaller area of the oval window, which concentrates the energy (because it takes more energy—about 30 dB—to push against fluid than to push against air). This area difference between the tympanic membrane and oval window recovers almost 25 dB of sound energy. The difference in length between the malleus and long process of the incus is called the "step-up function" and adds another 2 dB of sound energy. Finally, the tympanic membrane buckles in response to sound, but the surface of the membrane moves a greater distance than the malleus, reducing displacement velocity of the malleus and adding about 5 dB to the sound intensity. Together, approximately 30 dB of sound energy are added to the system to compensate for the impedance mismatch between the air-filled middle ear and the fluid-filled inner ear. However, the ability of the middle ear system to amplify the sound pressure depends on the signal's frequency; little amplification occurs for frequencies below 100 Hz or above 2500 Hz. The outer ear, however, amplifies sound energy by about 20 dB for frequencies between 2000 Hz and 5000 Hz. Taken together, this range of frequencies corresponds to the range of

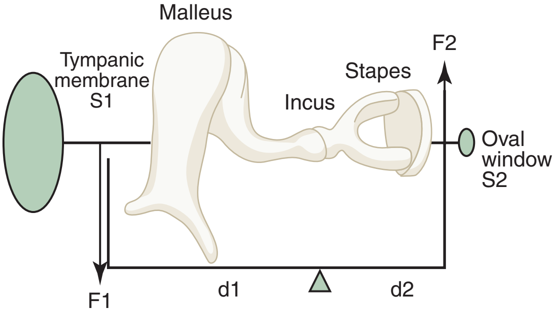

Figure 2.11 Schematic of the ossicular lever system and size differential between the tympanic membrane S1 and oval window S2.

frequencies in human speech that are most important for communication.

Also found in the middle ear cavity is the Eustachian (auditory) tube, which is composed primarily of cartilage and has two important functions: to equalize air pressure between the middle ear cavity and the nasopharynx and to help drain fluids that might accumulate in the middle ear into the nasopharynx. You may be familiar with the stuffed feeling in your ears when you take off or land in an airplane. The **Eustachian tube** is at work, equalizing the air pressure in the middle ear.

If the Eustachian tube is not functioning well, fluids can build up in the normally air-filled middle ear space, which compromises the ossicular chain movement. Additional sound pressure is needed to overcome this lack of ossicular movement, leading to a hearing loss caused by problems with sound conduction (i.e., a conductive hearing loss). This disorder, called otitis media (middle ear infection), is often caused by an upper respiratory infection and/or allergies and occurs most often in young children due to the immature angle of the Eustachian tube in comparison to adults (see Figure 2.12). Acute otitis media is usually caused by a bacterial infection and often presents with an elevated temperature (Rosenfeld et al., 2004). In many cases, this condition goes away on its own without treatment with antibiotics, but on occasion fluid will remain in the middle ear space because the Eustachian tube walls stick to each other and create a vacuum, which pulls the fluid from the skin cells lining the middle ear. This fluid is called effusion. The presence of effusion may result in a temporary loss of sound intensity (i.e., a conductive hearing loss). To remedy this situation, an otolaryngologist (ear–nose–throat surgeon) may surgically insert a tympanostomy (pressure-equalizing) tube into the eardrum. This tube helps to ventilate the middle ear space, thereby giving the dysfunctional Eustachian tube a chance to heal so that the middle ear cavity is once again aerated normally.

Finally, there are two muscles found in the middle ear, the **stapedius muscle** and the **tensor tympani muscle**. These muscles are specially designed for efficiency. They are (a) very tense, so that they stop vibrating instantly to limit distortion of incoming sound stimuli; (b) very elastic, to dampen

