teaches children how to start a conversation, make a request, solve a problem, negotiate, compromise, joke, tease, and use sarcasm.

Any degree of hearing loss presents a barrier to the casual acquisition of information from the environment.

Spoken Communication Function

Children learn to talk through listening—through paying attention to auditory information (Golinkoff, 2013; Hirsh-Pasek et al., 2015; Werker, 2006). Not surprisingly, spoken communication does not develop naturally or completely for an infant or child whose brain does not receive complete auditory information, unless technology and specific auditory strategies are used to improve the quantity and quality of their auditory brain access.

Verbal language takes form after a great deal of auditory information reaches the brain, augmented by active listening experience (Estabrooks, 2006; Golinkoff, 2013; Hayes et al., 2009; Lew et al., 2014; Ling, 2002). Because the inner ear is fully developed by the fifth month of gestation, an infant with normal hearing potentially has 4 months of in utero auditory brain stimulation prior to birth (Moon et al., 2013; Simmons, 2003). At approximately 1 year of age, after 12 months (or maybe 16 months if we count before-birth listening) of meaningful and interactive listening, a normal hearing child begins to produce words. The point is that listening time cannot be skipped, and a child who misses months of brain access due to hearing loss must make them up (Estabrooks, 2012; Estabrooks et al., 2016). The brain requires extensive listening experience to properly organize itself around the speech signal. Importantly, infants also must hear their own vocalizations, creating an auditory feedback loop that is a critical component motivating early vocalization frequency (Fagan, 2014).

The brain benefits from practice listening to music as well as speech. For babies and young children, we mean adult-directed, in person, singing as a social experience—not turning on a recording. Studies provide biological evidence that listening to music boosts the brain's ability to distinguish emotional aspects of speech by focusing on the paralinguistic (nonverbal) elements of speech (Sheridan & Cunningham, 2009). In addition, music training in children activates the cognitive functions of attention and memory and improves speech-in-noise performance (Kraus & Anderson, 2014).

Acoustics

To understand the causes of hearing loss, it is first important to establish an appreciation of the human ear. Though this intricate and complex mechanism may not appear very impressive from the outside, the inner structures of the ear enable a person to access a 10,000,000-to-1 range of sensitivity from the softest sound that can barely be detected to one that is loud enough to cause pain (Hall, 2014). The typical human ear has such amazing sensitivity that it can nearly detect random molecular movement.

When hearing sound, the brain interprets a pattern of vibrations initiated from a source in the environment. Vibrational energy produces the sound waves we can hear. Therefore, hearing is an event (Boothroyd, 2019). That is, we don't "hear mommy." We hear mommy talking, walking, eating, and so on. We hear the vibrations created by an action. Vibrations need two properties: mass and elasticity. Sound waves are similar to ring patterns in water produced when a pebble is thrown into a pond, only with sound, the waves are formed by the vibration of air molecules. Much like the effect of water ripples, sound waves originate from a point where the sound is first generated and spread out in circles of waves.

The speed at which sound travels through the air is called *velocity*. Sound travels through the air as fast as 770 miles per hour at sea level, or 1,130 feet per second. Water waves travel much slower, only a few miles an hour.

Graphed as a circle on a flat plane plot, a *sine wave* is the simplest form of sound called *simple harmonic motion*; it is heard as a pure tone (Figure 2–1).

The riddle, "If a tree fell in the forest and no one was around, would a sound still be made by the falling tree?" serves as a good example of whether one describes sound from a physical or psychological basis. The answer depends on one or the other. Existing independently of the observer are the physical parameters of intensity, frequency, and duration; these features can be measured by equipment. However, the psychological perceptions of loudness, pitch, and time require the presence of a person for interpretation.

Our ability to hear sound is defined by the three characteristics of frequency, intensity, and duration. A hearing loss may affect one's ability to receive and thus to perceive one or all of these features.

