Chapter 9

Hearing: Physiology and Psychoacoustics

The Function of Hearing

• The Function of Hearing
• What Is Sound?
• Basic Structure of the Mammalian Auditory System
• Basic Operating Characteristics of the Auditory System
• Intensity and Loudness
• Hearing Loss

The Basics:

– Nature of sound
– Anatomy and physiology of the auditory system
– How we perceive loudness and pitch
– Impairments of hearing
What Is Sound?

Sounds are created when objects vibrate. Vibrations of object cause molecules in object’s surrounding medium to vibrate as well, which causes pressure changes in medium.

Sound waves travel at a particular speed
- Depends on medium
- Example: Speed of sound through air is about 340 meters/second, but speed of sound through water is 1500 meters/second

Characteristics of Sound: Frequency

**Frequency**: For sound, the number of times per second that a pattern of pressure change repeats. Frequency is associated with pitch. **Low-frequency** sounds correspond to low pitches, (e.g., low notes played by a tuba). **High-frequency** sounds correspond to high pitches, (e.g., high notes from a piccolo).
Characteristics of Sound: Amplitude

Basic qualities of sound waves

– **Amplitude**: Magnitude of displacement of a sound pressure wave. **Intensity**: Amount of sound energy falling on a unit area.

– **Loudness**: The psychological aspect of sound related to perceived intensity or magnitude.

Intensity of Environmental Sounds

Humans can hear across a wide range of sound intensities. Ratio between faintest and loudest sounds is more than one to one million.

– In order to describe differences in amplitude, sound levels are measured on a logarithmic scale, in units called decibels (dB).

– Relatively small decibel changes can correspond to large physical changes (e.g., increase of 6 dB corresponds to a doubling of the amount of pressure).
**Characteristics of Sound: Timbre**

**Timbre**: Psychological sensation by which listener can judge that two sounds that have same loudness and pitch are dissimilar.

Harmonic spectra: Typically caused by simple vibrating source, (e.g., string of guitar, or reed of saxophone). **First harmonic**: Fundamental frequency-lowest frequency component of the sound.

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**Harmonic Sounds with the Same Fundamental**

*Graph showing harmonic spectra for different notes.*

First harmonic

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**What Is Sound?**

One of simplest kinds of sounds: Sine wave, or pure tone. Waveform for which variation as a function of time is a sine function. Time taken for one complete cycle of sine wave: Period.
There are 360 degrees of phase across one period.

Complex Sounds

Sine waves: Not common everyday sounds because not many vibrations in the world are so pure. Most sounds in world, e.g., human voices, birds, cars, etc. All sound waves can be described as some combination of sine waves.

Complex Sound Waves: Fourier Analysis

Complex sounds can be described by Fourier analysis. A mathematical theorem by which any sound can be divided into a set of sine waves. Combining these sine waves will reproduce the original sound.
Human hearing uses a limited range of electromagnetic energy: From about 20 to 20,000 Hz.

Basic Structure of the Mammalian Auditory System

How are sounds detected and recognized by the auditory system? Sense of hearing evolved over millions of years.

Outer Ear

Outer ear: Sounds are first collected from environment by the pinnae. Sound waves are funneled by the pinnae into ear canal. Length and shape of ear canal enhance sound frequencies. Main purpose of canal is to insulate structure at its end: Tympanic membrane.
Mammalian Pinnae

Outer Ear

Tympanic membrane: Eardrum; a thin sheet of skin at end of outer ear canal; it vibrates in response to sound.

Common myth: Puncturing your eardrum will leave you deaf. In most cases it will heal itself. It is possible to damage it beyond repair.

Middle Ear

Middle ear: Pinnae and ear canal make up outer ear. Tympanic membrane is border between outer and middle ear. Consists of three tiny bones: Ossicles, that amplify sounds.
Ossicles: Malleus, incus, stapes; smallest bones in body. Stapes transmits vibrations of sound waves to oval window, another membrane which represents border between middle ear and inner ear.

Amplification provided by ossicles is essential to ability to hear faint sounds.
- Inner ear is made up of collection of fluid-filled chambers.
- Ossicles also important for loud sounds.

Middle ear: Two muscles-tensor tympani and stapedius.
- Purpose: To tense when sounds are very loud, muffling pressure changes.
- However, acoustic reflex follows onset of loud sounds by about one-fifth of second, so cannot protect against abrupt sounds, (e.g., gun shot).
Inner ear: Fine changes in sound pressure are translated into neural signals. Function is roughly analogous to that of retina.

Stapes to push and pull flexible oval window in and out of vestibular canal at base of cochlea. If sounds are extremely intense, any remaining pressure is transmitted through helicotrema and back to cochlear base through tympanic canal, where it is absorbed by another membrane: Round window.

Cochlear canals and membranes. Cochlea: Spiral structure of the inner ear containing the organ of Corti. Cochlea is filled with watery fluids in three parallel canals, viz., the Tympanic canal, Vestibular canal, Middle canal.
Hair cells in each human ear: Arranged in four rows that run down length of basilar membrane.

