



Hearing Systems – Part 1 of 3

<https://hearingsystems.github.io/>

TU Ilmenau – Audio Signal Processing & Audio Systems

17. Januar 2024

Dr. rer. nat. Iko Pieper

•• Introduction

- audifon:
 - audifon GmbH & Co. KG develops, produces and sells hearing systems
 - Headquarter located in Kölleda, Thüringen (also place of production)
 - R&D offices in Köln (Electronics) and Ilmenau (Embedded Software)
 - About 200 employees
- myself:
 - Hobbies: drumming, music production
 - M.Sc. Physik, Ph.D. at Medical Physics Group (Oldenburg)
 - Developing audio signal processing algorithms at audifon since Mai 2022



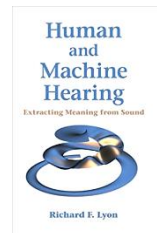
•• Introduction

- Three lectures and one seminar.
- Useful links:
 - <https://hearingsystems.github.io/>,
 - <https://moodle.tu-ilmenau.de/course/view.php?id=125>.
- Topics we will cover today:
 - **Basics**: units, hearing, tonotopy, cochlear gain & compression, hearing loss.
- Topics you will cover with Dr. Tamas Harczos:
 - **Devices**: hearing aids, cochlear implants, optogenetic stimulation, hearables.
 - **Technologies**: audiological features, fitness & medical features, hardware & software.
 - **Current trends** in research & development.

•• Further resources

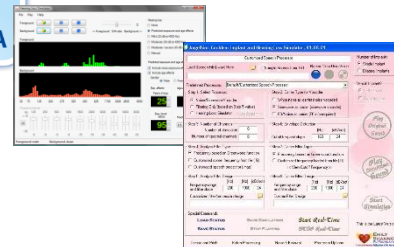
• Books:

- *Hörakustik 3.0 - Theorie und Praxis* (Jens Ulrich, Eckhard Hoffmann), ISBN: 978-3-9428-7336-9
- *Auditory Prostheses: New Horizons* (Zeng, Popper, Fay, eds.), ISBN: 978-1-4419-9434-9
- *Human and Machine Hearing* (Richard F. Lyon), ISBN: 978-1-1070-0753-6, see [draft online](#)



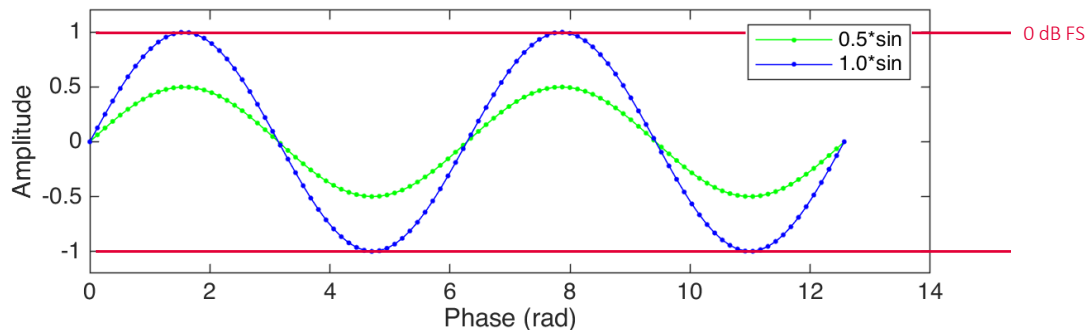
• Programming / Testing:

- [Oldenburg openMHA](#) (Master Hearing Aid)
- [Hearing Loss Simulator](#) (CDC, USA)
- [Cochlear implant \(CI\) and hearing loss simulator](#) (AngelSim)
- [CI simulation](#) (UT Dallas, USA), [CI simulation](#) (UGR, Spain)



