Hearing and the ear

Describes the anatomy and function of the outer, middle and inner ear. Discusses hair cells and basilar membrane motions.

WS 16/17
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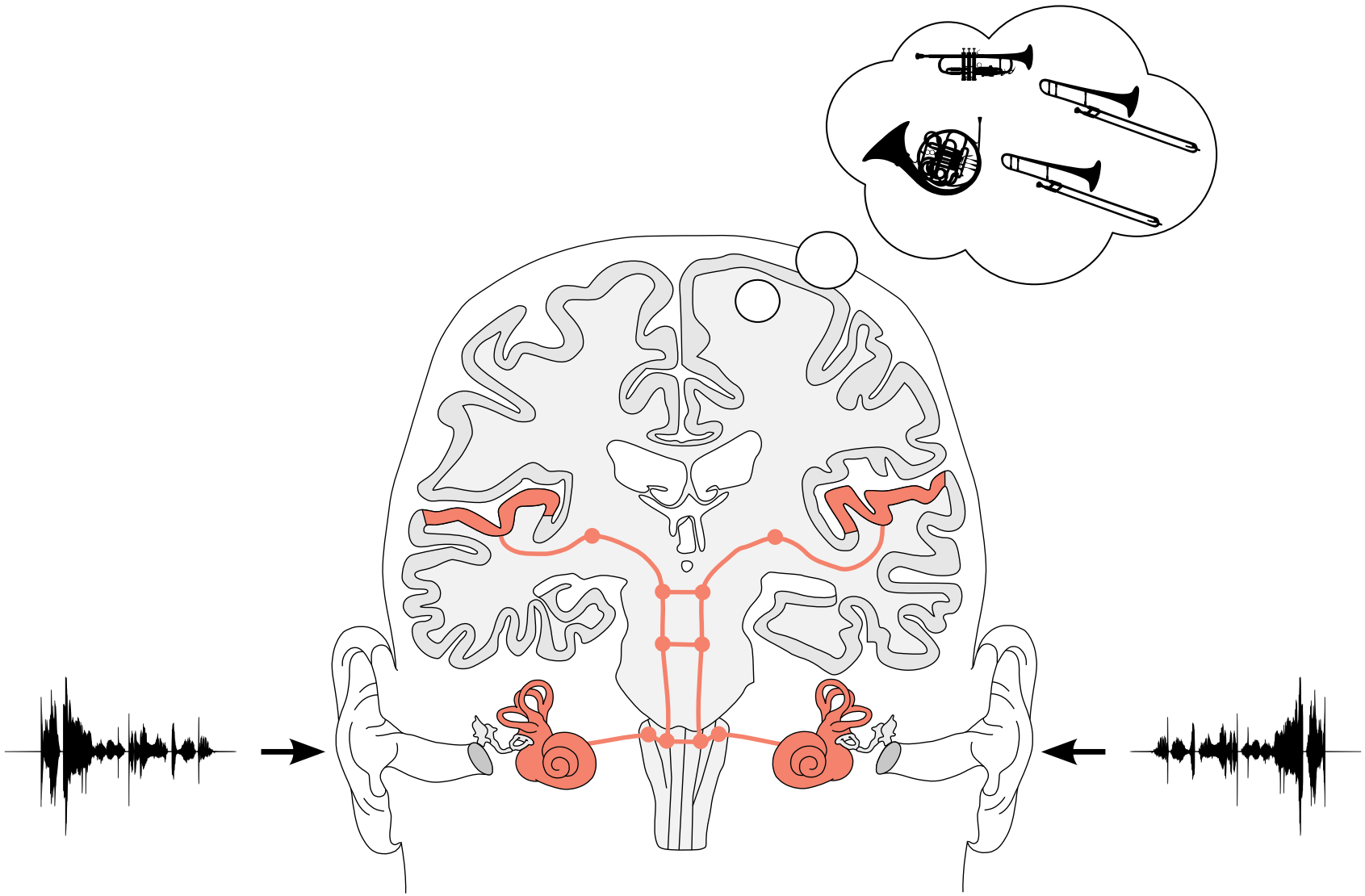
Hearing or auditory perception

Sound perception by organisms using sensory organs that pickup oscillations of a physical medium.

- **Sound:** sound event
- **Perception:** auditory event
- **Sensory organs:** ears
- **Physical medium:** air, water, or solid grounds

