Aalto University
School of Electrical
Engineering

Communication acoustics
Ch 7: Physiology and Anatomy of Hearing

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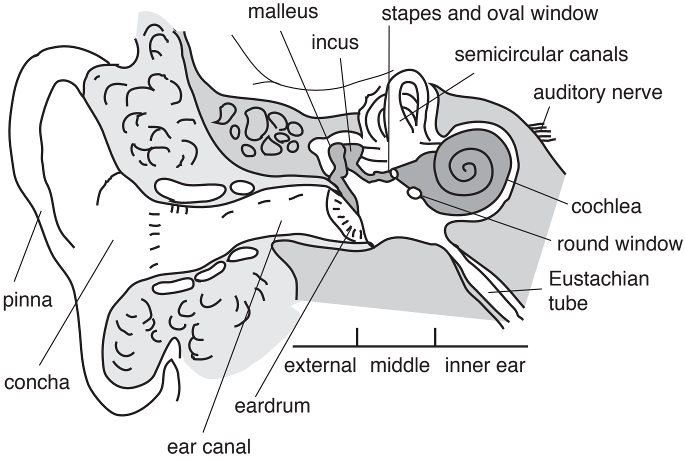
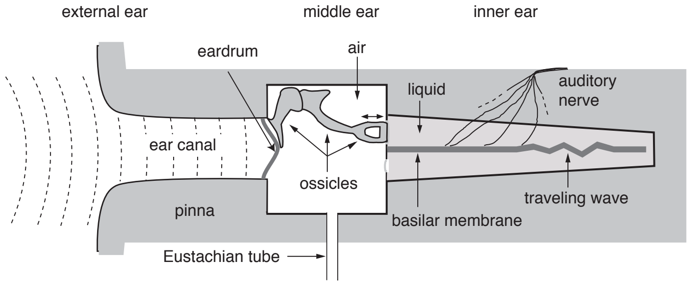
This chapter

- Structure of ear
  - Cochlea
  - Functioning of the cochlea
  - Cochlear non-linearities
- Auditory nerve
- Auditory nervous system

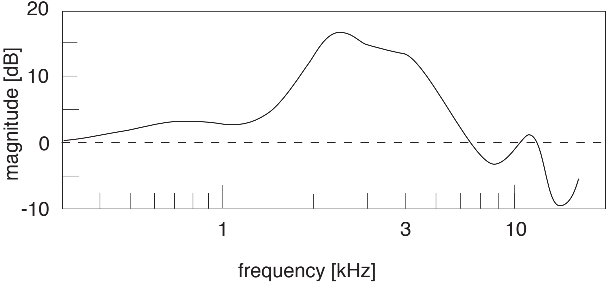
Structure of the ear



Simplified diagram of the ear



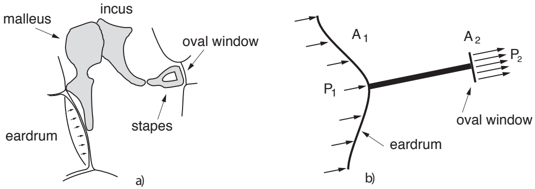
Acoustical effect of outer ear



Magnitude response from frontal sound source to eardrum

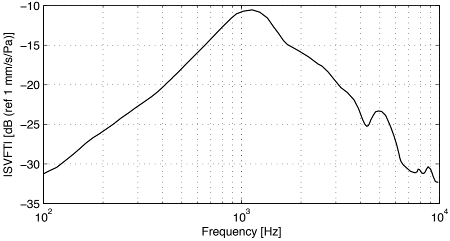
Middle ear: bone conduction

- Ossicles
  - Malleus (hammer-shaped bone)
  - Incus (anvil-shaped bone)
  - Stapes (stirrup-shaped bone)
- Match partially the impedance difference from air to liquid (1:3000),



