Communication acoustics
Ch 7: Physiology and Anatomy of Hearing

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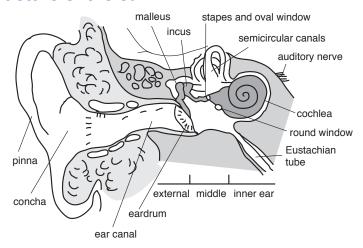
Department of Signal Processing and Acoustics
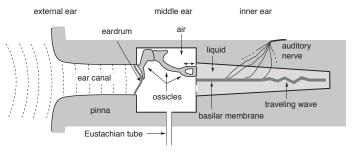*Aalto University, Finland*

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This chapter

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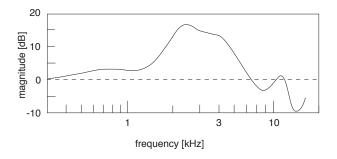- Auditory nerve
- Auditory nervous system
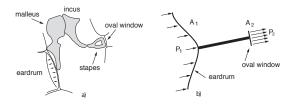
Structure of the ear

Simplified diagram of the ear

external ear   middle ear   inner ear

eardrum   air   liquid   auditory nerve

ear canal   ossicles   traveling wave

pinna   basilar membrane

Eustachian tube

Acoustic effect of outer ear

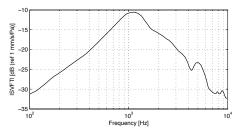Magnitude response from frontal sound source to eardrum

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),
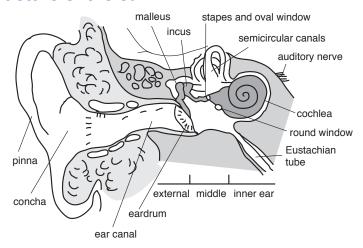
Middle ear conduction and features

- Signal transfer function is a bandpass filter
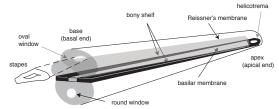

Adapted from Aibara et al. (2001)

- 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
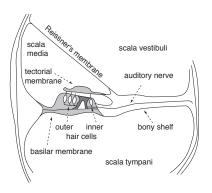
Structure of the ear

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
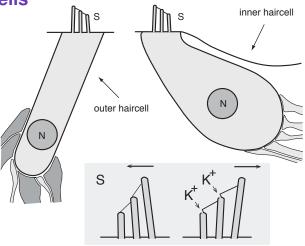- Basilar membrane divides the cochlea into two parts

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)
- Tectrorial membrane

Hair cells

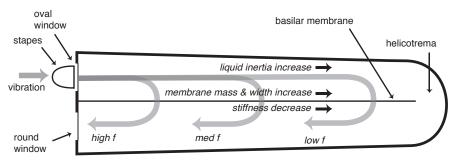S

S

inner haircell

outer haircell

N

N

S

K^+

K^+

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
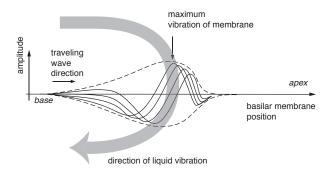- Next spike possible only after at least 1 ms

Passive frequency selectivity in cochlea

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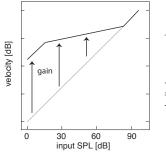- Frequencies resonate at different positions

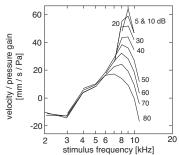# Traveling wave in basilar membrane

- 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
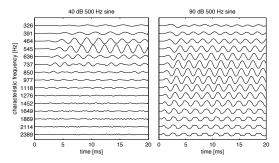- Effect is highest at low levels

Adopted from Ruggero et al. (1997)

Velocity of basilar membrane with different levels

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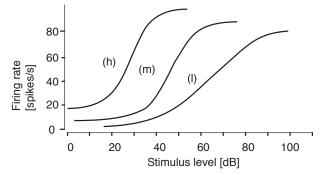- Excitation spreads more towards higher frequencies

Animations

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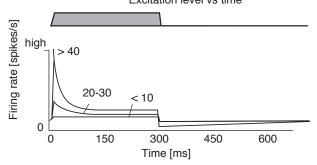
Auditory nerve fibers

- 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
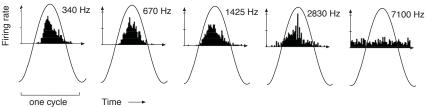- Different nerves are differently sensitive to level

Auditory nerve fibers

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

Excitation level vs time
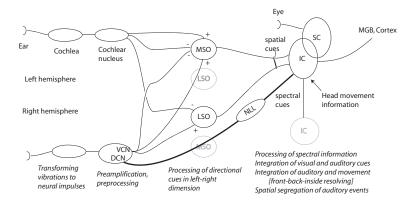
Auditory nerve fibers

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

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.

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