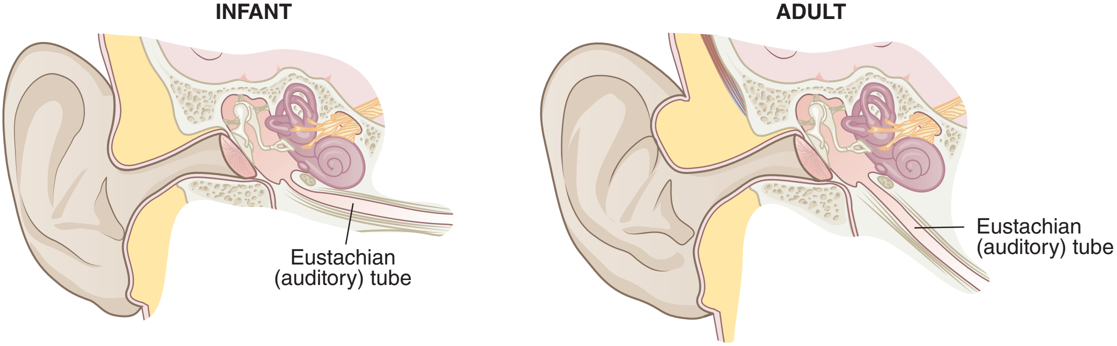

Figure 2.12 The angle difference between infant and adult Eustachian tubes.

(reduce) vibrations; and (c) very small, so that the vibratory energy does not spread. The stapedius muscle inserts into the posterior neck of the stapes and is innervated by the stapedial branch of the facial nerve (cranial nerve [CN] VII). The other muscle, the tensor tympani, originates from the cartilaginous portion of the Eustachian tube and the sphenoid facial bone and inserts into the manubrium. The tensor tympani muscle, which is innervated by trigeminal nerve (CN V), assists in the function of the Eustachian tube. When the tensor tympani contracts, it pulls on the malleus to draw the tympanic membrane inward, which increases the pressure in the middle ear and Eustachian tube. The tensor veli palatini muscle then contracts to open the Eustachian tube.

Bilateral contraction of the middle ear muscles in response to high-intensity sounds stiffens the ossicular chain to reduce the intensity of sounds to the inner ear, thereby serving as a protective mechanism. The tensor tympani muscle contracts to pull the malleus anteriorly and medially and the stapedius muscle contracts to pull the stapes posteriorly, resulting in attenuation of sound pressure reaching the inner ear. Depending on the frequency of the sound, there is a 15- to 20-dB decrease in sound pressure because the middle ear efficiency in transmitting sound energy is in the range of 75–120 dB SPL. This reflex is consensual, so that when either ear is stimulated appropriately, the muscles in both ears contract. It is also important for reducing the upward spread of masking of high frequencies by low-energy sounds because this effect is greatest at frequencies less than 2000 Hz. This information is used clinically with the electroacoustic measurement called the stapedial reflex, which measures the intensity needed to cause contraction of the stapedius muscle. This contraction fatigues because prolonged exposure to high-intensity environments may decrease the degree to which the stapedius contracts, which lessens the effectiveness at damping loud sounds.

The Inner Ear

The inner ear consists of the **auditory labyrinth** and **vestibular labyrinth**, which are intricate pathways in the petrous portion of the mastoid process of each temporal bone. The petrous portion of the temporal bone's mastoid process is the densest bone in the body, protecting the delicate organs of hearing and balance. The auditory and vestibular labyrinths are comprised of two labyrinths: the **osseous labyrinth**, which is a channel in the temporal bone that encases the auditory and vestibular labyrinths, and the **membranous labyrinth**, which consists of soft-tissue, fluid-filled channels within the osseous labyrinth containing the end-organ structures of the hearing and vestibular systems. The auditory labyrinth is called the **cochlea** and is the sensory end organ of hearing; the **semicircular canals** are the sensory end organs of balance. These two end organs are connected via the **vestibule**, which houses two additional organs of balance, the **saccule** and **utricle**.

The cochlea is a snail-shaped, spiral, fluid-filled canal within the temporal bone that, when straightened out, measures about 3.5 cm in length. Within each membranous duct are three chambers—the scalae vestibuli (upper chamber), media (middle chamber), and tympani (lower chamber)—that are filled with fluid. The scalae vestibuli and tympani are incompletely separated by the osseous spiral lamina, a bony shelf protruding from the central core, the modiolus. Circulating through the scalae vestibuli and tympani is **perilymph**, which is secreted by the epithelial lining of the osseous labyrinth and has a higher concentration of sodium ions (Na^+) than potassium ions (K^+), making it chemically similar to extracellular fluid. In contrast, **endolymph**, which has a higher concentration of K^+ than Na^+, is chemically similar to intracellular fluid and is found in the **scala media**. This difference in ionic concentration between endolymph and perilymph gives rise to an **endocochlear electrical potential** ("cochlear battery") of about 180 mV (millivolts) in the scala media, which helps to conduct neural transmission of sound. The "floor" of the cochlear duct is the **basilar membrane**, whereas the membranous roof is called the **vestibular membrane**. Two tissue-covered openings are found on the cochlea: The **oval window** (which is covered by the stapes footplate) is between the basilar membrane and **scala vestibuli**, and the **round window**, which is between the **scala tympani** and middle ear. The membranous portion is slightly smaller than the bony portion; the point where the scalae vestibuli and tympani communicate is called the **helicotrema**.