Middle ear conduction and features

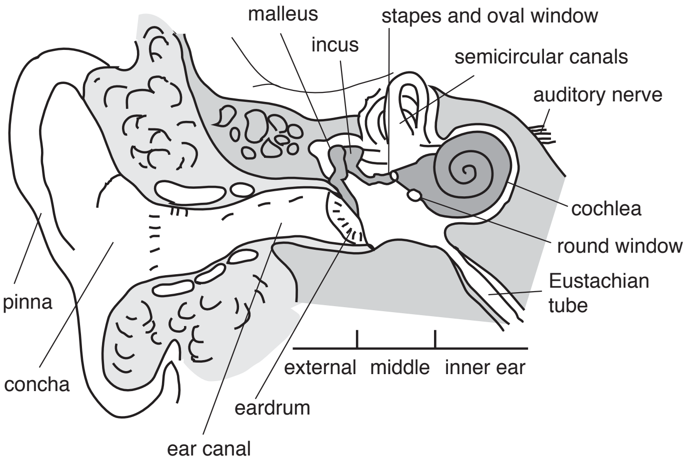
- Signal transfer function is a bandpass filter



Adapted from Aibara et al. (2001)

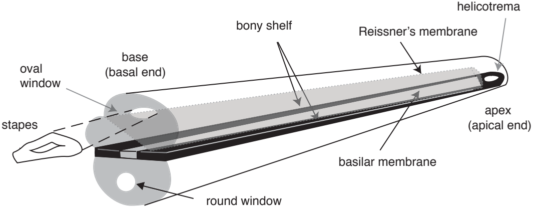
- Other middle ear features
  - Acoustic reflex = stiffening of muscles attached to ossicles with loud sounds
  - Eustachian tube, balancing air pressure between the middle ear and the environment

Structure of the ear



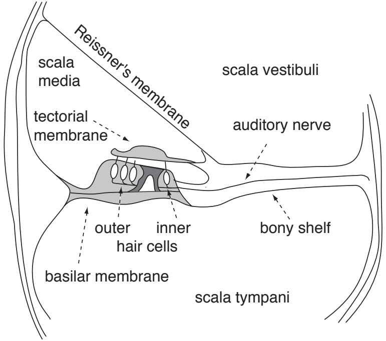
Inner ear, the Cochlea

- Cochlea is a spiral-shaped, liquid-filled tube of about 2.7 turns and 35 mm long
- Stapes vibration enters the cochlea through oval window, and exits from round window
- Basilar membrane divides the cochlea into two parts

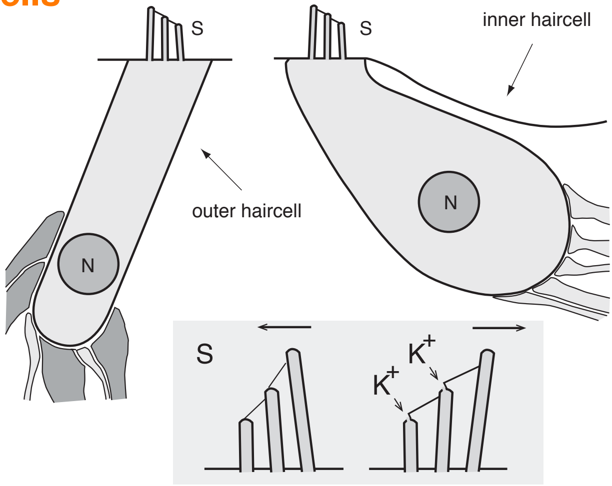


Inner ear, the Cochlea

- Basilar membrane between bony shelves
  - Division to scala vestibuli and scala tympani
- Reissner's membrane separates scala media, where higher concentration of K^+
- Organ of Corti: hair cells (shown as shaded)
- Tectorial membrane



Hair cells

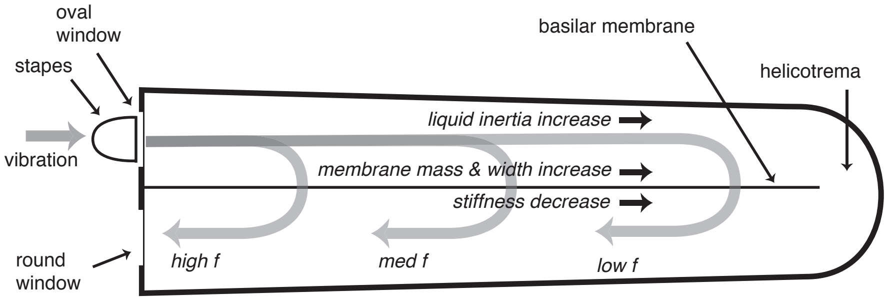


Hair cells

- Vibration of the basilar membrane causes bending of stereocilia and this opens ion channels which modulates potential within the cell
- Activation of the cell releases neurotransmitter to synaptic junctions between hair cell and neural fibers of the auditory nerve
- A neural spike is generated that propagates in the auditory nerve fiber
- Next spike possible only after at least 1 ms