•• Scales and units in audio signal processing

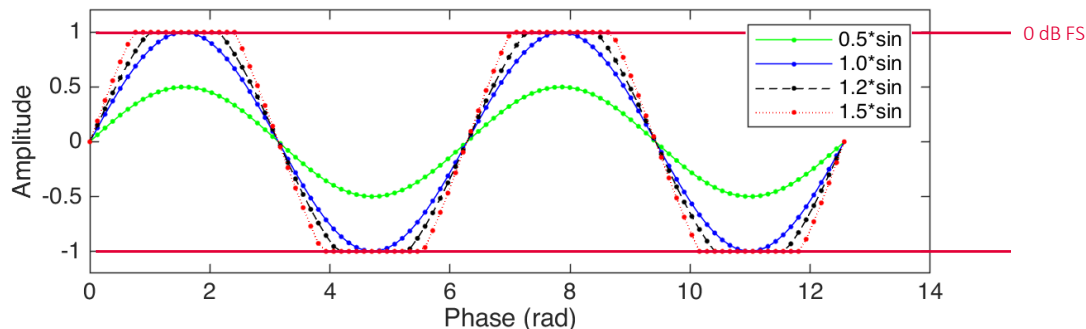
- First of all: Decibel (dB) alone is not a unit, it's a scale. It describes a relationship between two levels.
- Definition for (sound) amplitudes: $A_{dB} = 20 \log_{10}(\text{AmplitudeRatio})$, meaning:
 - if $\text{AmplitudeRatio} = A_1/A_2 = 1/100 \rightarrow 20 \log_{10}(1/100) = -40 \text{ dB}$,
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 - if $\text{AmplitudeRatio} = A_1/A_2 = 1/2 \rightarrow 20 \log_{10}(1/2) = -6.02 \text{ dB} \approx -6 \text{ dB}$.
- The unit **dB FS** (Decibel full scale): A_2 is the maximum output of the given system.
 - E.g.: Audio sample amplitudes in MATLAB are in range $[-1, +1] \rightarrow 0 \text{ dB FS}$ means $|\text{signal}|$ values approach 1.



Further increase in amplitude
 \rightarrow clipping.

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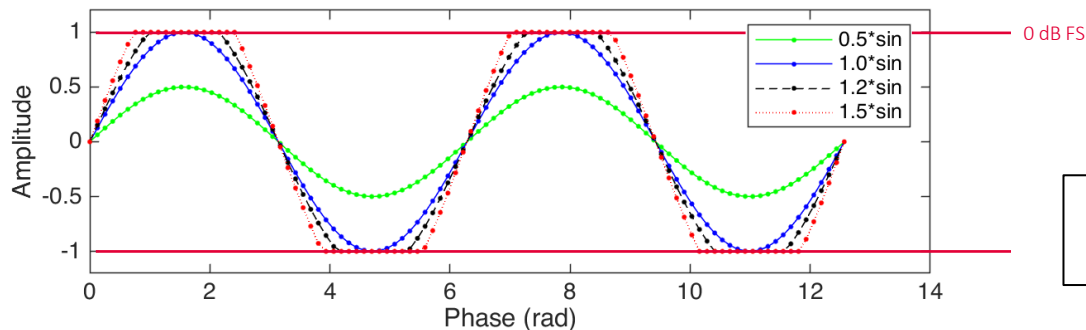


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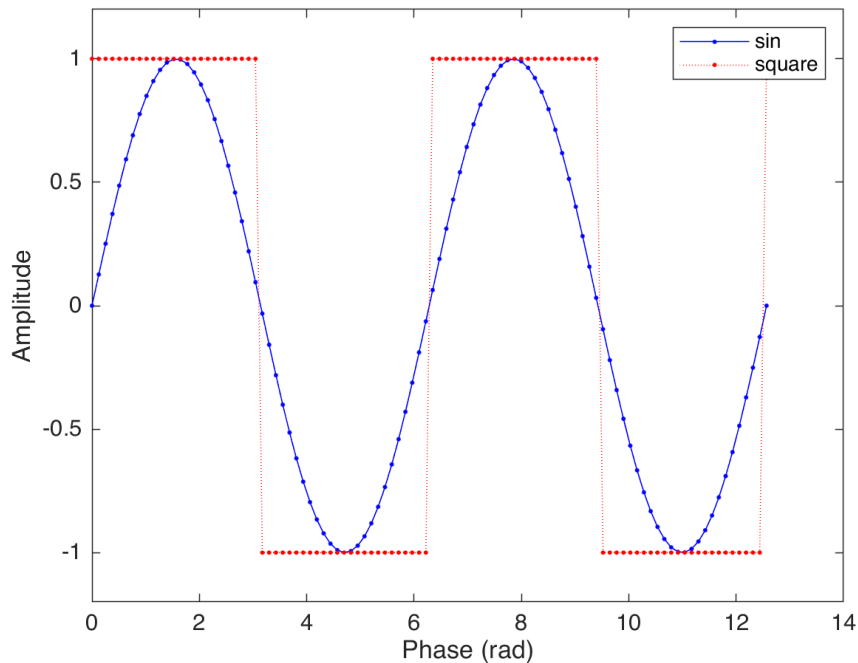