Within the cochlear duct is the **organ of Corti**, which contains the sensory cells of hearing and which lies on the basilar membrane. These mechanoreceptor cells are shaped like hair and are called, appropriately, hair cells. The **outer hair cells**, of which there are about 15,000, form three rows shaped like a *W* and have their nerve fibers embedded into the **tectorial membrane**, a gel-like membrane that forms the roof of the basilar membrane. Because the basilar and tectorial membranes have different pivot points, vibration of the basilar membrane causes the cilia of the outer hair cells to bend, which alternately hyperpolarizes and depolarizes the nerve fibers of the eighth cranial nerve (CN VIII, auditory portion). **Figure 2.13** shows the movement of the tectorial membrane in response to hair-cell polarization; **Figure 2.14** depicts the electrochemical response of hair-cell polarization within the cochlea. The lengths of the outer hair cells increase at this point of maximum amplitude so that a vigorous electrical response is created by the incoming stimulus. The overall effect of this change of amplitude is a more precise analysis of stimulus frequency because of the different characteristic frequencies of the auditory nerve fibers, which are arranged tonotopically. Near the oval window, at the base, the nerve fibers in the hair cells are attuned to higher frequencies; at the apex, toward the central core of the cochlea, the hair cells are attuned to low-frequency sounds. Outer hair cells are tuned primarily to sound intensity; they act like transducers, changing fluid energy into electrical energy. In fact, this cochlear transduction of sound is like that of a microphone, which changes acoustic energy to electrical energy, and is often referred to as the cochlear microphonic. This transduction function is described as the shearing force and is applied to

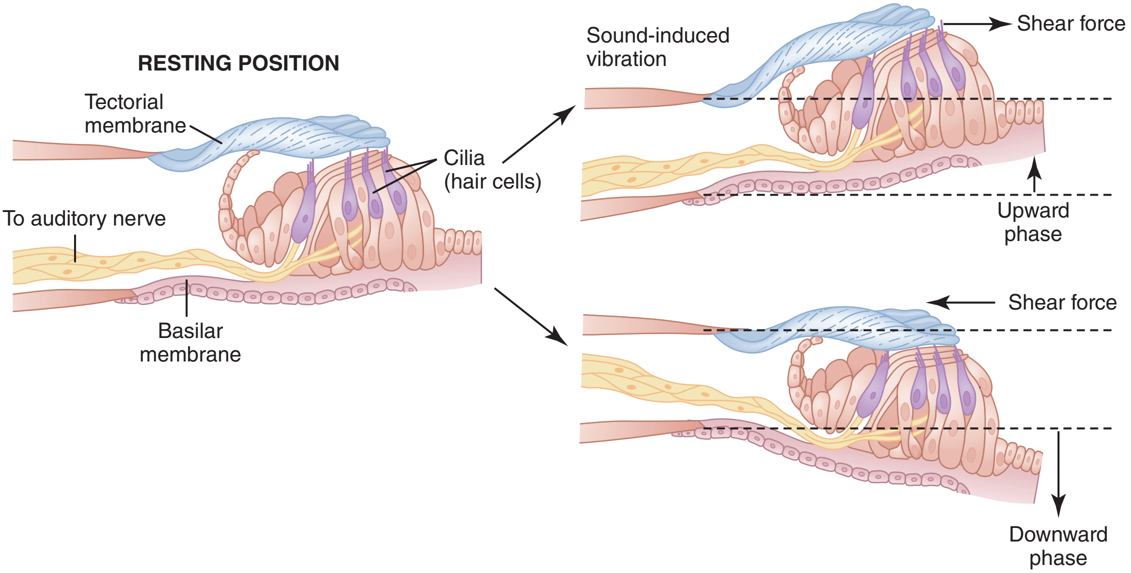

Figure 2.13 Shearing action of the hair cells and movement of the basilar membrane.