Basic Structure of the Mammalian Auditory System

Inner and outer hair cells
- Inner hair cells: Convey almost all information about sound waves to brain
- Outer hair cells: Convey information from brain (use of efferent fibers). They are involved in elaborate feedback system
Basic Structure of the Mammalian Auditory System

Tectorial membrane: Extends atop organ of Corti; a gelatinous structure.

Firing of auditory nerve fibers into patterns of neural activity finally completes process of translating sound waves into patterns of neural activity.

Place Code

Coding of amplitude and frequency in the cochlea. **Place code**: Tuning of different parts of cochlea to different frequencies, in which information about the particular frequency of incoming sound wave is coded by place along cochlear partition with greatest mechanical displacement.
The Cochlea is Tuned to Different Frequencies

AN Fibers

The auditory nerve:

- Responses of individual AN fibers to different frequencies are related to their place along the cochlear partition.
- Frequency selectivity: Clearest when sounds are very faint.
- Threshold tuning curve: Map plotting thresholds of a neuron or fiber in response to sine waves with varying frequencies at lowest intensity that will give rise to a response.

Threshold Tuning Curves
Two-tone Suppression

Two-tone suppression: Decrease in firing rate of one auditory nerve fiber due to one tone, when a second tone is presented at the same time.

Isointensity curves

- Are AN fibers as selective for their characteristic frequencies at levels well above threshold as they are for the barely audible sounds?
  - To answer this, look at isointensity curves:
    Chart by measuring an AN fiber’s firing rate to wide range of frequencies, all presented at same intensity level.
  - Rate saturation: Point at which a nerve fiber is firing as rapidly as possible and further stimulation is incapable of increasing the firing rate.

Isointensity Functions
Rate intensity function: A map plotting firing rate of an auditory nerve fiber in response to a sound of constant frequency at increasing intensities.

Temporal code for sound frequency
- Auditory system has another way to encode frequency aside from the cochlear place code.
- Tuning of different parts of the cochlea to different frequencies, in which information about the particular frequency of an incoming sound wave is coded by the timing of the neural firing as it relates to the period of the sound.

Phase Locking
- Phase locking: Firing of a single neuron at one distinct point in the period (cycle) of a sound wave at a given frequency.
- Existence of phase locking: Firing pattern of an AN fiber carries a temporal code.
The volley principle: An idea stating that multiple neurons can provide a temporal code for frequency if each neuron fires at a distinct point in the period of a sound wave but does not fire on every period.

Auditory brain structures
- AN (cranial nerve VIII) carries signals from cochlea to brain stem.
- There, all AN fibers initially synapse in cochlear nucleus.
Auditory System Pathways

Neural impulses travel from cochlea, superior olive, inferior colliculus, medial geniculate nucleus to primary auditory cortex.

The First Stages of Auditory Processing

Tonotopic organization: An arrangement in which neurons that respond to different frequencies are organized anatomically in order of frequency

- Maintained in primary auditory cortex (A1).
- Neurons from A1 project to belt area, then to parabelt area.

Auditory and Visual Systems

Comparing overall structure of auditory and visual systems

- Auditory system: Large proportion of processing is done before A1.
- Visual system: Large proportion of processing occurs beyond V1.
- Differences may be due to evolutionary reasons.
Psychoacoustics

Psychoacoustics: The study of the psychological correlates of the physical dimensions of acoustics; a branch of psychophysics.

Intensity and Loudness

Audibility threshold: A map of just barely audible tones of varying frequencies.

Temporal integration: Process by which a sound at a constant level is perceived as being louder when it is of greater duration.
Tonotopic organization of auditory system suggests that frequency composition is determinant of how we hear sounds.

Psychoacousticians: Study how listeners perceive pitch
- Research done using pure tones suggests that humans are good at detecting small differences in frequency.
- Masking: Using a second sound, frequency noise, to make the detection of another sound more difficult; used to investigate frequency selectivity.

Psychoacousticians: Study how listeners perceive pitch
- White noise: Consists of all audible frequencies in equal amounts; used in masking.
- Critical bandwidth: Range of frequencies that are conveyed within channel in auditory system.
Hearing can be impaired by damage to any of structures along chain of auditory processing:

- Obstructing the ear canal results in temporary hearing loss (e.g., earplugs).
- Excessive buildup of ear wax (cerumen) in ear canal.

Hearing can be impaired by problems with the bones of the middle ear, (e.g., during ear infections, otitis media).

- Otosclerosis: More serious type of conductive loss. Caused by abnormal growth of middle ear bones; can be remedied by surgery.
Hearing Loss

Hearing can be impaired by damage to any of structures along chain of auditory processing.

- **Sensorineural hearing loss:** Most common, most serious auditory impairment. Due to defects in cochlea or auditory nerve; when hair cells are injured, (e.g., as result of antibiotics or cancer drugs, ototoxic)
- **Common hearing loss:** Damage to hair cells due to excessive exposure to noise

Hearing Loss

Hearing loss: Natural consequence of aging

- **Young people:** Range of 20–20,000 Hz.
- **By college age:** 20–15,000 Hz.
- **Hearing aids:** Earliest devices were horns; today—electronic aids.

Hearing Loss in Easter Islanders

![Graph showing hearing levels for different groups](image)