The Nature Of Hearing And Hearing Loss

I wonder about the trees/Why do we wish to bear/Forever the noise of these/More than any other noise/So close to our dwelling place… From *The Sound of Trees* by Robert Frost

By Kathryn H. Arehart, Ph.D.

If a tree falls in a forest and no one is there to hear it, does it make a sound? The answer to this question depends on the way in which we define sound. An objective definition of sound relates to a physical characterization of pressure waves traveling through the air. A subjective definition relates to the human perception of the physical disturbance caused by the sound source.

Soundscapes may contain many different sounds: in addition to the sound of trees, there may be also be the sounds of distant thunder, a mountain quail and a running stream. As Plomp points out,

> When we say that we hear one or another "sound" we refer to our ability to identify the various percepts one to one with their sources. Implicitly, such usage also indicates that although the vibrations produced by the various sound sources are superimposed seemingly inextricably in the air, the ear is able to disentangle these vibrations so faithfully that we are not aware of the fact that they were ever mixed. [Plomp, 2002, *The Intelligent Ear*, page 1]

This disentanglement typically occurs without our awareness except when something interferes with the natural process. This interference can be competing vibrations (e.g., an airplane flying over a natural soundscape) or it can be due to a problem within the auditory system itself. The purpose of this article is to describe the nature of human hearing and how hearing loss can disrupt the ability to listen within a soundscape.

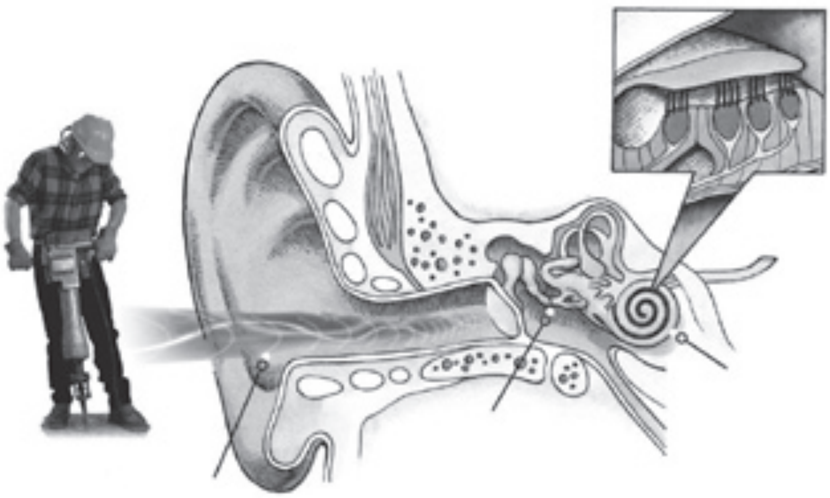
Nature of Hearing

Hearing involves a complex process in which the auditory system changes sound vibration from the environment into neural impulses that the brain perceives as sound. As shown in Figure 1, the ear has three major parts. The outer ear consists of the pinna (which is the part of the ear that is visible) and the outer ear canal. The eardrum separates the outer ear from the middle ear. The middle ear is an air-filled space that contains the ossicles, which are three small bones called the malleus, incus and stapes. The stapes interfaces with a membrane called the oval window, which forms a boundary between the middle ear and the inner ear. The inner

Figure 1—How We Hear

Healthy inner-ear nerves (hair cells) are the key to good hearing. Although some die off naturally as you age, many more are killed early if your ears aren't protected from harmful noise.

Courtesy, E. Berger, Aearo Co.



Hair cells within the cochlea of the inner ear respond to vibrations by generating nerve (electrical) impulses. The brain interprets these as sound.

The outer ear collects and funnels sound waves along the earcanal to the eardrum

The middle ear contains a chain of three tiny bones, called ossicles, which link the eardrum to the inner ear. When sound waves strike the eardrum, the ossicles conduct the vibrations to the cochlea in the inner ear.