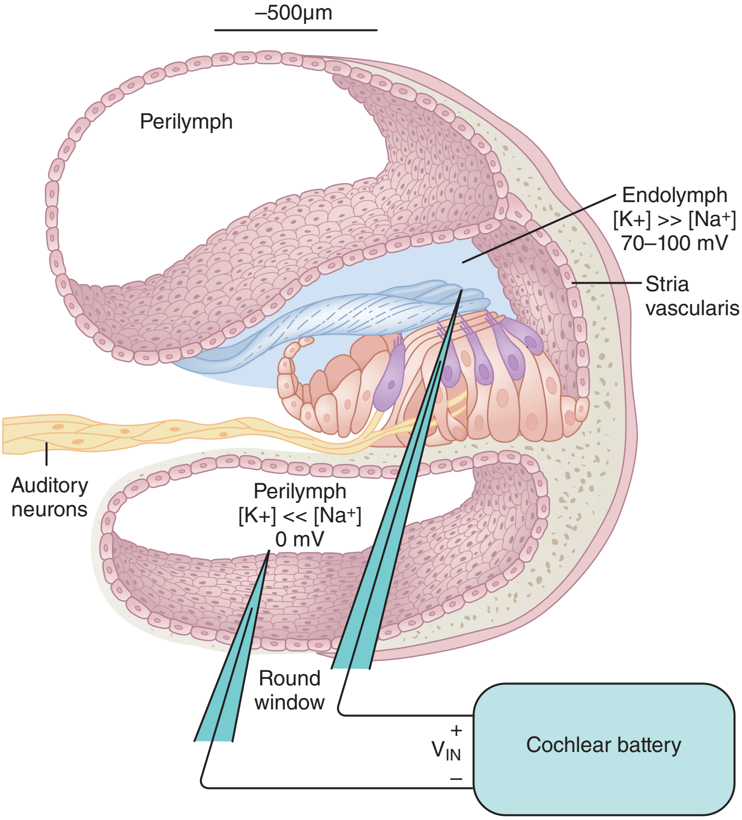

Figure 2.14 Cross-section of the cochlear duct showing membranous structures.

the cilia in response to the acoustic stimulation, giving rise to electrical (i.e., receptor) potentials. Fewer than 10% of the outer hair cells are neurologically connected to the brain, but they enhance the cochlear mechanical response to vibrations so that we can hear lower-intensity sounds. Outer hair cells also generate their own vibrations, both spontaneously and by using an evoking stimulus; we can measure these sounds (called otoacoustic emissions) clinically to determine cochlear function.

Inner hair cells, in contrast, are far fewer in number (about 3,500 altogether), and form a row stretching from base to apex in proximity of the tectorial membrane, near the modiolus (bony core) of the cochlea. However, more than 90% of these hair cells are neurologically connected to the brain via nerve fibers—they preferentially encode sound clarity.

The basilar membrane is where the cochlea begins its analysis of both frequency and intensity of incoming sound signals; these incoming complex sound waves are transformed into simple sine waves similar to Fourier analyses. The stapes footplate rocks back and forth in the oval window, which establishes a transverse wave within the scala vestibuli. Inward displacement of the perilymph at the oval window is matched by the outward displacement of the fluids via the round window due to increased pressure. This perilymph wave displaces the scala media, setting up a wave on the basilar membrane that moves from the base to the apex. The vibrations of the basilar membrane progress dynamically as the incoming traveling waves move from the cochlear base toward the helicotrema at the apical end. The stiffness gradient of the basilar membrane is the primary physical feature that accounts for the direction in which the traveling wave progresses—the greater stiffness in the basal portion of the cochlea opposes displacement when stimulated by low-frequency sound, and forces the wave to travel further up the cochlea toward the apex to a region having less stiffness and less opposition to low-frequency vibration. Thus, more of the basilar membrane is stimulated by low-frequency sounds. High-frequency sounds displace the basilar membrane only near the basal end, at the oval window, and do not travel further toward the apex. This basilar membrane displacement pattern increases gradually in amplitude until the point of maximum amplitude is reached, and then decreases abruptly. There is also a stronger mechanical/electrical response to low- and moderate-intensity sounds; this is called the cochlear amplifier. Although we are uncertain how intensities are encoded in the cochlea, it is thought that the relative rate of nerve impulse spikes transmits this information to the brain (see Zemlin, 1998, pp. 486–487).