Hearing or auditory perception



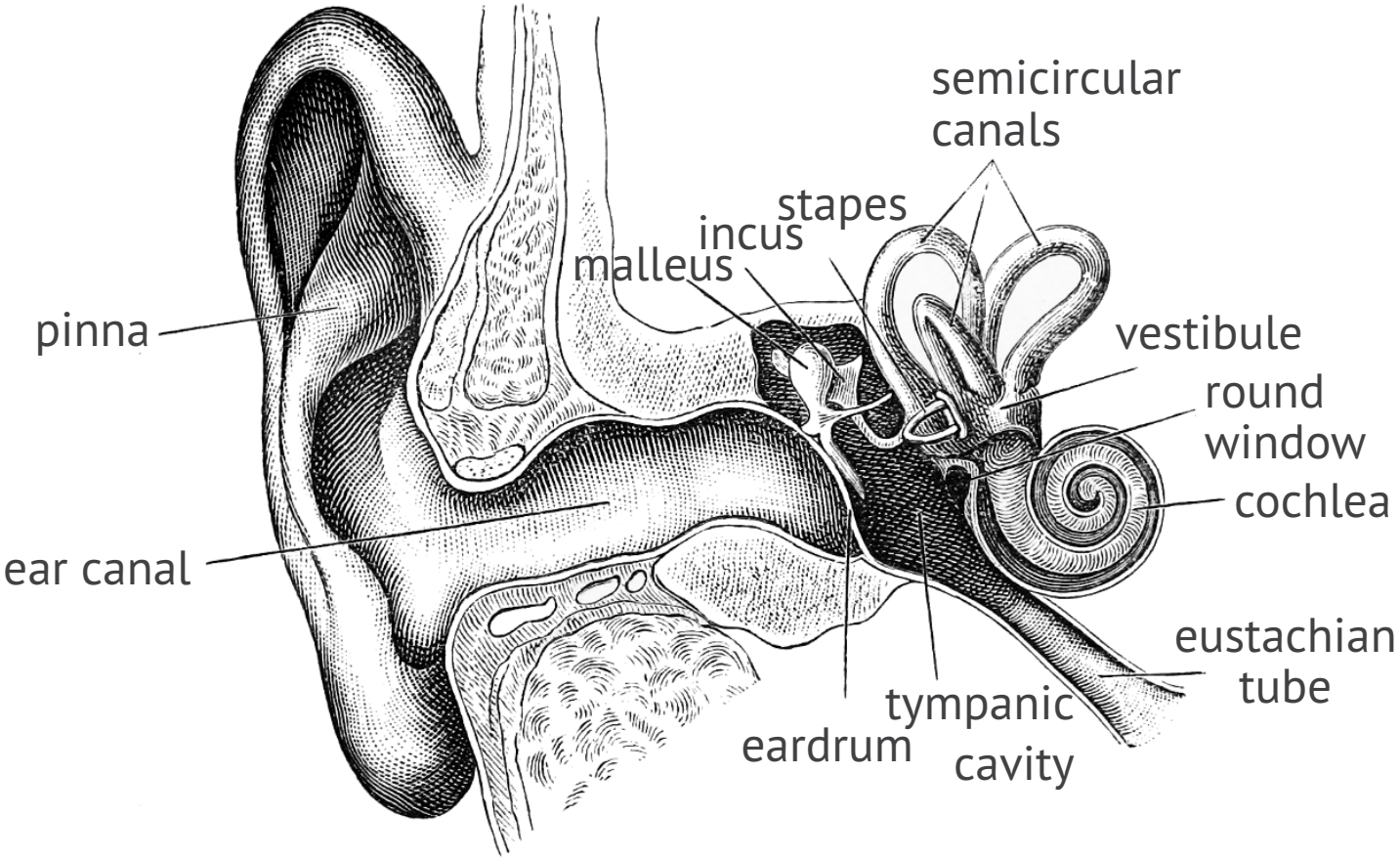
[1]

Facts about hearing

Hearing system is extremely sensitive.

- Large dynamic range from 0 dB HL up to 120 dB HL
- Large frequency range from 20 Hz up to 20000 Hz
- Corresponds to a wave length of 17 m to 17 mm
- In visual perception the range is 380 nm to 750 nm

Anatomy and function of the ear



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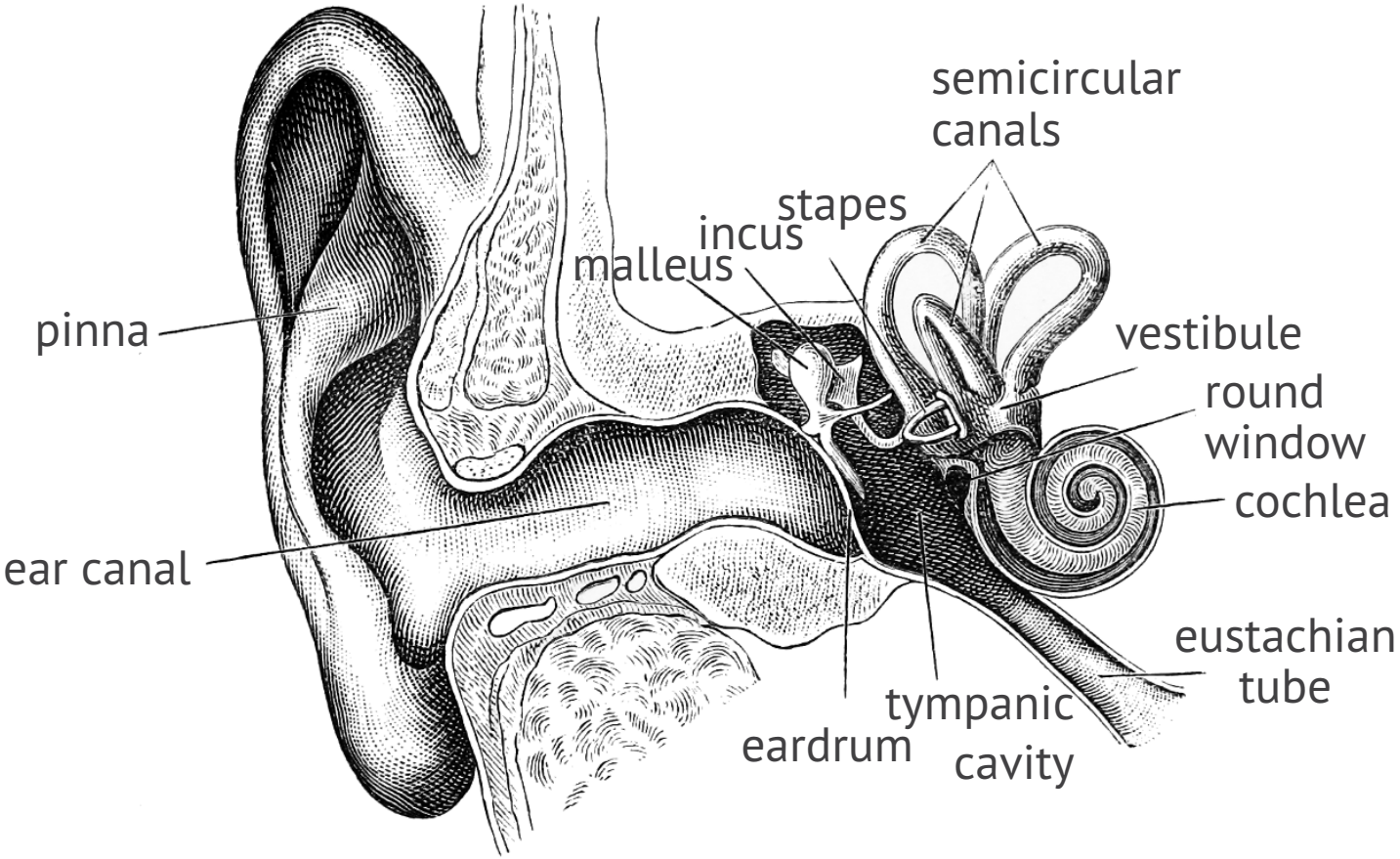
Anatomy