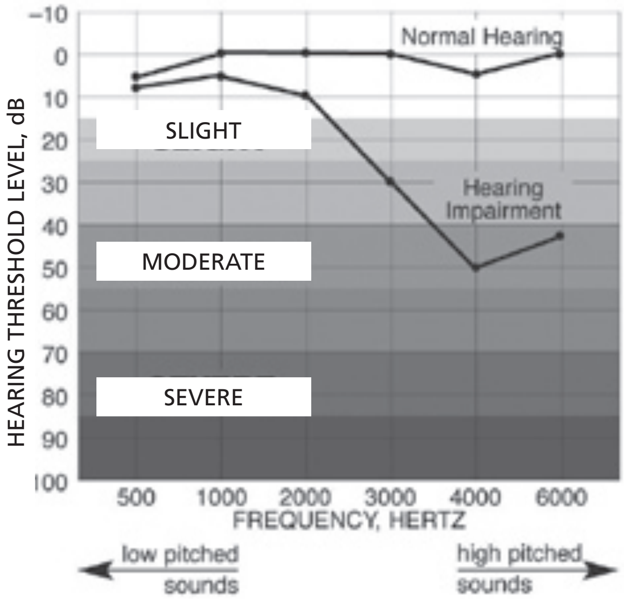


Fig 2—Degrees of hearing loss with audiometric profiles representative of normal and impaired hearing.

Courtesy, E. Berger, Aearo Co.

ear is fluid filled and consists of the sensory organs for hearing (the cochlea) and for balance (the semicircular canals). Within the cochlea are rows of hair cells. The hair cells communicate with nerve fibers in the hearing nerve, that in turn connect to the auditory cortex in the brain by way of the central auditory nervous system.

The outer and middle ears are the *conductive* part of hearing. The outer ear collects sounds from the environment. When sound waves travel through the ear canal and strike the eardrum, the sound waves cause the vibrations to be transmitted through the chain of ossicles and transferred to the fluids of the cochlea. The cochlea and hearing nerve are called the *sensorineural* part of hearing. The cochlea transduces sound vibrations into neural impulses that are sent along the hearing nerve up to the auditory cortex in the brain. The cochlear hair cells are an essential part of this transduction process. As the stapes pushes and pulls on the oval window, it causes the fluid within the cochlea to move. This fluid movement causes the hair cells to bend and release neurotransmitters, which in turn causes the hearing nerve fibers to fire. The cochlea is organized with a frequency map, such that higher frequencies are processed closest to the middle ear and lower frequencies are processed at the end furthest from the middle ear. This frequency-by-place organization plays an important role in the ear's ability to distinguish different frequencies. Finally, the brain uses the complex neural code coming from the auditory periphery to interpret the soundscape.

The interpretation of the soundscape involves several layers of complexity. The simplest layer is the *detection* of sound. That is, is sound present? A second layer of processing is *resolution*. That is, can specific characteristics of one sound source be perceptually separated from another sound source? When listening in a soundscape, spatial resolution allows us to discern that two sounds are coming from different locations. Frequency resolution refers to our ability to distinguish two or more frequencies in a complex sound. Temporal resolution refers to our ability to perceive changes that occur in sounds over time. A third layer of processing is the identification of sounds in the auditory environment (e.g., naming different instruments playing in an orchestra or identifying the several bird calls present in one scene).

Nature of Hearing Loss

Hearing loss can impact both the detection and resolution of sound. The effects of a particular hearing loss will depend on three characteristics, including the *degree* of the loss, the *configuration* of the loss and the *type* of the loss.

Figure 2 shows an audiogram, which is one way to quantify hearing loss in terms of a person's ability to detect sound. Along the horizontal axis is the frequency of the sound, which is described in terms of the number of cycles per second or Hertz. (Middle C on the piano corresponds to 256 Hz). While the human auditory system is sensitive to frequencies ranging from 20 Hz to 20,000 Hz, normally only the frequencies from 250 to 8000 Hz are tested in a hearing evaluation.

The vertical axis shows the volume or the level of the sound using a scale called the decibel (dB) Hearing Level scale. During a hearing test, an audiologist establishes the softest level at which someone can just detect a pure tone of a particular frequency. These levels are called the *threshold of hearing* and are plotted on the audiogram.

Question: Why do the test frequencies in the audiogram chart in Figure 2 only extend up to 6000 Hz?

Answer: Because of testing and calibration problems at higher frequencies, audiometric testing generally only extends to 6 or 8 kHz, even though young, normal-hearing adults can hear sounds out to 16 to 20 kHz. Today there are earphones and test systems that do extend hearing testing to 16 kHz, but there are no normative data or official standards against which one could make comparisons. When testing is done at those frequencies it often uses the individual as a baseline against which future comparisons are made, as in the case of monitoring hearing that might be changing in a patient who is being administered a cancer treatment that includes ototoxic drugs. One should also consider that few if any natural or musical sounds contain fundamental and important energy above 10 kHz, so that hearing losses at those high frequencies are not only difficult to measure but also difficult to detect by the person experiencing them.