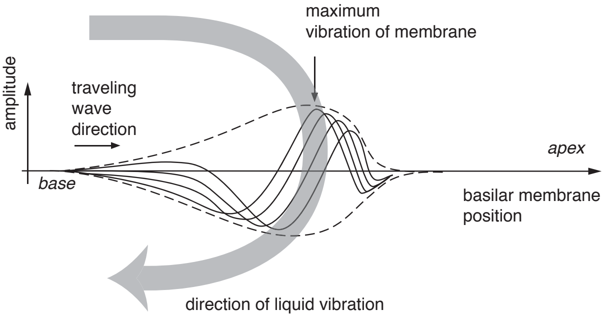
Passive frequency selectivity in cochlea

- Basilar membrane is nonhomogeneous transmission line
- Frequencies resonate at different positions



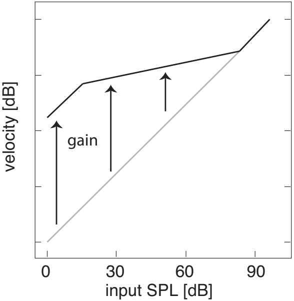
Traveling wave in basilar membrane

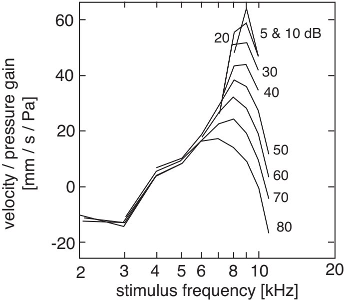
- Traveling wave has maximum vibration amplitude depending on the frequency of wave (characteristic frequency = CF)
- High frequencies resonate close to the oval window and low frequencies close to helicotrema



Active processing in cochlea

- Outer hair cells actively amplify vibration at their characteristic frequency
- Effect is highest at low levels

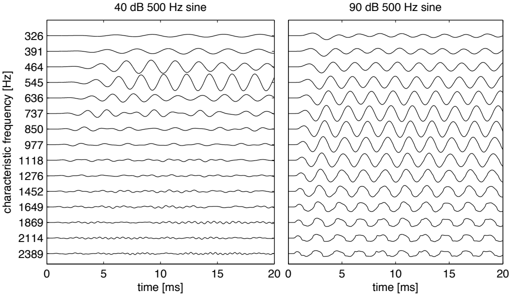




Adopted from Ruggero et al. (1997)

Velocity of basilar membrane with different levels

- Higher level causes broader excitation in frequency
- Excitation spreads more towards higher frequencies

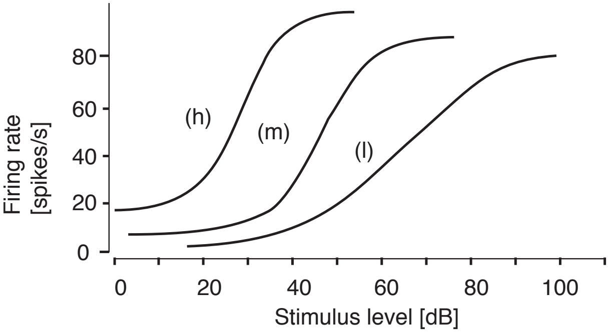


Animations

- Link to cochlea / organ of corti animation
- Link to cochlea anatomy animation
- Auditory nerve / auditory cortex demo