- **Outer ear:** head, “ear”, ear canal
- **Middle ear:** ear drum, ossicles
- **Inner ear:** cochlea, auditory nerve

Anatomy and function of the ear



[2]

Function

- **Outer ear:** directional hearing
- **Middle ear:** impedance matching air/liquid
- **Inner ear:** “Fourier analysis” and conversion to neuronal signals

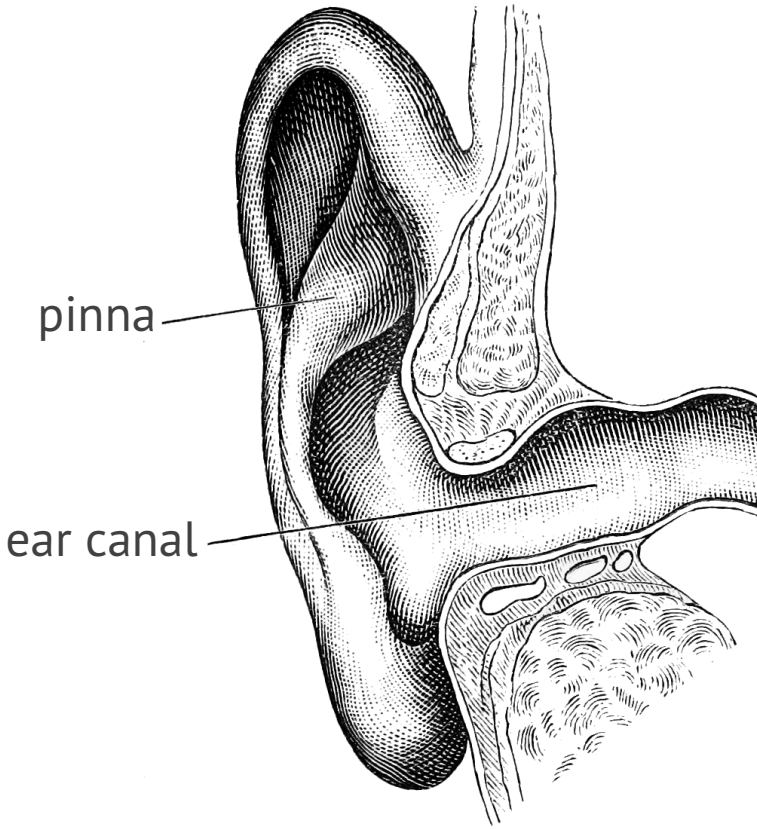
Outer ear

Pinna

- Cartilage material, covered with skin
- Individual shape
- Inter-ear distance $\approx$ 18 cm

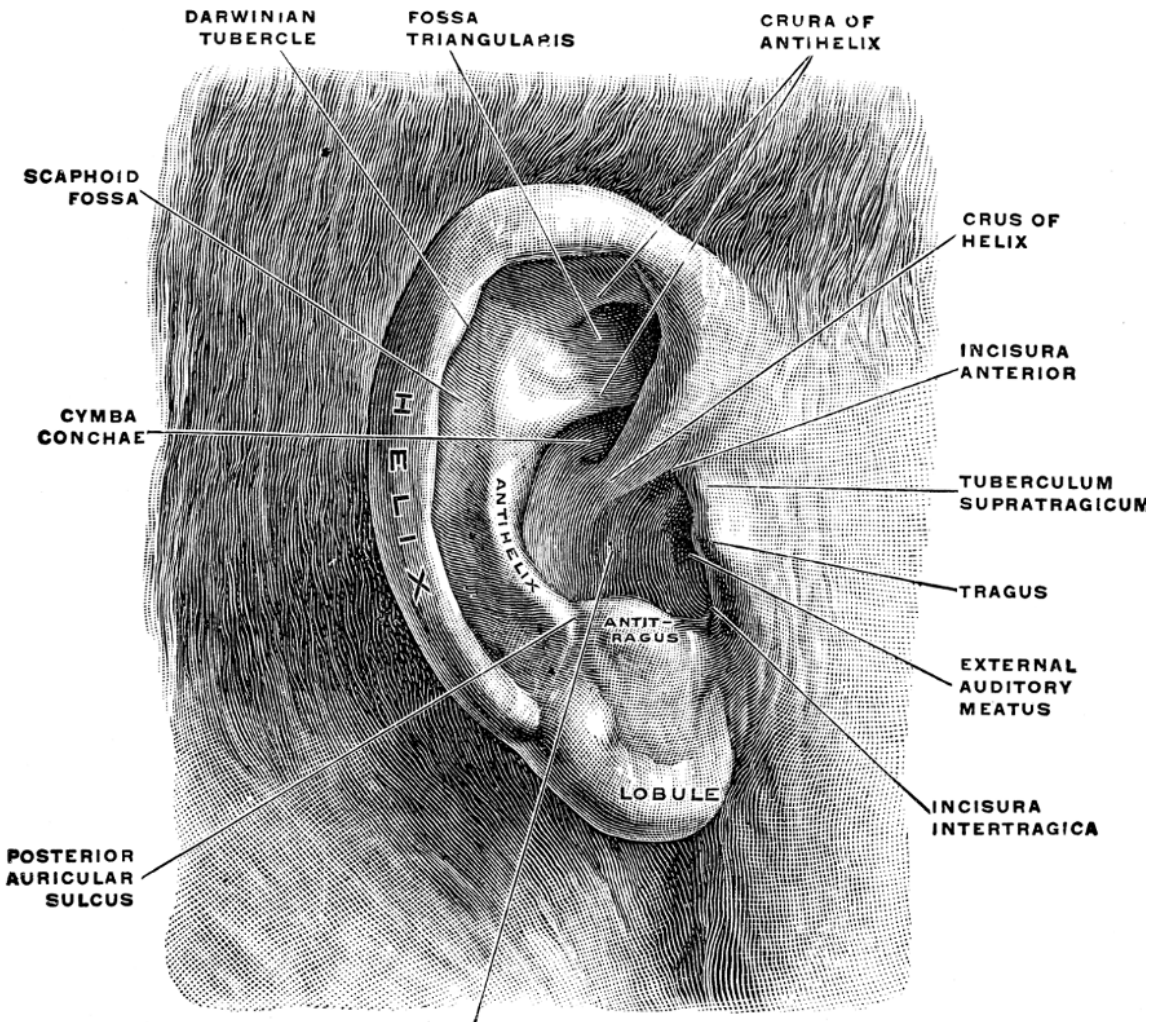
Ear canal

- Covered with skin, slight curvature
- $L \approx 25$ mm, $d \approx 7$ mm
- Sound propagation as plane wave



