Chapter 10

**THE AUDITORY SYSTEM**

The sound stimulus is the periodic variations in air pressure traveling out from the source of the variations. Sound waves are the waves of pressure changes that occur in the air as a function of the vibration of a source. Cycle is the amount time between one peak of a sound wave and the next peak. Pure tones are sound waves in which air pressure changes follow the basic sine wave. Amplitude is the difference between the maximum sound and minimum sound pressures. Thus, taller waves are stronger waves. Loudness is the perceptual experience of amplitude. Loud sounds can result in hearing loss. Frequency is the number of cycles in a sound stimulus that occur in 1 second and is measured in hertz (Hz). Pitch is the perceptual experience of frequency. The normal range of frequencies that can be heard by humans is 20 to 20,000 Hz. Nearly all sounds are complex sounds, which consist of mixes of frequencies. Complex sounds can be broken down into its composite frequencies through Fourier analysis. The fundamental frequency is the lowest frequency present and the one that determines the perceived pitch.

Harmonics are higher frequencies present in a complex sound that are integer multiples of the fundamental frequency. Timbre is the musical term that refers to the perceived sound difference between sounds with the same pitch but possessing different harmonics.

The ear is a complex system whose purpose is to transduce sound waves into neural impulses that we perceive as hearing. In the outer ear, the pinna collects and funnels sound into the external auditory canal, which then conducts sound to the tympanic membrane. When sound hits the tympanic membrane, it vibrates causing motion of the three bones of the middle ear. These bones, called ossicles (malleus, incus, and stapes), amplify sound so that the sound does not dissipate by the time it reaches the cochlea of the inner ear, which is immersed in water. The ossicles also play a role in attenuating sustained loud sounds. Another important part of the middle ear is the Eustachian tube, which equalizes air pressure on either side of the tympanic membrane. The stapes beats against the oval window of the inner ear. The cochlea is the snail-shaped structure of the inner ear that houses the hair cells that transduce sound into a neural signal. The basilar membrane of the cochlea converts sound energy that beats against the oval window into mechanical movement along its length with any particular location on it responding to characteristic frequencies of sound. The organ of Corti lies on the basilar membrane, housing hair cells which transduce sound into a neural signal through the use of stereocilia. Damage to any part of the ear can cause hearing loss. Conducive hearing loss is characterized by damage to some aspect of sound transmission in the outer or middle ear. Sensorineural hearing loss occurs because of damage to the cochlea, auditory nerve, or primary auditory cortex. Tinnitus is the condition when people perceive sounds when none are present, due to damage to the cochlea or auditory nerve. Hearing aids and cochlear implants may be used to help restore some hearing to those affected by hearing loss.

Introduction

* We see only what is in front of us, but sound comes to us from all 360o, making hearing different from vision.
* Our world is immersed in sound.
* The crux of hearing is transforming information in the environment, sound pressure waves, into a perception that can be used to understand the world and guide action.

Sound as Stimulus

* There must be a medium, such as air or water, to conduct sound. In the absence of such a medium, as in the near vacuum of space, sound cannot exist.
* The **sound stimulus** is the periodic variations in air pressure traveling out from the source of the variations.
  + These periodic variations in pressure are the sound wave.
  + The source of the variations is the object making the sound.
* Air pressure will increase and decrease slightly, and these small changes in air pressure constitute sound if they occur strongly and quickly enough.
* When you clap your hands, you disturb the air around your hands and initiate a pattern of high- and low-pressure air movements that move out in all directions from the source in a pattern called a sound wave.
  + **Sound waves** are the waves of pressure changes that occur in the air as a function of the vibration of a source.
* Air molecules do not travel very far themselves, but the wave of pressure change moves across space, causing compression (high pressure) and rarefaction (low pressure) across space.
* Sound can be measured by measuring wavelength and its inverse, frequency.
  + Frequency can be measured in **cycles**, the amount of time between one peak of high pressure and the next.
* Under normal conditions, sound travels fast (about 761.2 mph), but slower than light.
  + Because of this, we may sometimes notice a lag between sound and sight.

The Relation of Physical and Perceptual Attributes of Sound

* Sound has similar attributes to light, namely amplitude and frequency.
* Waveform is how different frequencies interact with each other to create complex sounds.
* First, however, **pure tones** are considered, i.e., sound waves in which air pressure changes follow the basic sine wave format.

Amplitude and Loudness

* **Amplitude** is the difference between the maximum sound and minimum sound pressures. Thus, taller waves are stronger waves.
* **Loudness** is the perceptual experience of amplitude.
  + High-amplitude sounds will be heard as loud and low-amplitude sounds will be heard as soft.
* Amplitude is usually measured in **decibels (dB)**, which are 1/10 of a bel.
  + The decibel scale is logarithmic, meaning that the amplitude increases more quickly than the numbers along the decibel scale.
* We can hear over a wide range of amplitudes.
* We can also discriminate between differences in loudness very well, at differences as low as 1 dB.
* Loud sounds can be dangerous.
  + Prolonged contact to sounds over 85 dB can eventually cause hearing loss.
  + Sounds louder than 120 dB are painful.
  + Sounds louder than 130 dB will generally result in immediate and permanent hearing loss.