The **traveling wave theory** of sound transduction (proposed by Georg von Bekesy [1899–1972], and for which he received the Nobel Prize for Physiology in Medicine in 1961) through the cochlea describes how higher-frequency sounds are analyzed (Zemlin, 1998). This theory does not account for all basilar membrane mechanics, however, because the membrane itself is not displaced sharply enough to distinguish low-frequency sounds by place of stimulation. As noted in Zemlin (1998), Ernest Glen Wever hypothesized in 1937 and published in 1949 that low-frequency sounds are determined by the number of clusters of firing nerve fibers in synchrony with the low frequency; high-frequency sounds are analyzed through place theory (because neurons cannot fire at high frequencies) and/or volley theory (which describes cooperation of neurons in neural transmission of high frequencies).

Retrocochlear Pathway and Auditory Cortex

The auditory nerve fibers fire in an all-or-nothing fashion, needing only about 2 ms to rise to maximum amplitude of neural firing. They are arranged on the basilar membrane in a tonotopic fashion—nerve fibers at the apical end of the cochlea respond preferentially to low-frequency stimuli, and high-frequency sounds are encoded at the base. Similarly, the auditory nerve is tonotopically arranged so that low-frequency sounds are found in the core of the auditory nerve and high-frequency sounds are arranged around the periphery. Thus, the brain obtains information regarding frequency of the incoming sound. In addition to frequency coding, the neural fibers of the auditory nerve also encode intensity for sounds with frequencies less than 5000 Hz; neural firing approximates the period of the stimulus waveform.

Neural firing of the auditory portion of CN VIII generates action potentials; this electrical signal then travels from the cochlea to the auditory cortex in the temporal lobe. Although most of these fibers travel up to the auditory cortex to form the ascending (afferent) pathways, some neural fibers travel from either the brainstem or auditory cortex to form the descending (efferent) pathways. All auditory nerve fibers terminate at the level of the ipsilateral cochlear nucleus, where frequency and timing information about the auditory stimulus are further encoded. Although some neural pathways are ipsilateral and project into the next structure along the central auditory pathway (**Figure 2.15**), the superior olivary complex (in the medulla), most of these afferent pathways are contralateral (opposite side) so that the nerve fibers decussate (cross over) to the opposite superior olivary complex. Therefore, auditory information from both ears is represented in each ear, which enables us to localize sounds in space

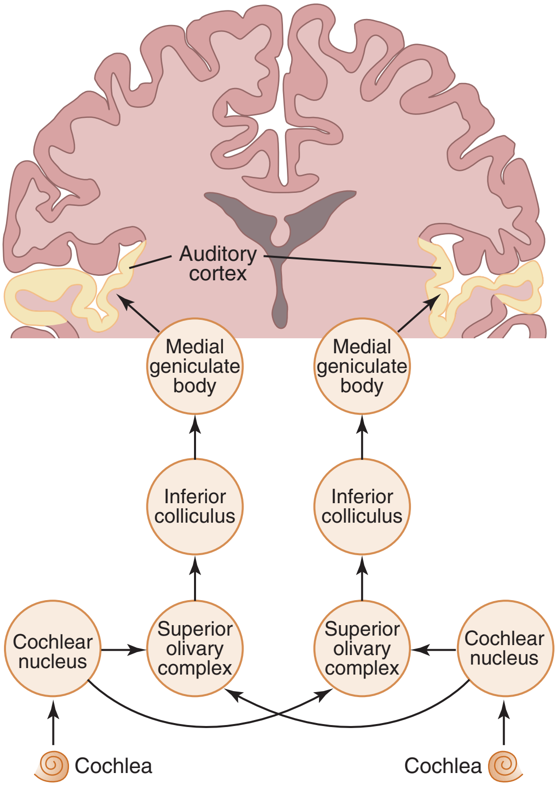

Figure 2.15 The central auditory pathway.

and to improve speech perception because ipsilateral fibers are excitatory and contralateral fibers are inhibitory. In addition, low-frequency stimuli are encoded for differences in timing, whereas high-frequency stimuli are encoded for differences in latency. Other structures along the afferent auditory pathway include the lateral lemniscus (at the level of the pons), the inferior colliculus (in the midbrain, where the second decussation occurs), and the medial geniculate body (at the level of the thalamus), where all ascending fibers terminate before radiating into the appropriate cortex (in this case, the auditory cortex). **Tonotopic organization** of frequency to place is preserved throughout the afferent auditory pathway, which preserves the redundancy of speech.