Pinna

- Pinna is an acoustic resonance system
- Resonances depend on distance and direction of sound event



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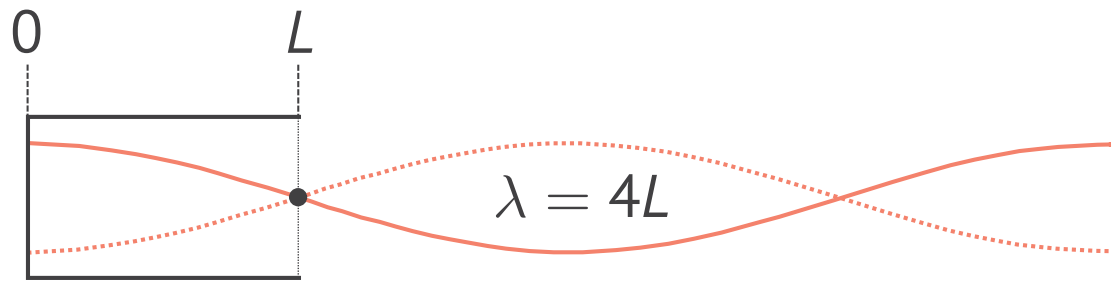
Ear canal



Tube of length $L = 25\,\text{mm}$, diameter $d \ll \lambda$, one end acoustically hard, other end soft

Solution of wave equation

- Sound pressure: $P(x,\omega) = A(\omega)\mathrm{e}^{-ikx} + B(\omega)\mathrm{e}^{ikx}$
- Sound velocity: $V(x,\omega) = -ikA(\omega)\mathrm{e}^{-ikx} + ikB(\omega)\mathrm{e}^{ik_x x}$
- Boundary condition: $V(0,\omega) = 0$, $P(L,\omega) = 0$

Non-trivial solutions for $A = B$ and $k = \frac{(2m-1)\pi}{2L}, m \in \mathbb{Z}$

First resonance for $m = 1 \Rightarrow f_{\text{resonance}} = \frac{c}{\lambda} = 3.4\,\text{kHz}$

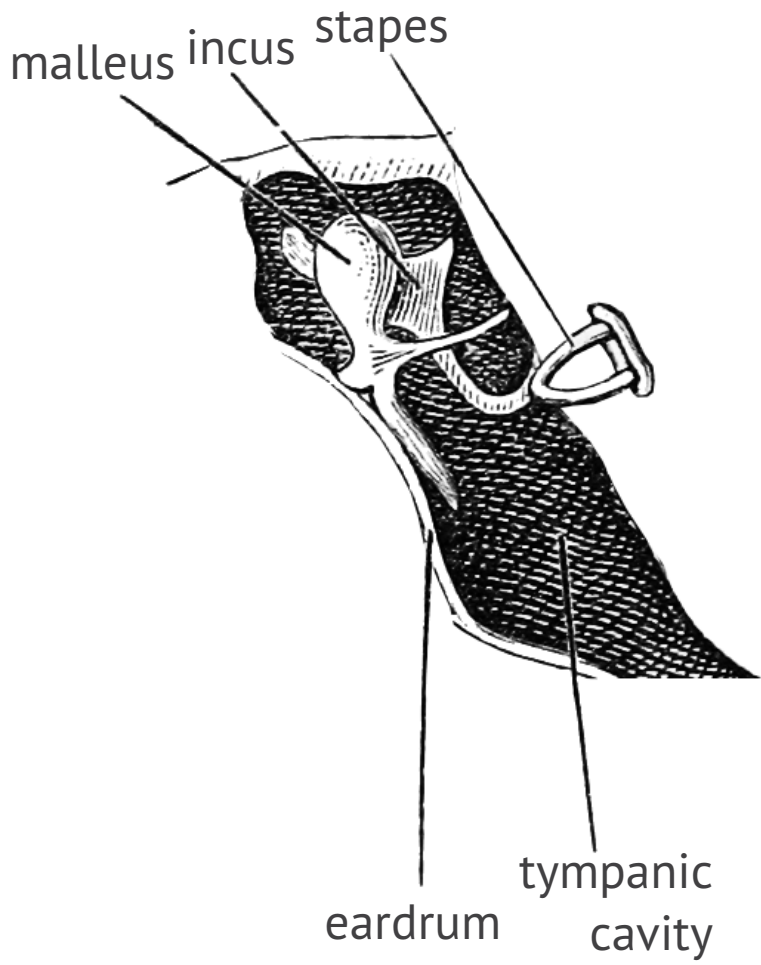
Middle ear

Eardrum

- Stiff membrane
- Excitation by sound waves
- $A \leq 100\,\mathrm{mm}^2$, $\Delta x = 0.1\,\mathrm{mm}$

Ossicles

- Impedance matching between ear canal and inner ear
- Transforming low p, high $\mathbf{v}$ to high p, low $\mathbf{v}$
- Ratio size eardrum / oval window $\approx 50 : 3$
- Ratio pressure transformation $\approx 1 : 22$