Normal-hearing young adults can perceive sounds that extend across a wide range of levels ranging from sounds that are at threshold (0 dB HL) to sounds that are intolerably loud (120 dB HL). This range of levels is called the *dynamic range of hearing*. Thresholds less than 15 dB HL are considered normal hearing, so any thresholds that fall in the unshaded portion of the audiogram are considered normal. If a person has thresholds which are 15 dB HL or greater, they are considered to have a hearing loss. A hearing evaluation often includes determination of a listener's tolerance for loud sounds (level at which sounds become uncomfortably loud). For many people with hearing loss, this level will be similar to or even lower than the tolerance of someone with normal hearing (at or below 120 dB HL). Therefore, individuals with hearing loss often have a reduced dynamic range (e.g., from thresholds of 40 dB HL to intolerably loud at 110 dB HL).

The *degree* of hearing loss (see Figure 2) refers to the amount of hearing loss and is described in terms of being slight (15—25 dB HL), mild (25—40 dB HL), moderate (45—55 dB HL), moderately severe (55—70 dB HL), severe (70—85 dB HL) and profound (greater than 85 dB HL).

The *configuration* of hearing loss tells us how hearing loss changes across the frequency range. Hearing loss can occur at all frequencies or at just some frequencies. The "hearing impairment" line on the audiogram illustrates a configuration with normal hearing in the low frequencies and sloping downward to a moderate hearing loss in the higher frequencies. A person with this configuration of hearing loss will not be able to detect any sounds that are at frequencies and levels in the region above the "hearing-impairment line." This hearing loss will impact a person's ability to hear some but not all speech sounds. Consider, for example, the word "Sue." Sounds like the /s/ are called fricatives and mostly consist of higher-frequency sounds that are low level (below about 40 dB HL). In contrast, vowel sounds have most of their energy in the lower frequencies and are often more moderate in level. Thus, the person with this configuration of hearing loss might be able to hear the vowel sound but not be able to detect the fricative. In contrast to the sloping configuration shown here, a hearing loss might also have a flat configuration, such that the thresholds are the same across the entire frequency range.

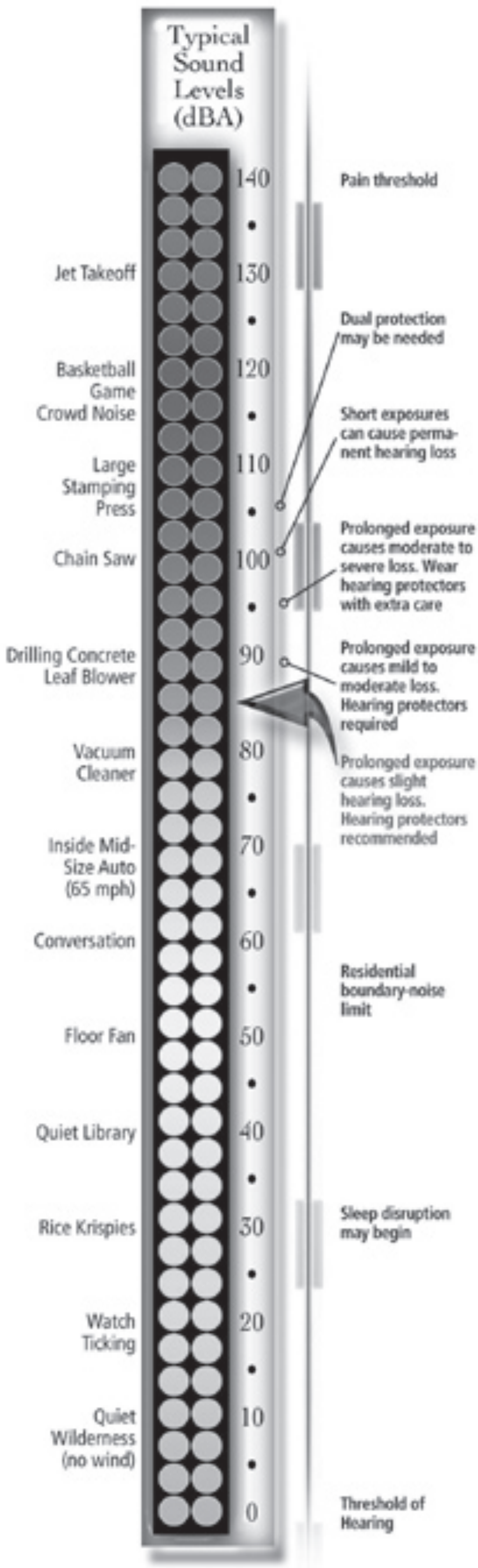
Question: What is the threshold of auditory pain and why is it variously shown as 120, 130 or 140 dBA?