Frequency and Pitch

* **Frequency** is the number of cycles in a sound stimulus that occur in 1 second.
  + As frequency gets larger, wavelength gets shorter.
  + By convention, wavelength is used when discussing vision and frequency is used when discussing sound.
  + Frequency is measured in **hertz (Hz)**, a unit of measurement indicating the number of cycles per second.
* **Pitch** is the subjective experience of sound that is closely associated with frequency.
  + Lower frequencies are heard as lower in pitch; higher frequencies are heard as higher in pitch.
* Children and young adults can hear over the range of 20 to 20,000 Hz.
  + As individuals age, hearing in the highest range dissipates.
  + By the time one is 50 years old, the upper limit may be down to 12,000 Hz.
  + The loss may be made worse by exposure to loud sounds when young.
  + The lowest frequencies tend to remain stable with age.
* Below 20 Hz and above 20,000 Hz, humans are simply deaf regardless of amplitude.
  + Other animals can hear beyond this range, such as dolphins who can hear frequencies up to about 200,00 Hz and elephants who can hear frequencies down to 1 Hz.
* Losing high frequencies has few consequences for understanding speech, but does interfere with the perception of timbre.

Waveform and Timbre

* Nearly all sounds are **complex sounds**, which consist of mixes of frequencies.
* A complex waveform can be broken down into its composite frequencies through **Fourier analysis**, a mathematical procedure for determining the simpler waveforms that make up a given complex waveform.
* A Fourier analysis breaks down a complex sound into its fundamental frequency and its harmonics
  + The **fundamental frequency** is the lowest frequency present and the one that determines the perceived pitch.
  + **Harmonics** are higher frequencies present in a complex sound that are integer multiples of the fundamental frequency.
* **Timbre** is the musical term that refers to the perceived sound difference between sounds with the same pitch but possessing different harmonics.

Phase

* **Phase** refers to the position in one cycle of a wave.
* Two waves that have the same frequency but are 180o out of phase with each other cancel each other out if played at the same time.

Anatomy of the Ear

* The ear is a complex system whose purpose is to take sound energy and turn it into meaningful information.
* The ear transduces sound waves into neural impulses that we perceive as hearing.

The Outer Ear

* The **pinna** is the visible part of the ear that collects sound and funnels it into the external auditory canal.
  + The shape of the pinna helps in sound localization.
* The **external auditory canal** conducts sound from the pinna to the tympanic membrane.
  + In all people, the external auditory canal is about 25mm long.
  + This length helps amplify certain higher frequencies.
* Commonly known as the eardrum, the **tympanic membrane** is a thin elastic sheet that vibrates in response to sounds coming through the external auditory canal.
  + Sound moving down the auditory canal hits against the membrane, which vibrates in response to that sound.
  + Damage to the tympanic membrane can result in hearing loss.

The Middle Ear

* The middle ear consists of three small bones, called **ossicles,** which transmit sound to the inner ear.
* When the tympanic membrane vibrates, it causes motion in the ossicles, which then conduct the sound mechanically.
  + In order, the tympanic membrane causes sound transmission in the **malleus**, which transmits sound the **incus**, which transmits sound to the **stapes**.
* The stapes pushes against the oval window of the cochlea, and sound moves into the inner ear.
* The purpose of the ossicles is to amplify sound so that the sound does not dissipate by the time it reaches the cochlea in the inner ear, which is immersed in water.
  + First, the ossicles use lever action to increase the amount of pressure change.
  + Second, the ossicles transfer energy from the larger surface area tympanic membrane to the smaller surface area oval window. The tympanic membrane is about 18 times the size of the oval window; thus, the ossicles increase the sound pressure 18 times at the oval window, critical to transmitting sound into the liquid environment of the cochlea.
* Another important part of the middle ear is the **Eustachian tube**, the thin tube that connects the middle ear with the pharynx and equalizes air pressure on either side of the tympanic membrane.
  + Usually, the Eustachian tube is closed, but opens briefly when swallowing or yawning. This is also responsible for “popping” of the ears.
* Except when the Eustachian tube is open, the middle ear is cut off from changes in air pressure in the outside environment.
  + For optimal function of the tympanic membrane, it is important for the air pressure on both sides of it to be equal.
  + The Eustachian tube opens to allow the two air pressures to equalize when there is a change in pressure due to altitude or weather.
* The ossicles also play a role in attenuating sustained loud sounds.
  + Muscles attached to the malleus and stapes, the **tensor tympani** and **stapedius**, respectively, tense in the presence of very loud noises. Doing so restricts the movements of the ossicles and avoiding inner ear damage.
  + This **acoustic reflex** protects somewhat against chronic loud noises but is too slow for sudden loud noises.