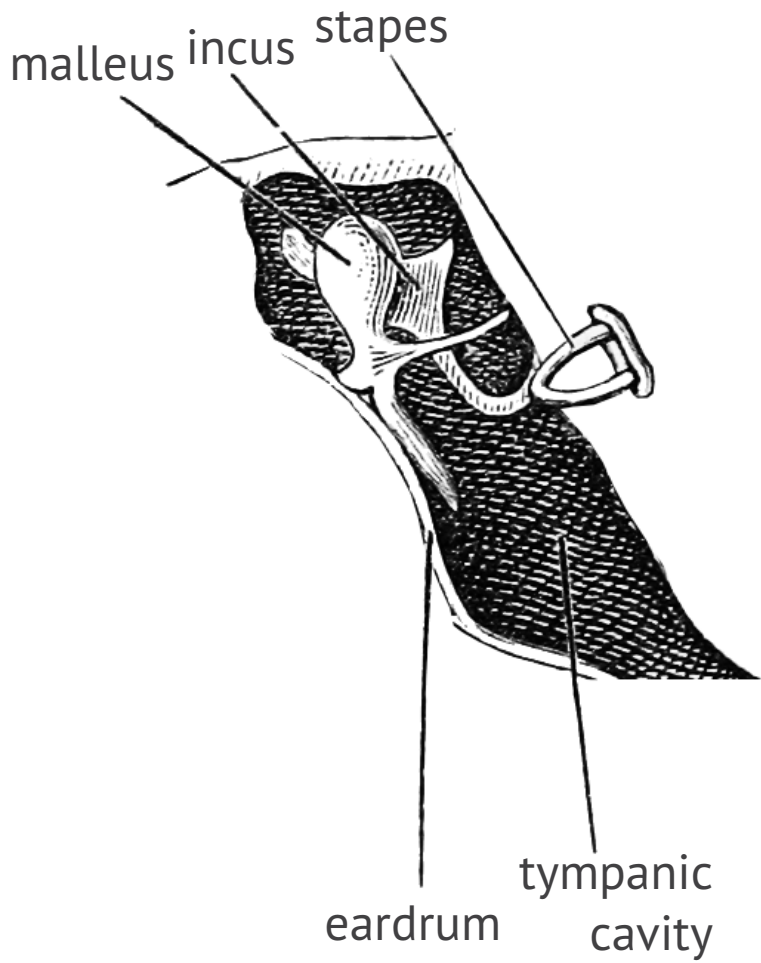
Middle ear

Musculus stapedius

- Sound pressure $>$ 90 dB HL
  $\Rightarrow$ increase of muscle tension
- Stapedius reflex protects hair cells in inner ear
- $\approx$ 15 dB attenuation, 50 ms reaction time

Musculus tensor tympani

- Avoids unwanted strong movements of ossicles (e.g. sneezing)



Inner ear

Oval window

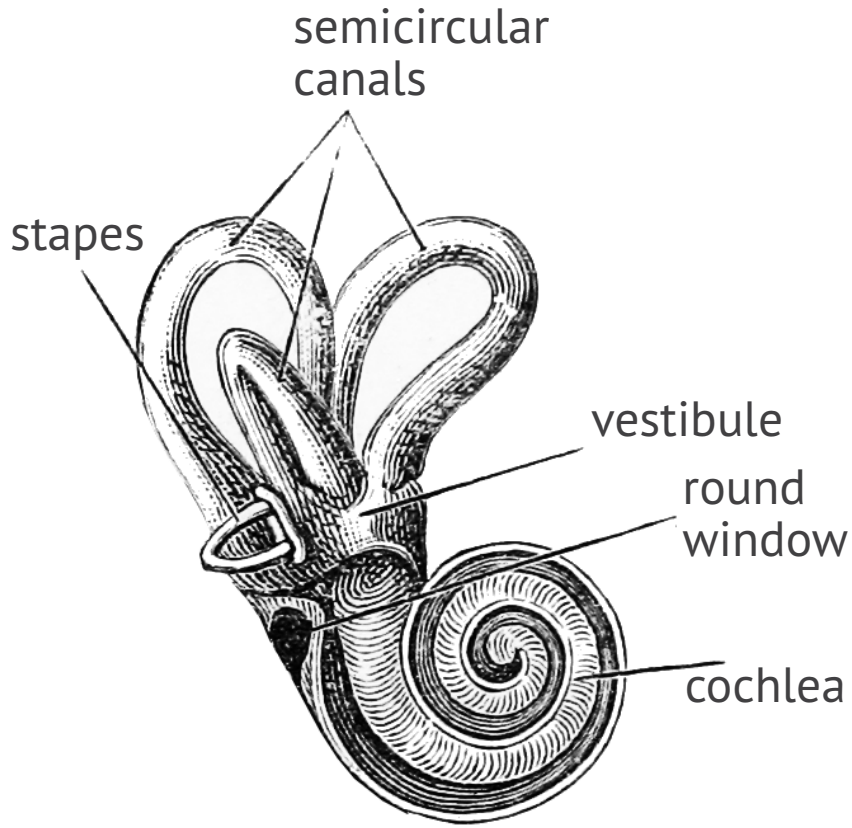
- Connection between stapes and inner ear