Answer: Although some may think of auditory pain as an extreme discomfort in the hearing of a sound, which is certainly true of sounds above 110 dB and approaching 120 dB, auditory physiologists have defined it differently. It is the point at which a physical, i.e tactile sensation is felt in the middle ear, as opposed to a sound being sensed or heard in the inner ear. The definitive research on this topic was done in the US Air Force in the 1950s by von Gierke and his associates. It involved test signals such as speech, pure tones, and jet-engine noise. This painful and dangerous research is rare, especially today, because of human-subject review board concerns. The values found in that early work were 140 dB. For more information please see Von Gierke et al. (1953). "Aural Pain Produced by Sound," *Benox Report—An Exploratory Study of the Biological Effects of Noise*, ONR Project NR 144079, Univ. of Chicago, p. 29—36.

The *type* of hearing loss describes the place within the auditory system that the hearing problem occurs. There are three types of hearing loss: conductive, sensorineural and mixed. A *conductive* hearing loss affects the conduction of sound through the outer ear and/or through the middle ear. A conductive hearing loss causes an attenuation of the sound volume reaching the inner ear due to a problem in the effective transmission of the sound. Therefore, it will primarily affect a listener's ability to detect sounds. The degree of hearing loss resulting from a conductive loss will usually be in the slight to moderate range. Examples of conditions that cause a conductive hearing loss include the following: earwax (cerumen) that becomes impacted in the outer ear canal; a foreign object (e.g., a bead) trapped in the ear canal; an infection (such as "swimmer's ear") in the ear canal; a rupture (hole) in the eardrum; fluid in the middle ear due to an ear infection; and a break or discontinuity in the chain of ossicles. A conductive hearing loss is often successfully resolved with surgical or medical treatment. For example, antibiotics might help resolve a temporary hearing loss due to an ear infection in the middle ear or surgical repair of an ossicular break might restore efficient conduction of sound through the middle ear.

A *sensorineural* hearing loss is due to a problem in the cochlea and/or the hearing nerve. Whereas a conductive loss primarily affects the detection of sound, a sensorineural hearing loss will affect both the detection and the resolution of sound. The impact of the sensorineural hearing loss on detection will be evident on the audiogram. The degree of impairment resulting from sensorineural hearing loss can range from slight to profound. Such

Fig 3—Representative sound levels together with indications of safe vs. hazardous exposures. Courtesy, E. Berger, Aearo Co.



hearing loss can also introduce distortions that affect a person's ability to resolve sounds. This degraded resolution is not evident on the audiogram, but is evident in a person's ability to effectively hear in complex auditory environments. Often, someone with a sensorineural hearing loss will report greater difficulty hearing in noisy environments. The person's ability to resolve or perceptually separate different sounds (e.g., the speech from the competing background noise) becomes more difficult. Sensorineural hearing losses are usually permanent and not curable through medical treatment. Hearing aids are a common prescription for a person with a sensorineural hearing loss.

Question: I am surprised that the chart of sound levels indicates that a crowd at a basket ball game reaches nearly 120 dBA, which is more than 10-dB louder than a chain saw.

Answer: Surprising though it may be, values that high are easily (though not always) reached when over 10,000 screaming fans get pumped up in a large reverberant indoor arena. And though chain saws are loud indeed, and certainly require the use of hearing protection, they fall short of crowd noise when the fans are fanatically excited. Both crowd noise and chain saws are potentially hazardous sounds depending upon the duration and regularity of the exposures. For a listing of estimates of noise levels for about 1,000 different sources see www.e-a-r.com/pdf/hearingcons/T88_34NoiseLevels.xls

Examples of conditions that can cause a sensorineural hearing loss include hereditary hearing loss, medications that are toxic to the cochlea, viruses, head trauma, tumors, aging and most commonly, exposure to noise. The gradual hearing decline associated with aging is called presbycusis, mainly affecting higher-pitched sounds. Unlike the loss in Figure 2 that indicates a recovery at the highest test frequency, presbycusic losses are monotonic, showing increasing loss with increasing frequency. According to the National Institutes of Health, presbycusis affects approximately 35 percent of adults between 65 and 75 years of age and up to 50 percent of adults who are older than 75.