The Inner Ear

* The inner is the part of the ear that transduces sound into a neural signal.
* Hair cells along the organ of Corti in the cochlea receive vibrations and convert them into a neural signal, analogous to rods and cones in the retinae.
* The **cochlea** is the snail-shaped structure of the inner ear that houses the hair cells.
  + Within the cochlea are three liquid-filled chambers, called the **tympanic canal,** the **middle canal**, and the **vestibular canal**.
  + In the apex (end of the cochlear) is an opening called the helicotrema that allows fluid to flow between the tympanic and vestibular canals.
  + Seated just below the oval window is the **round window**, a soft tissue substance at the base of the tympanic canal whose function is an “escape” valve for excess pressure from loud sounds.

The Basilar Membrane of the Cochlea

* Two membranes separate the cochlear canals.
  + **Reissner’s membrane** separates the vestibular and middle canals.
  + The **basilar membrane** separates the tympanic and middle canals.
    - At the base, the basilar membrane is thicker and stiffer, making it more responsive to high-frequency sounds.
    - Conversely, at the apex, it is less thick and less stiff and therefore more responsive to low-frequency sounds.
    - Each location along the basilar membrane responds to a **characteristic frequency**, the frequency to which any particular location along the basilar membrane responds best.
    - In effect, the basilar membrane conducts a Fourier analysis.

The Organ of Corti

* Along the basilar membrane within the middle canal is the **organ of Corti**, which contains the hair cells.
* The **hair cells** transduce sound into a neural signal through the use of **stereocilia**, hairlike filaments that bend in response to movement of the basilar membrane.
* The first row of hair cells along the basilar membrane is the **outer hair cells** and the next row is called the **inner hair cells**.
  + Inner hair cells are responsible for transduction, whereas outer hair cells refine and amplify the neural responses of the inner hair cells.
* The **tectorial membrane** sits above the hair cells and helps hold them in place.
  + When a vibration of the basilar membrane causes it to move upward, the stereocilia brush against the tectorial membrane, causing a change in the cell’s voltage potential,
  + The change in voltage causes the release of neurotransmitters, causing the auditory nerve to send a signal.
* **Place code theory** states that frequency representation occurs because of a match between frequency and the firing rates of the auditory nerve.
* As we age, the basilar membrane gets stiffer, accounting for hearing loss of higher frequencies.

Hearing Loss, Hearing Aids, and Cochlear Implants

* Hearing loss affects millions of people.
* Presbycusis is the term for hearing loss associated with aging.
* Audiologists are specialists who evaluate, diagnose, and treat hearing impairments.
* During an audiology exam, an audiologist administers a set of tests using an **audiometer**, which presents pure tones at set frequencies and known amplitudes to either ear. The result is an **audiogram**, a graph illustrating thresholds for the frequencies as measured by the audiometer.

Conductive Hearing Loss

* Conducive hearing loss is characterized by damage to some aspect of sound transmission in the outer or middle ear.
* This results in sound not properly arriving to the cochlea.
* It can occur due to blockage of the auditory canal, a torn tympanic membrane, or damage to the ossicles.
* In particular, it may occur due to **otosclerosis**, an inherited bone disease in which there is calcification of the ossicles, making them less conducive to sound.

Sensorineural Hearing Loss

* **Sensorineural hearing loss** occurs because of damage to the cochlea, auditory nerve, or primary auditory cortex.
* This form of hearing loss is usually precipitated by damage to hair cells resulting from loud noises or certain drugs.

Tinnitus

* **Tinnitus** is the condition when people perceive sounds when none are present.
* Most cases are thought to involve a neural signal being sent to the brain in the absence of an actual sound, which can interfere with the perception of real sounds.
* Tinnitus may result due to damage to the cochlea or auditory nerve associated with noise or infection.

Hearing Aids

* **Hearing aids** are electronic devices that amplify sound.
* In the past, most hearing aids were analog devices but now most are digital.
  + Digital hearing aids convert the sound signal into a computer code, which is then reconverted into an analog sound for the wearer.
  + Digital hearing aids can be fitted to a particular individual’s pattern of hearing loss.
  + They can also be programmed to have directionally sensitive microphones, meaning that sound coming from in front can be amplified but sound coming from other directions can be blocked out. This can be useful for conversations in noisy environments.
* Hearing aids require a functioning cochlea, but cochlear implants can be used in those with a damaged cochlea.

Cochlear Implants

* **Cochlear implants** are devices that restore some hearing, typically of spoken voices, to deaf individuals.
* They stimulate the auditory nerve artificially with an electronic system, replacing the hair cells of the cochlea.
* After implantation, patients require many hours of training and therapy to essentially relearn to hear.
* A divisive issue regarding cochlear implants is whether or not they should be placed in congenitally deaf infants.