Cochlea

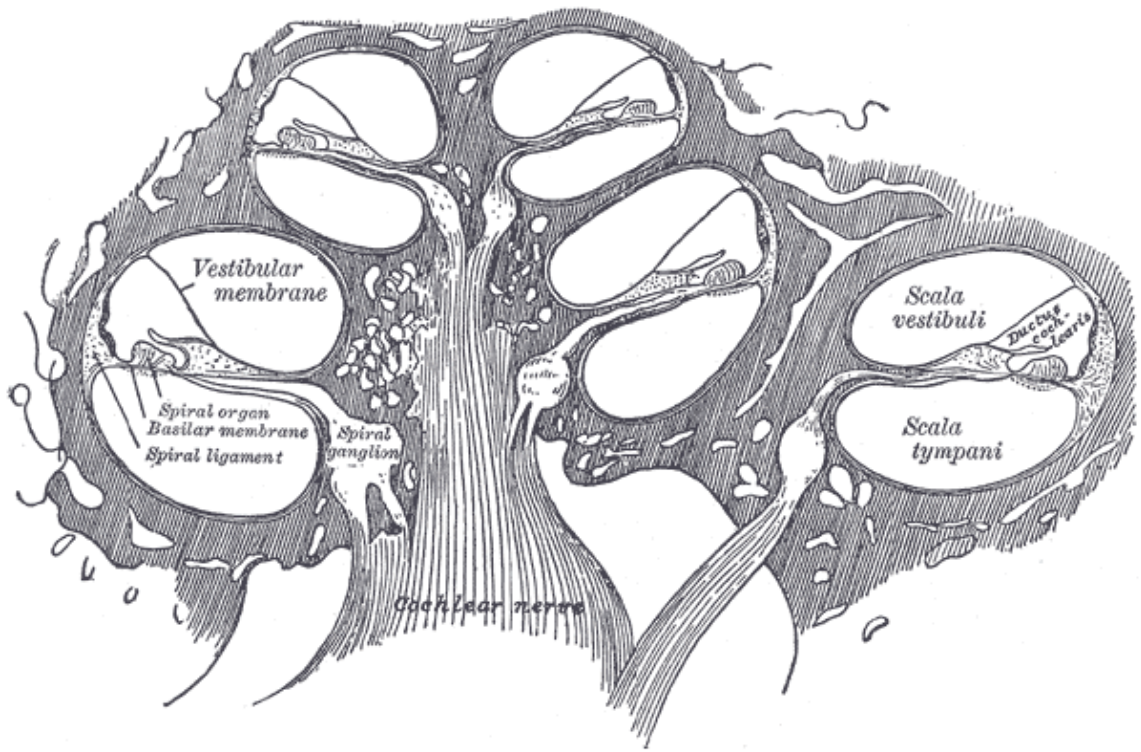
- Located in petrous bone, bony-like walls
- 2.5 windings, $L \approx 34\,\text{mm}$
- Perceptual organ

Semicircular canals

- Detection of rotary movements
- Sense of balance



Anatomy and function of the cochlea

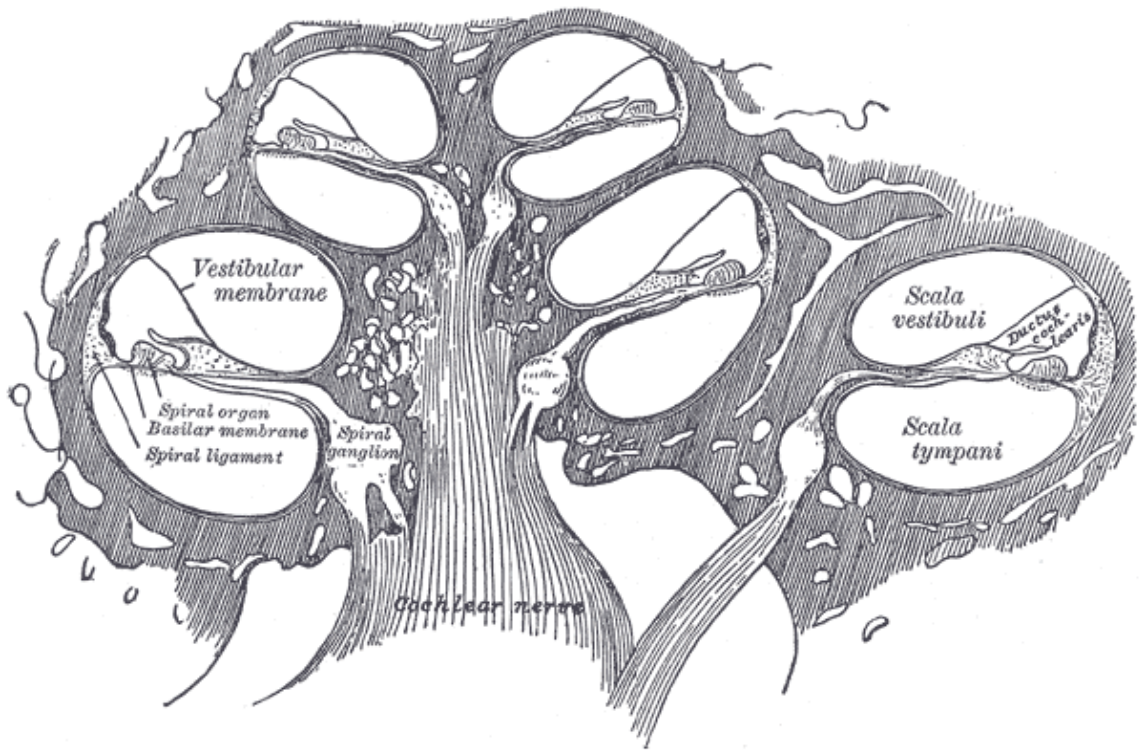


[3]

Anatomy

- **Scala vestibuli:** filled with perilymph; hardly compressible
- **Scala tympani:** connected at helicotrema with scala vestibuli
- **Cochlear duct:** filled with endolymph; houses the organ of corti

Anatomy and function of the cochlea



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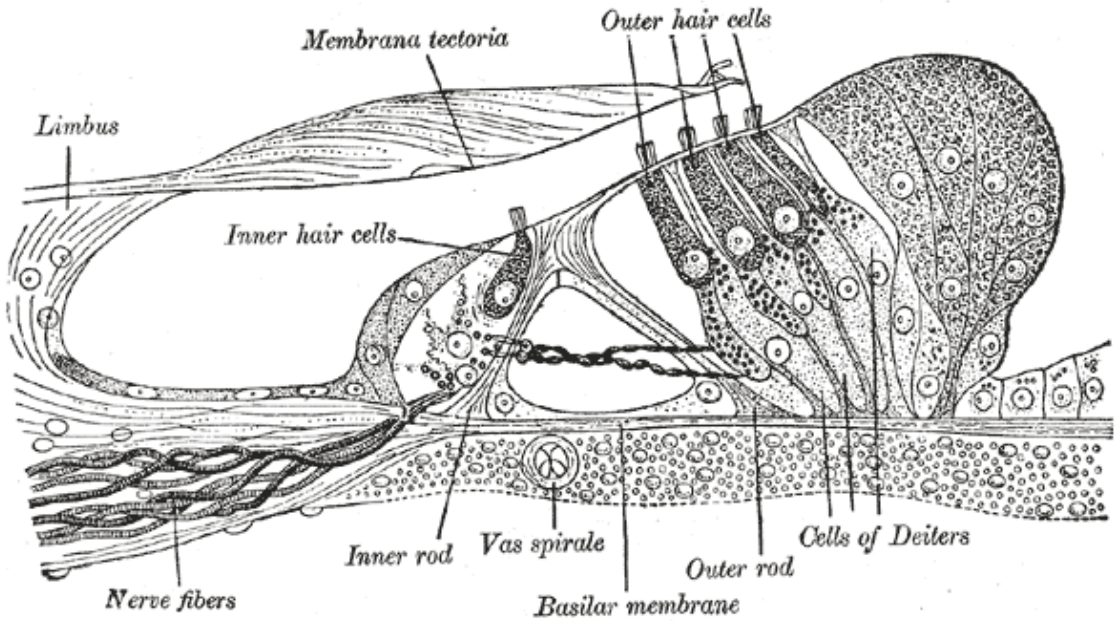
Function