The psychological attributes of sound are pitch and loudness. The physical

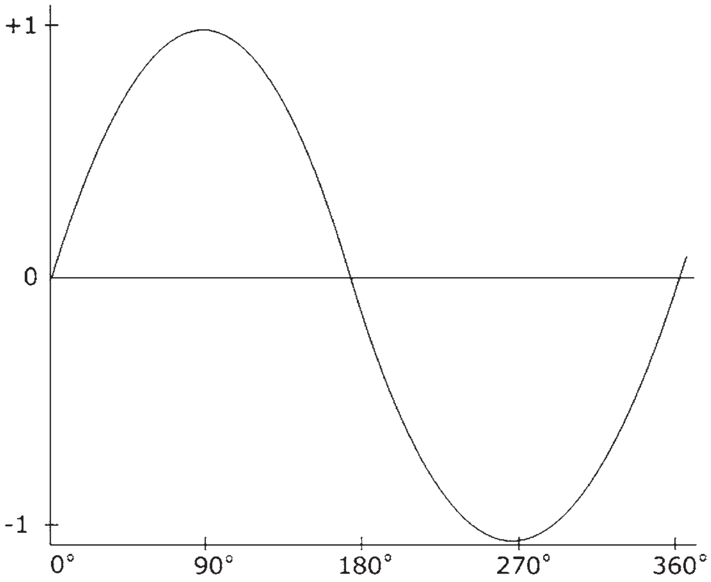

Figure 2–1. Graphed as a circle on a flat plane plot, a sine wave is the simplest form of sound.

parameter of frequency corresponds to the psychological attribute of pitch. The listener hears high-frequency sounds as high in pitch, whereas the perception of low-frequency sounds is that of a low pitch. The physical parameter of intensity or sound pressure is the psychological correlate of loudness. So, when a sound has more intensity—more sound pressure—the listener perceives it as louder.

The number of back-and-forth oscillations produced by a sound source in a given time period is called *frequency*. The terms *hertz* (Hz) and *cycles per second* (cps) are measures of frequency. By counting the number of cycles per second of a sound wave, one can measure the frequency of sound. The distance between the top (crest) of one sound wave and the top of the next sound wave is one cycle. To have a frequency of 1000 Hz, a sound source would need to complete 1,000 back-and-forth cycles in 1 second. Low frequencies are characterized by fewer cycles per second, whereas many cycles per second indicate a higher-frequency sound. In Figure 2–2 the frequency of the sound increases as the wavelengths