Further increase in amplitude
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Conversion:
 $dB = 20 \log_{10}(\text{mag}) \Leftrightarrow \text{mag} = 10^{(dB/20)}$

•• Scales and units in audio signal processing: dB FS

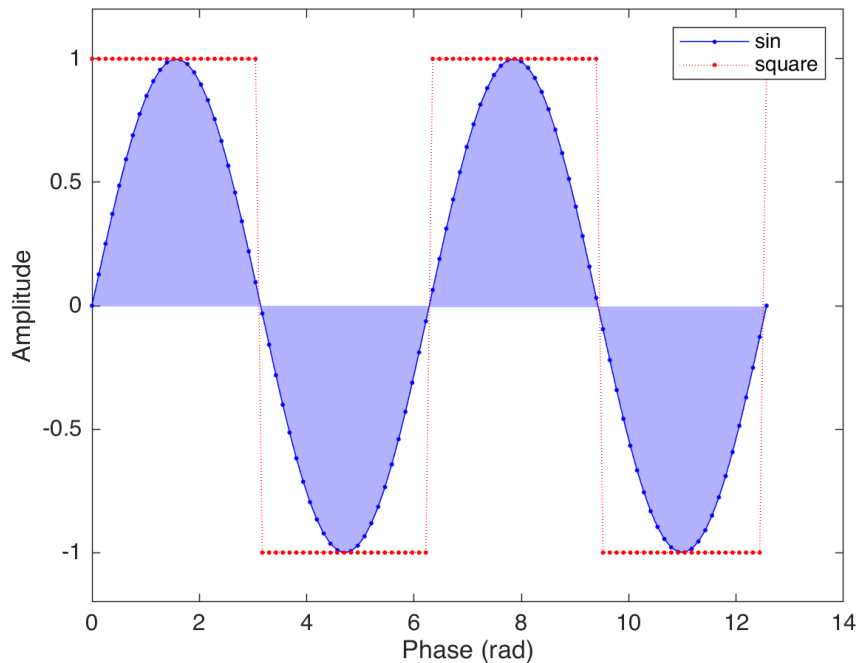
- The peaks (dB FS) of a signal do not necessarily reveal its impact on “loudness”. Calculating the RMS (root-mean-square) of chunks of samples helps → **signal form matters!**



```
max(|sine|) = 1.000 = -0.001 dB FS  
max(|square|) = 1.000 = 0.000 dB FS
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•• Scales and units in audio signal processing: dB FS (RMS)

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$$RMS = \sqrt{\frac{1}{N} \sum_{n=1}^N x_n^2}$$