- **Scala vestibuli:** excitation via oval window
- **Scala tympani:** pressure equalization via round window
- **Cochlear duct:** receptor organ for hearing

Anatomy and function of the cochlea

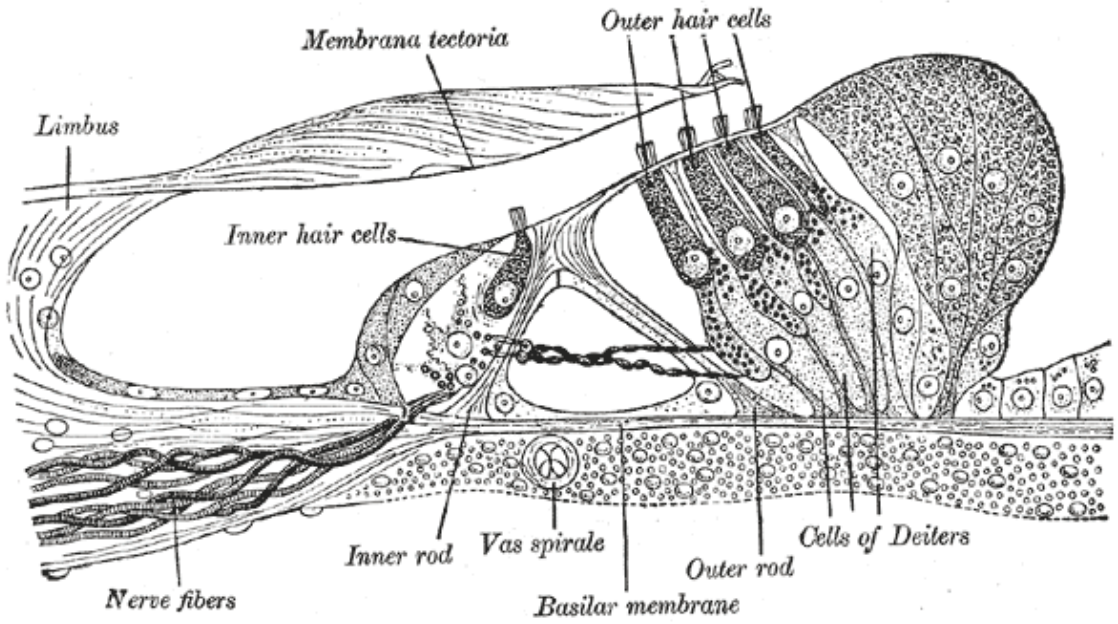


[3]

Anatomy

- **Basilar membrane:** carries sensory cells; changes in stiffness
- **Inner hair cells:** about 3500; mainly afferent synapses
- **Outer hair cells:** about 25000; mainly efferent synapses

Anatomy and function of the cochlea



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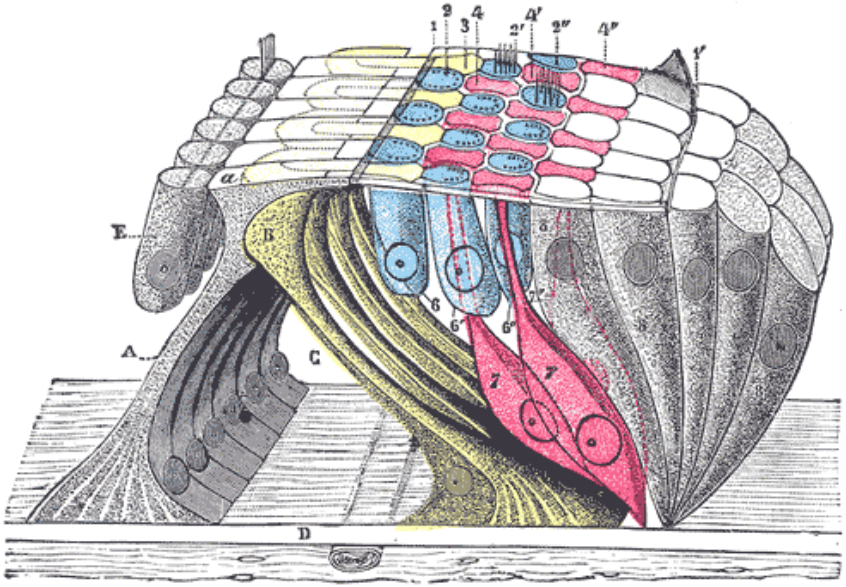
Function

- **Basilar membrane:** movement due to sound; trigger hair cells
- **Inner hair cells:** “analogue-digital” conversion; transmission to brain
- **Outer hair cells:** active amplifications