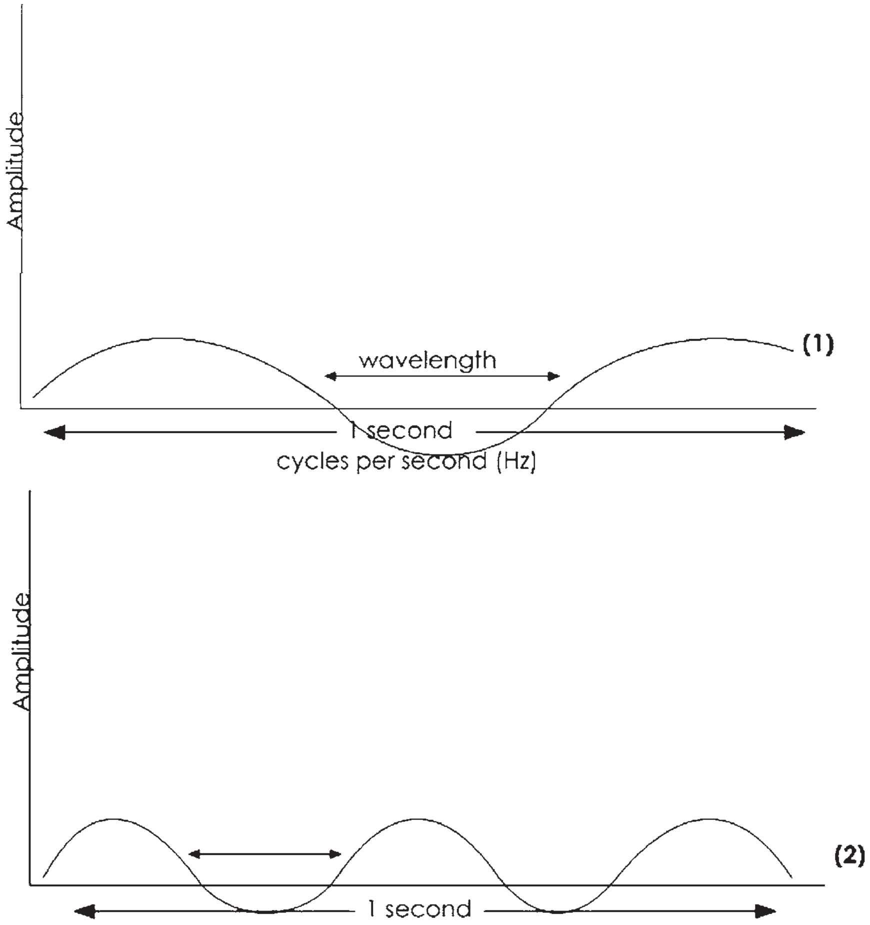

Figure 2–2. Low frequencies are characterized by fewer cycles per second, whereas many cycles per second indicate a higher-frequency sound.

become shorter and the number of cycles per second increases. Interestingly, frequency is independent of distance (Chasin, 2018). For example, the vowel /a/ will still sound like /a/ whether you are close to the speaker or at the other end of the room.

Although humans can hear frequencies ranging from 20 to 20,000 Hz, frequencies between 250 and 8000 Hz are of particular importance for the perception of speech. Middle C on the piano corresponds to 262 Hz. Frequencies of 500 Hz and below are identified as low-pitched sounds, and they have a bass quality. Relative to individual speech sounds (phonemes), those that are low pitch carry melodies of speech, vowel sounds, and most environmental sounds (Kramer & Brown, 2019). On the other hand, high-pitched sounds are 1500 Hz and above, and they have a tenor quality. The high frequencies are important for understanding speech because they carry the energy that helps distinguish among the consonants. Put simplistically, the meaning of speech is carried by high frequencies (mostly consonants), whereas low frequencies carry the melody. About 70% of all English speech sounds are above 1000 Hz, making speech discrimination more of a high-frequency event. Contrastively, music is more of a low-frequency event because about 70% of all fundamental frequencies are below 1000 Hz.

The softest and loudest sounds in conversational speech are separated by approximately a 30 dB range. The *th* sound, as in *thin*, is the least intense speech sound. The most intense speech sound is /a/ as in *law*. Table 2–1 has a more detailed description of speech information carried by each relevant frequency.

A sound's intensity can be defined as pressure or power. Graphed as the amplitude of a sine wave caused by displacement of air molecules, intensity is measured in decibels (dB) and perceived as loudness (Figure 2–3). The degree of air particle displacement that occurs while a sound is made determines a sound's intensity. The abbreviation dB stands for decibel; the "B" is capitalized in honor of Alexander Graham Bell. The hearing level (HL), defined as 0 dB HL, is the softest sound a young adult with normal hearing can just barely detect. The loudness of a person whispering a few feet away is about 25 to 30 dB HL. Typical conversational speech in a quiet environment when the speaker is a few feet away is heard at 45 to 50 dB HL. City traffic is about 70 dB HL, a food blender is about 90 dB HL, an alarm clock is about 80 dB HL, a rock concert can be louder than 110 dB HL, a jet airport can produce sounds reaching an intensity as high as 120 dB HL, and a firecracker can produce a bang at approximately 140 dB HL (Hall, 2014; Northern & Downs, 2014).

Because the decibel has a logarithmic and not a linear scale, every dB counts a great deal. For example, if a sound increases or decreases 10 times in intensity, the change is only 10 dB. A 20 dB change means a sound is 10 × 10, or 100 times the intensity of the original sound. The average hearing loss caused from ear infections is about 20 dB—usually described as a "slight" or "minimal" hearing loss. When understanding the dB scale as logarithmic, one recognizes that in reality, the child's slight hearing loss means that the auditory information available to the brain is approximately 100 times weaker when the fluid is present than can be heard when the fluid is cleared.

Most environmental sounds are complex in structure. Complex sounds are composed of many frequencies with varying intensities occurring at the same time.