Sensorineural hearing loss is often due to damage to the cochlear hair cells. For example, exposure to intense noise can result in the death of hair cells in specific regions of the cochlea. As illustrated in Figure 3, the amount of noise that can cause hearing loss depends on both its level and duration. Damage to hair cells can occur due to repeated exposure to moderate-level sounds or due to a single exposure to a very intense sound. The damage may also be temporary (called a *temporary threshold shift,* or TTS) that will recover typically within minutes or hours, or permanent (called a *permanent threshold shift*, or PTS). One might notice for example, a dullness in the listening experience due to a TTS after a day of work in a noisy environment, or subsequent to a lengthy airplane ride or time spent in other loud forms of transport, or from a too-loud listening session to one's favorite music or at a concert, etc. Though this may well recover by the next morning, if one repeatedly experiences TTSs, it is likely that with time they will become permanent. One strategy for avoiding noise-induced hearing loss is to be sure to allow the ears time for recovery before the next hazardous exposure.

The National Institute of Health estimates that noise is a primary factor in the hearing loss of about one third of the 28 million Americans with hearing loss. Hearing loss due to noise can happen at any age and often is accompanied by tinnitus (see accompanying tinnitus article by Martin et al.). Except for exposures to unexpected blasts/explosions, hearing loss due to noise is almost completely avoidable. Education about hazardous sound levels is an important first step in its prevention. A helpful strategy is to monitor sound levels in your listening environment with an inexpensive sound level meter (e.g., Radio Shack sound level meter model 33—4050 costs about $40).

A *mixed* hearing loss occurs when a person has both a conductive and a sensorineural hearing loss at the same time. For example, a person with a noise-induced hearing loss may also have a chronic ear infection, resulting in a mixed hearing loss. Finally, a hearing loss can occur in one ear (unilateral) or in both ears (bilateral). In a bilateral hearing loss, the hearing loss can be similar in both ears (symmetrical) or different in each ear (asymmetrical).

Listening in the soundscape with a hearing loss can affect a person's ability to both detect faint sounds as well as to clearly resolve the frequencies, the location and/or the duration of the sounds in the auditory environment. The soft and subtle whisper of a light breeze through the trees may be one of the first sounds that we loose and with that—if we concur with Robert Frost's words at the beginning of this article—a profound sense of connectedness to nature. Persons who are concerned about their hearing might consult with a hearing health care professional. Otolaryngologists are physicians and surgeons who specialize in diseases of the ear, nose, throat, head and neck. Audiologists are trained to evaluate hearing loss and other disorders, including tinnitus and balance disorders. They also provide non-medical rehabilitation for persons with hearing loss, including the fitting of hearing aids and assistive listening devices.

Resources regarding hearing loss

The websites of the American Academy of Audiology (www.audiology.org) and the American Speech—Language—Hearing Association (www.asha.org) have helpful information regarding hearing and hearing loss, including screening questionnaires that can assist in determining if you might have a hearing loss or need a hearing test. The National Institutes of Health has helpful health information on many problems that cause hearing loss, www.nidcd.nih.gov.

Acknowledgements

The figures used in this article were kindly provided by Elliott H. Berger, Senior Scientist, Auditory Research of E•A•R / Aearo Company.

References

Plomp, Reinier (2002). *The Intelligent Ear: On the Nature of Sound Perception*, Lawrence Erlbaum Associates London.

KATHRYN H. AREHART is an Associate Professor of Audiology and Hearing Sciences in the Department of Speech, Language and Hearing Sciences, University of Colorado at Boulder. Her research focuses on the impact of cochlear hearing loss on perception of speech in noisy environments. Her favorite soundscapes are in the Indian Peaks Wilderness area outside Rocky Mountain National Park and in the waters outside of Juneau Alaska. Kathryn.Arehart@colorado.edu

"A British study among 23 DJs indicated that many DJs, themselves, suffer from the loud music. Seventeen in 23 said they experienced some degree of tinnitus, and 16 reported that they had suffered from temporary hearing loss. Three DJs suffered from permanent noise induced hearing loss (NIHL) after years of excessive noise exposure at work. On average, the 23 DJs worked for 1 hour and 53 minutes without a break with noise levels of 103 dB." Read More: www.youth.hear-it.org/page.dsp?page=2978