Further details on hair cells



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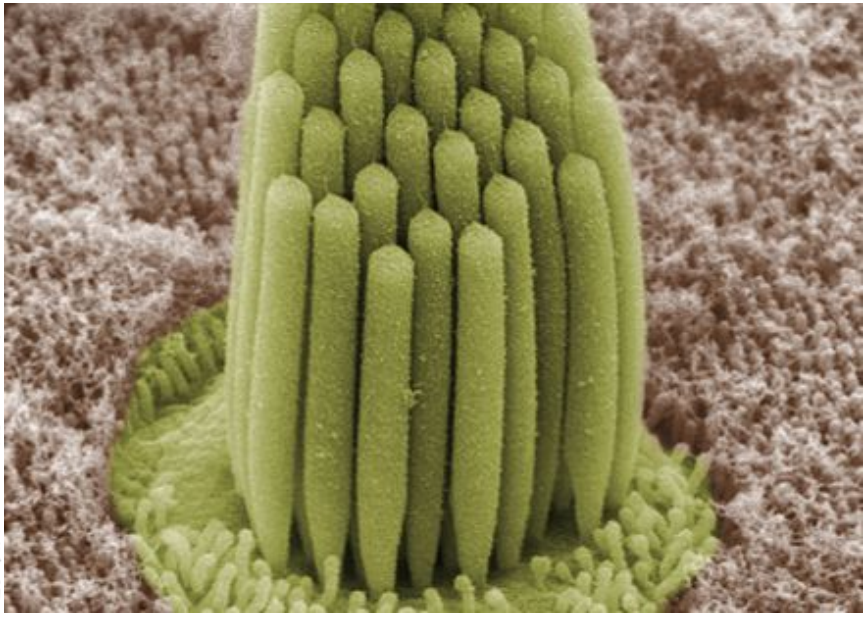

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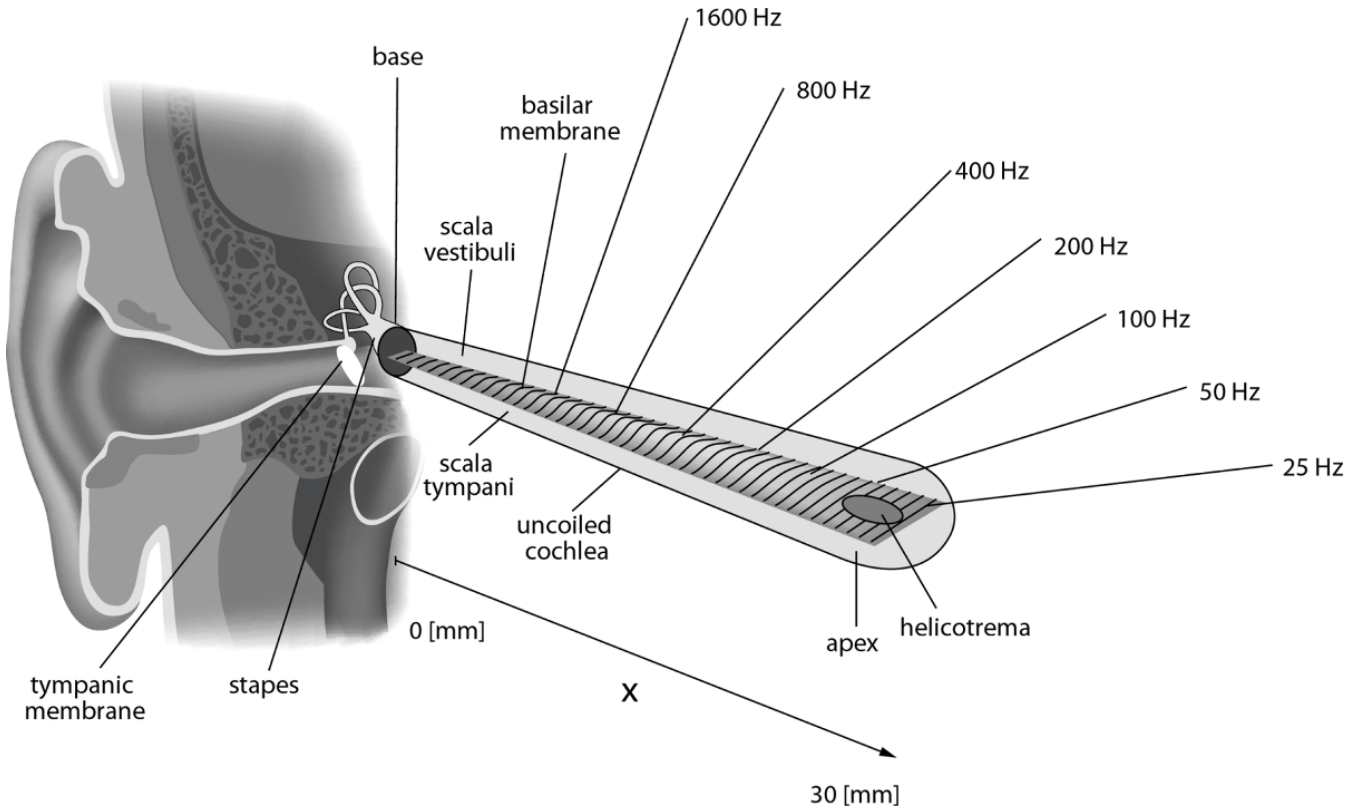
Stereocilia

- Outer hair cells have about 40 cilia per hair cell
- Inner hair cells about 40
- Inner hair cells connect via cilia to tectorial membrane
- Movement of basilar membrane leads to sharing movements
  $\Rightarrow$ hair cell fires nerve spike

Place-frequency transformation of basilar membrane



[5]

- Position of excitation frequency dependent
- Frequency-place transformation like a filter bank
- Travelling wave (von Békésy, 1960)
- Related to pitch perception

Bibliography

[1] This figure is based on B. Grothe, M. Pecka, and D. McAlpine. “Mechanisms of Sound Localization in Mammals”. Physiological Reviews 90 (2010), pp. 983–1012; K. Talbot et al. “Synaptic dysbindin-1 reductions in schizophrenia occur in an isoform-specific manner indicating their subsynaptic location.” PLoS ONE 6.3 (2011), e16886; L. Chittka and A. Brockmann. “Perception space–the final frontier.” PLoS Biology 3.4 (2005), e137.

[2] la Cour, P., “Tidens naturlære (Nature of time)”, (Gyldendalske boghandels forlag, Kopenhagen, 1903).

[3] Gray, H., “Gray’s Anatomy: Descriptive and Applied,” (Lea & Febiger, Philadelphia, 2013).

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[5] Kern, A. Heid, C. Steeb, W. H. Stoop, N. and Stoop, R., “Biophysical parameters modification could overcome essential hearing gaps,” PLoS Computational Biology, doi:10.1371/journal.pcbi.1000161, 2008.