Table 2–1. Speech Information Carried by the Key Speech Frequencies of 250 to 4000 Hz (± one-half octave)

250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
• First formant of vowels /u/ and /i/ • Fundamental frequency of females' and children's voices • Nasal murmur associated with the phonemes /m/, /n/, and /ng/ • Prosody • Suprasegmental patterns (stress, rate, inflection, intonation) • Male voice harmonics • Voicing cues	• First formants of most vowels • Harmonics of all voices (male, female, child) • Voicing cues • Nasality cues • Suprasegmentals • Some plosive bursts associated with /b/ and /d/	• The important acoustic cues for manner of articulation • Second formants of back and central vowels • Consonant-vowel and vowel-consonant transition information • Some plosive bursts • Voicing cues • Suprasegmentals • Unstressed morphemes	• The important acoustic cues for place of articulation • The key frequency for speech intelligibility • Second and third formant information for front vowels • Consonant-vowel and vowel-consonant transition information • Acoustic information for the liquids /r/ and /l/ • Plosive bursts • Affricate bursts • Fricative turbulence	• The key frequency for /s/ and /z/ audibility that is critical for language learning: – plurals – idioms – possessives – auxiliaries – third-person singular verb forms – questions – copulas – past perfect • Consonant quality

Source: Adapted from Ling, D. (2002). *Speech and the Hearing-Impaired Child* (2nd ed.). Washington, DC: The Alexander Graham Bell Association for the Deaf and Hard of Hearing (http://www.listeningandspokenlanguage.org). Reprinted with permission. All rights reserved.

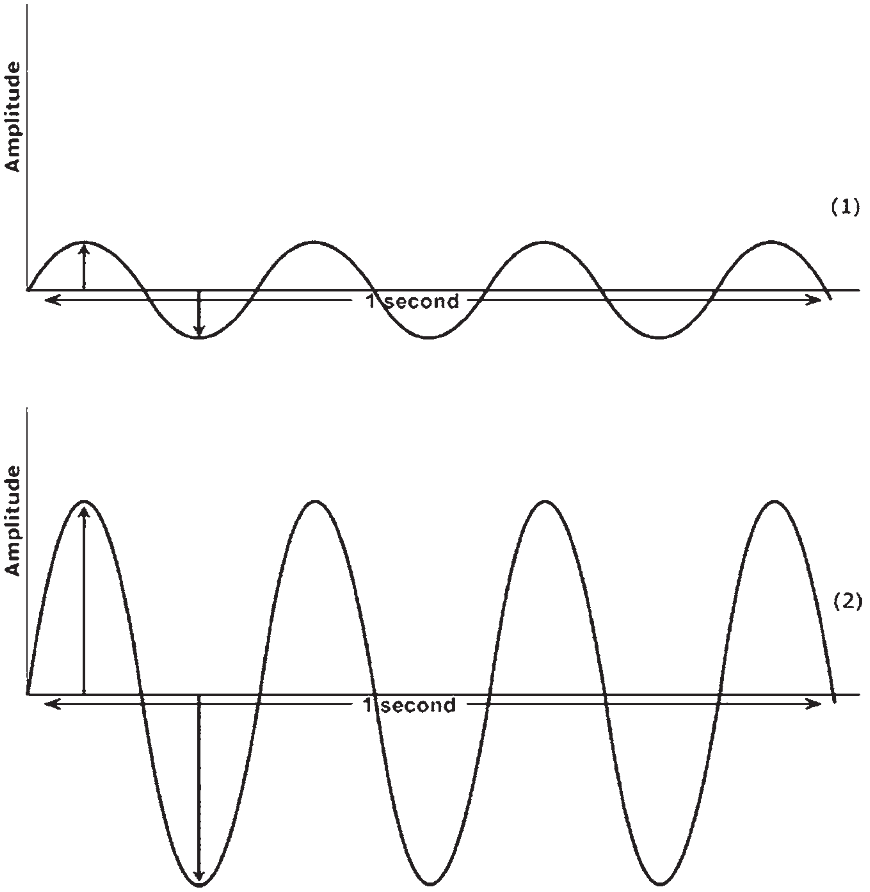

Figure 2–3. Graphed as the amplitude of a sine wave caused by displacement of air molecules, intensity (sound pressure) is measured in decibels (dB) and perceived as loudness.

Speech is one example of a complex sound. The spectrum of a speech wave specifies the frequencies, amplitudes, and phases of each of the waves' sinusoidal components.