The auditory cortex is located in the temporal lobes of the brain and is divided into three basic areas: primary, secondary, and tertiary cortices. The primary auditory cortex, the first cortical region of the auditory pathway, is tonotopically arranged in a fashion similar to that found in the cochlea and is largely responsible for discrimination of frequency and intensity of the incoming auditory stimulus. The location of a sound stimulus in space is also identified in the primary auditory cortex. The secondary and tertiary auditory cortices are largely responsible for language production, processing, and perception, and include **Broca's area** (inferior frontal gyrus), where motor production of language and processing of sentence structure, grammar, and syntax are located, and **Wernicke's area** (in the lower temporal lobe), where speech perception is located. In addition, other areas within the brain—the superior temporal gyrus (where morphology and syntactic processing occur in the anterior section, and integration of syntactic and semantic information in the posterior section), the inferior frontal gyrus (working memory and syntactic processing), and the middle temporal gyrus (lexical semantic processing)—contribute to language comprehension. In almost all right-handed individuals, the left hemisphere is usually dominant, with bilateral activation occurring for syntactic processing; this left hemisphere dominance is true for most left-handed individuals also. The right hemisphere is important in processing suprasegmental features like prosody and melodic contours.

Although the retrocochlear auditory pathway is primarily sensory and contains afferent pathways from the cochlea up to the auditory cortex, a complex efferent system is also present containing descending neural fibers that correspond closely to the ascending auditory fibers. These efferent fibers connect the auditory cortex to the central auditory pathway and to the cochlea, and are thought to inhibit neural activity along this pathway to increase neural activation at lower brain centers. This inhibitory feedback improves stimulus processing by decreasing background noise that may interfere with the stimulus.