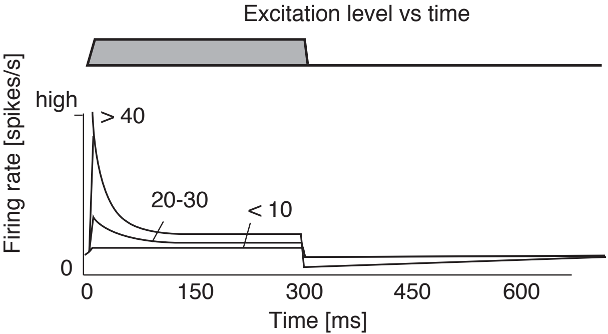
Auditory nerve fibers

- Several auditory nerves are connected to each inner hair cell
- Auditory nerves send a spike (binary output) when they receive enough neurotransmitter from hair cell
- Different nerves are differently sensitive to level



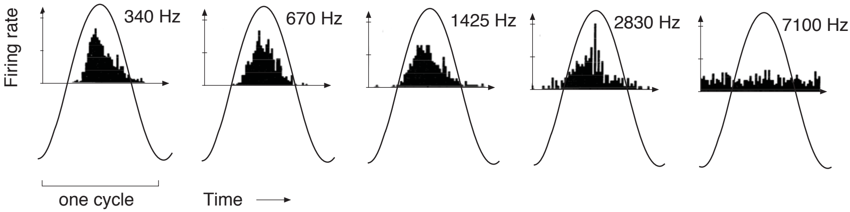
Auditory nerve fibers

- Firing rate overshoot and undershoot with onset and offset of excitation



Auditory nerve fibers

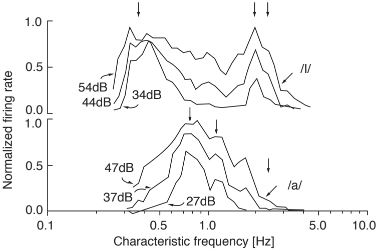
- Response of nerves with different frequencies
- Statistically, half-wave rectification appears



Adapted from Joris et al. (1994)

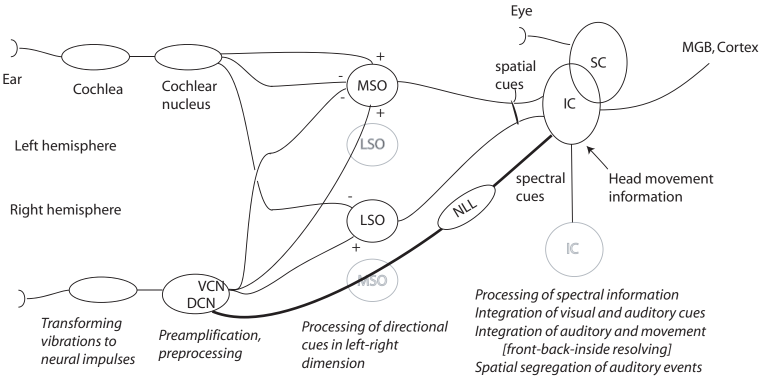
Auditory nerve fibers

- Response of nerves in cat with vowel sounds /a/ and /I/ with different levels
- Average rate shows increasing saturation with level
- Frequency distribution of firing rate does not carry all information
- The instantaneous temporal pattern of activation seems to carry more information



Adapted from Sachs and Young (1979)

Higher levels in processing



References

These slides follow corresponding chapter in: Pulkki, V. and Karjalainen, M. Communication Acoustics: An Introduction to Speech, Audio and Psychoacoustics. John Wiley & Sons, 2015, *where also a more complete list of references can be found.*

References used in figures:

Aibara, R., Welsh, J.T., Puria, S., and Goode, R.L. (2001) Human middle-ear sound transfer function and cochlear input impedance. Hearing Res., 152(1), 100–109.

Joris, P.X., Carney, L.H., Smith, P.H., and Yin, T. (1994) Enhancement of neural synchronization in the anteroventral cochlear nucleus. I. responses to tones at the characteristic frequency. J. Neurophys., 71(3), 1022–1036.

Ruggero, M.A., Rich, N.C., Recio, A., Narayan, S.S., and Robles, L. (1997) Basilar-membrane responses to tones at the base of the chinchilla cochlea. J. Acoust. Soc. Am., 101(4), 2151–2163.

Sachs, M.B. and Young, E.D. (1979) Encoding of steady-state vowels in the auditory nerve: Representation in terms of discharge rate. J. Acoust. Soc. Am., 66, 470–479.