In all learning domains—home, school, and community settings—there are a variety of sounds from many sources. Undesirable sounds typically are referred to as *noise*. Noise levels tend to be more intense in the low frequencies and less powerful at the high frequencies. The weaker consonant sounds (i.e., *th, s, sh, f, p*) are more affected by noise than are the louder vowel sounds. In noisy situations, the intelligibility of speech (the ability to hear word-sound distinctions clearly) is compromised even though the sounds might still be audible.

Audibility Versus Intelligibility of Speech

There is a big difference between an *audible* signal and an *intelligible* signal. Speech is audible if the person is able simply to detect its presence. However, for speech to be intelligible, the person must be able to discriminate the word-sound distinctions of individual phonemes and speech sounds. Consequently, speech might be very audible but not consistently intelligible to a child with even a minimal hearing loss, causing the child to hear, for example, words such as *walked*, *walking*, *walker*, and *walks*, all as “ah.”

Vowel sounds (e.g., *o, u, ee*) have strong low-frequency energy, about 250 to 500 Hz. They are the most powerful sounds in English. Vowels carry 90% of the energy of speech. On the other hand, consonant sounds (like *f* and *s*) are very weak high-frequency sounds, with energy focused at 2000 and 4000 Hz and above (see Table 2–1). Consonants carry only 10% of the energy of speech but 90% of the information needed to perceive the differences among the sounds. The octave band at 2000 Hz carries the greatest amount of speech information. For speech to be perceived clearly, both vowels and consonants must be acoustically available to the brain. Persons with hearing losses typically have the most difficulty hearing the weak, unvoiced, high-frequency consonant sounds.

There is a science called speech acoustics that informs our analysis of the relationship between the child’s brain perception of auditory information and their motor production of speech; children speak what and how they hear.

The Ling 6-7 Sound Test: Acoustic Basis and Description

The Ling sound test allows a quick and easy way to verify that a child detects the vowel and consonant sounds of spoken language (Ling, 2002; Perigoe & Paterson, 2013). The sounds used for this test were selected because they encompass the entire speech spectrum as noted below:

- /m/ corresponds to 250 Hz, plus-minus one-half octave.
- /u/ is like a narrow band of noise corresponding to 500 Hz on the audiogram, plus-minus one-half octave.
- /a/ corresponds to 1000 Hz, plus-minus one-half octave.
- /sh/ is a band of noise corresponding to 2000 Hz, plus-minus one-half octave.
- /s/ is a band of noise corresponding to 4000 Hz and higher.
- /i/ has a first formant (resonance of the vocal track) around 500 Hz, and a second formant around 2000 Hz; the second formant must be heard for

The Ling 6-7 Sound Test allows parents, professionals, and teachers to know the child’s distance hearing or earshot. Knowing a child’s distance hearing has vital instructional ramifications if one intends to use audition as a viable modality for the reception of information. Sounds must first be detected before the brain can be stimulated. Frequent administration of this test can help parents, professionals, and teachers monitor for hearing aid malfunction and/or cochlear implant failure, changes in the child’s hearing, or onset of middle ear conductive involvement that would be reflected by reduced earshot. Refer to Chapter 4 for a further discussion of distance hearing, and to Appendix 2 for specific Ling 6-7 Sound Test application and instructions.

the listener to be able to distinguish between front and back vowels.

- The silent interval is really a seventh "sound" that is necessary to track false-positive responses.

Audiovestibular Structures

The ear develops from the same embryonic layer as the central nervous system (Northern & Downs, 2014). This means that normal development of the auditory mechanism including neural innervation begins in the early weeks of embryological development. At the time of birth, the auditory system of a baby with normal hearing has been sufficiently developed to have allowed acoustic brain stimulation beginning in the 20th week of gestation. Middle ear structures are developed and functional by the 37th week of prenatal development. Interestingly, the external ear and auditory canal continue to grow as the child grows, up to the age of about 9 years (Hall, 2014; Simmons, 2003).

The auditory system is an incredible structure. Figure 2–4 shows a cross section of the auditory system. The peripheral portion can be subdivided into three general areas: the outer ear, the middle ear, and the inner ear; the central portion includes the brainstem and cortex.

To understand how the auditory system breaks down resulting in hearing loss, it is first necessary to discuss how the ear is put together and how it normally functions.