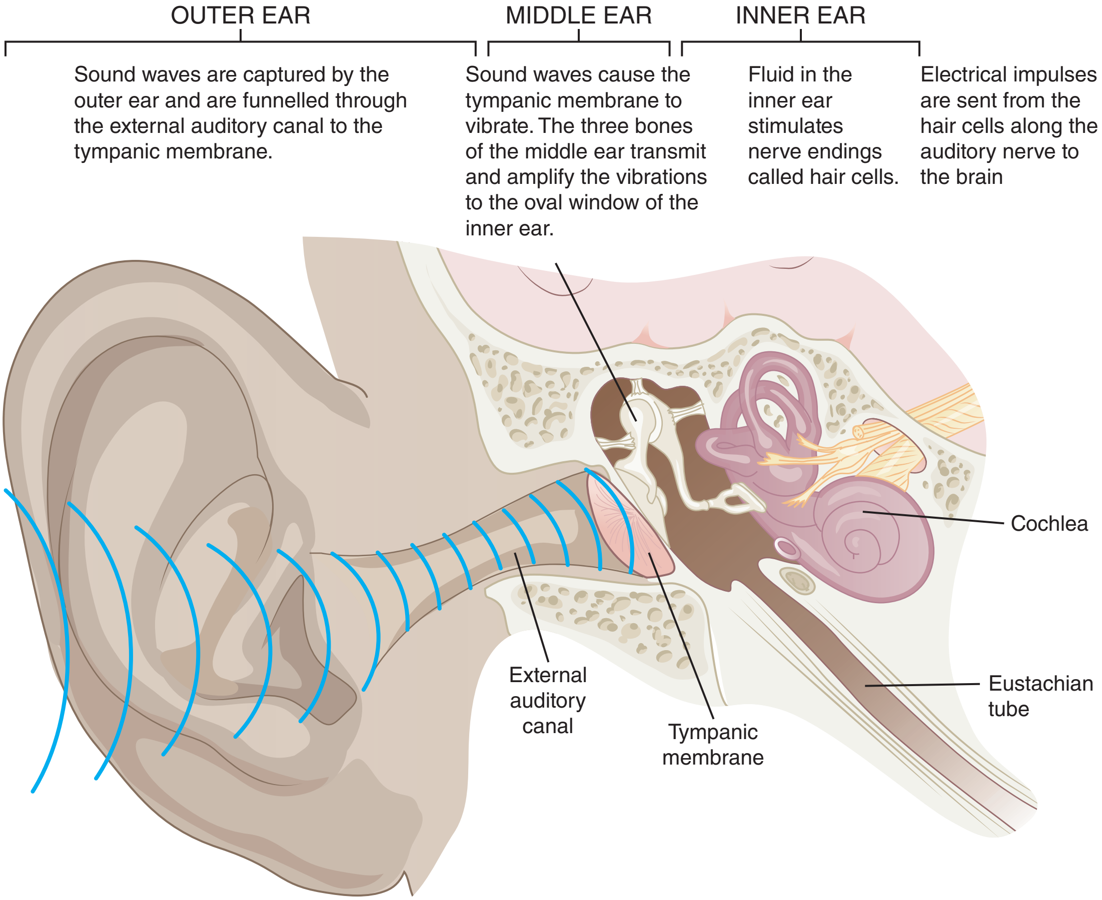

Figure 2.16 An overview of the process of sound transduction through the auditory system.

Figure 2.16 provides an overview of the process of sound transduction through the auditory system.

Hearing Loss: An Error of Sound Transduction

Hearing loss may occur at any point along the auditory pathway. When damage occurs in the outer and/or middle ears, a conductive hearing loss is the result. Some examples of **conductive hearing loss** include outer ear disorders such as microtia (small or absent pinna) and atresia (lack of external auditory meatus), and middle ear disorders such as otitis media with or without effusion (fluid in the middle ear space) and otosclerosis (fixation of the stapes footplate to the oval window of the cochlea). Disorders affecting the outer and/or middle ear are usually amenable to medical and/or surgical intervention to correct the problem. Conductive hearing loss results in the decrease of sound intensity reaching the cochlea; typically, clarity of speech is preserved in conductive hearing loss because the cochlea is usually unaffected. However, chronic conductive hearing loss can also affect speech perception because of alterations in the normal inertial mechanisms of the middle ear, which affect conduction of sound through bone.

Those individuals whose hearing loss is found in the inner ear have sensorineural hearing loss.

Sensorineural hearing loss occurs due to damage to the cochlea and/or retrocochlear pathway, resulting in alterations of perception of sound frequency and intensity. In addition to a decrease of sound intensity, sensorineural hearing loss also results in a loss of speech clarity due to damage to the neural fibers located in the cochlea. Examples of sensorineural hearing loss include acoustic trauma from noise, tumors on CN VIII, ototoxic agents like loop diuretics, systemic neural diseases like diabetes mellitus, hypoxia (lack of oxygen), meningitis (both bacterial and viral, leading to inflammation of the meninges covering the brain), and Ménière's disease (which results in an increase of endolymph fluid in the cochlea, leading to fluctuating hearing loss, aural fullness, and/or vestibular dysfunction). Sensorineural hearing loss may also result from the normal aging process (presbycusis), leading to both cochlear and retrocochlear dysfunction, and which usually results in poorer speech understanding due to damage to the cochlea and higher auditory centers.

When both conductive and sensorineural components are present in hearing loss (e.g., an individual with sensorineural hearing loss develops otitis media), a **mixed hearing loss** results. Mixed hearing loss may result from complications of middle ear surgery, otosclerosis, and the like. Medical/surgical intervention may limit the conductive portion of the hearing loss, but the sensorineural component of the loss is still present.

SUMMARY

To understand hearing and the presence of hearing loss, one must first understand what sound is. Sound is defined as the movement of a disturbance through an elastic medium (such as air molecules) without permanent displacement of the particles. There are three prerequisites for production of sound: (1) a source of energy such as a force, (2) a vibrating object that generates an audible pressure wave, and (3) a medium of transmission. Sounds may be described by their frequency, intensity, and phase, all of which are physical characteristics that are measurable. Sound moves through the human ear in stages—the outer ear (which collects sound), the middle ear (which acts as a transducer to change acoustic energy to fluid energy via mechanical energy), and then the inner ear (which sends frequency and intensity information up to the brain via the central auditory pathway). Errors in sound transduction and the location of that damage will determine the presence and type of hearing loss that results. As we journey through how a hearing loss is determined and resulting treatments, the basic understanding of sound and its transmission is crucial as the underlying concept.

DISCUSSION QUESTIONS

1. List the characteristics of sound.
2. What is simple harmonic motion?
3. How are the characteristics of frequency and pitch related?
4. How are intensity and loudness related?
5. Why do we use the decibel to describe sound intensity?
6. For each part of the ear, identify the type of energy used for sound transduction.
7. What is the primary function of the middle ear?
8. In the inner ear, name the end organs of hearing and balance.
9. What does the term *tonotopic organization* mean regarding cochlear function?

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