Data Input Analogy

Together, the outer, middle, and inner ear are known as the *peripheral auditory system* and function to receive sounds. The brainstem and auditory cortex, called the *central auditory system*, take the sounds that are received through the peripheral system and code them for more complex, higher-level auditory processes.

Therefore, two general processes of hearing exist: (a) transmission of sounds to the brain through the outer, middle, and inner ear; and (b) understanding the meaning of those sounds once they have been transmitted to the brain. Before understanding can take place, sounds (auditory information) must first be heard, similar to how computer data input precedes data manipulation. There can be no auditory perception without the sensory evidence of sound input (Berlin & Weyand, 2003; Boothroyd, 2019).

One way to illustrate the potentially negative effects of any type of a degree of hearing loss on a child's language and overall development and to further explain the peripheral-central distinction is to use a computer analogy. The primary concept is that *data input precedes data processing*.

> *It is important to recognize that when we talk about hearing "sounds," what is meant is the reception and transmission of auditory information and knowledge from the environment through the outer, middle, and inner ear to auditory brain centers where the child learns, through exposure and practice, the meaning of the auditory event.*

An infant or toddler (or anyone) must have information or data to learn. A primary avenue for entering information into the brain is through the ears, via

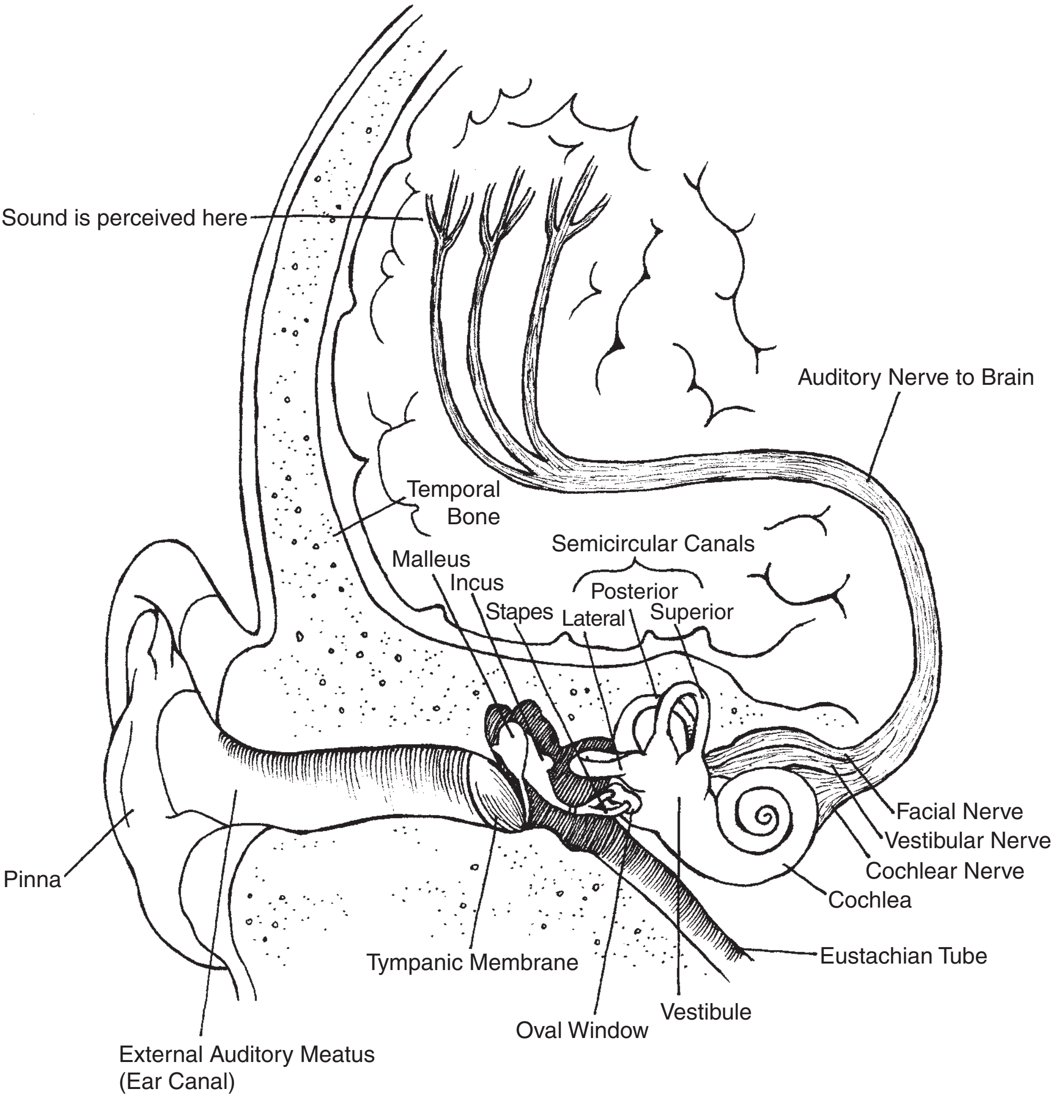

Figure 2–4. The peripheral portion of the ear can be subdivided into three general areas—the outer ear, the middle ear, and the inner ear; the central portion includes the brainstem and cortex.

hearing. So, the ears can be thought of as analogous to a computer keyboard, and the brain could be compared to a computer hard drive. As human beings we are neurologically wired to code and hence to develop spoken language and reading skills through the auditory centers of the brain, the hard drive (Pugh, Sandak, Frost, Moore, & Menci, 2006; Sharma et al., 2004; Sharma & Nash, 2009). Therefore, auditory data input is critical, and it is worth our time and effort to make detailed auditory information available to a child with any degree of hearing loss. If data are entered inaccurately, incompletely, or inconsistently, analogous to using a malfunctioning computer keyboard or to having one's fingers on the wrong keys on a computer keyboard, the child's brain or hard drive will have incorrect or incomplete information to process. How can a child be expected to learn when the information that reaches his or her brain is deficient? The brain can organize itself only around the information that it receives.

Amplification technologies, such as hearing aids, personal remote microphone (RM) systems, sound-field systems, and biomedical devices such as cochlear implants can all be thought of as keyboards—as a means of entering acoustic information into the child's hard drive. So, technology is really a more efficient keyboard. Unfortunately, technology is not a perfect keyboard and it does not have a life of its own, any more than a car has a life of its own. Technology is only as effective as the use to which it is put, and only as efficient as the people who use it. Conversely, without the technology, without acoustic data input, auditory brain access is not possible for persons with hearing loss.

To continue the computer analogy, once the keyboard is repaired or the figurative "fingers" are placed on the correct keys of the keyboard—allowing data to be entered accurately, analogous to using amplification technology that enables a child to detect word-sound distinctions—what happens to all of the previously entered inaccurate and incomplete information? Is there a magic button that automatically converts inaccurate data stored in the brain to complete and correct information? Unfortunately, all of the corrected data need to be reentered. Thus, the longer a child's hearing problem remains unrecognized and unmanaged, the more destructive and far-reaching are the snowballing effects of hearing loss. **Early intervention is critical—the earlier the better.**

Hearing is only the first step in the intervention chain. Once the auditory brain has been accessed as much as possible through appropriate amplification or biomedical technology, the child will have an opportunity to discriminate word-sound distinctions as a basis for learning language, which in turn provides the child with an opportunity to communicate and acquire knowledge of the world. All levels of the acoustic filter effect of hearing loss discussed previously need to be understood and managed. In other words, just medically managing/correcting a conductive hearing loss, or simply wearing hearing aids or a cochlear implant, does not ensure development of an effective language base.

The longer a child's peripheral auditory system remains unmanaged, the longer data entry to the central auditory system (the brain) will be incomplete and inaccurate, causing the snowballing effects of the acoustic filter to negatively impact the child's overall knowledge and life development. Conversely, the more intelligible and complete the data entered are, the better opportunity the infant or toddler will have to learn language that serves as a foundation for later reading and academic skills. **It cannot be said enough; the peripheral auditory system (the doorway) must be managed and accessed early to provide the best acoustic access of information to the central auditory network—the brain.**

The point is, from the inception of early intervention programming, comprehensive audiologic and hearing management is an absolutely necessary first step for a child of any age and with any type of hearing or listening difficulty to have an opportunity to learn.