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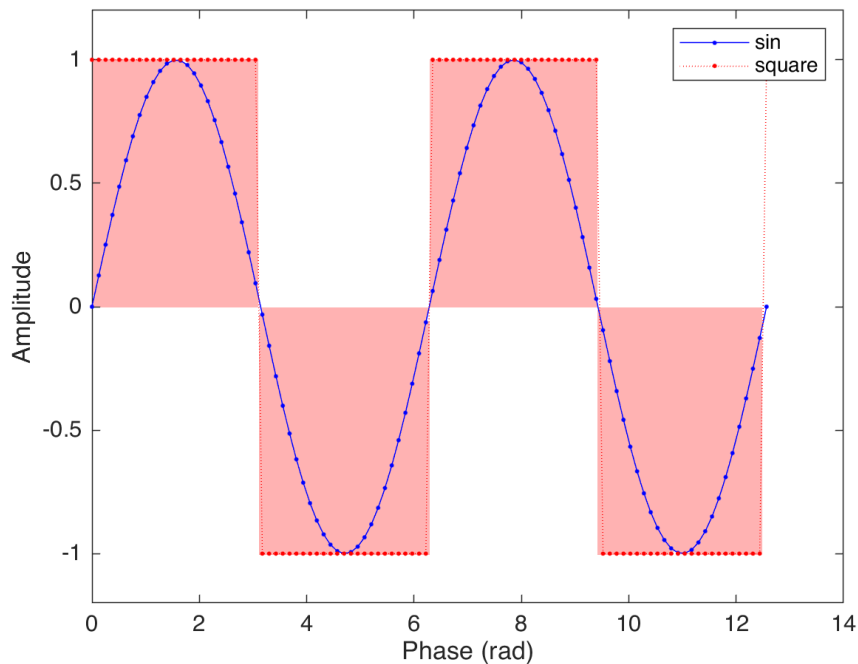
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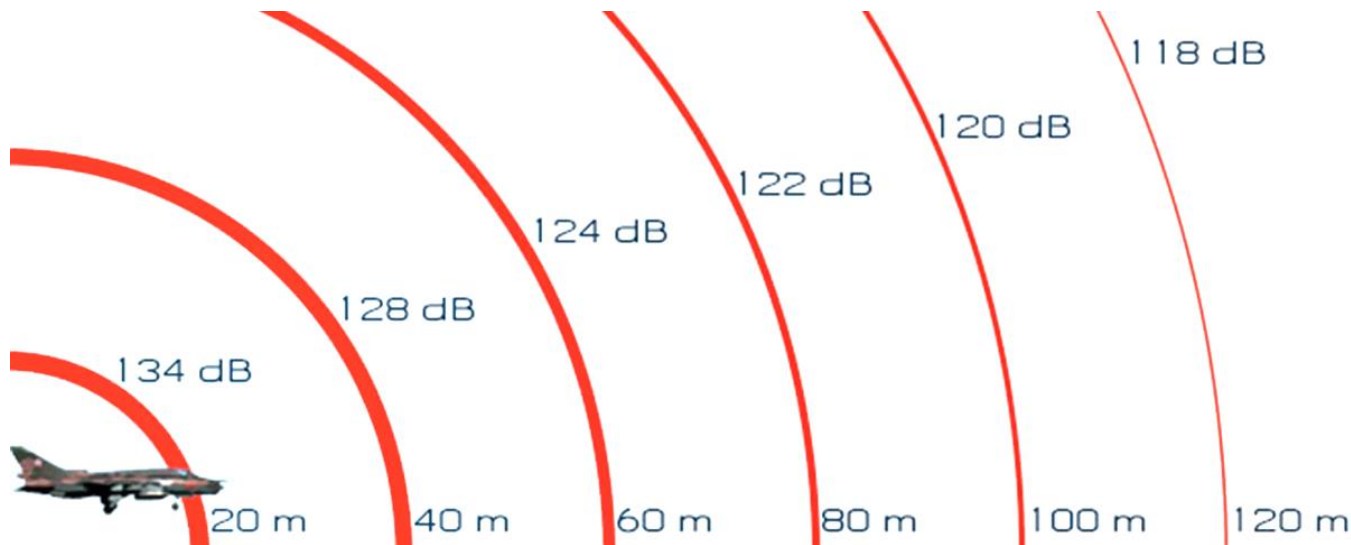
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•• Scales and units in audio signal processing: dB SPL

- The unit **dB SPL** (Decibel sound pressure level): relates the RMS of the pressure fluctuations in the air p to the reference sound pressure $p_0 = 20 \mu\text{Pa}$ (approx. threshold of human hearing for 1 kHz sine). $L_{\text{dB SPL}} = 20 \log_{10} (p/p_0)$.
 - Distance (source to receiver) is important, 1 m is frequently used as standard distance.
 - Doubling the distance halves the pressure in free field (-6 dB SPL).

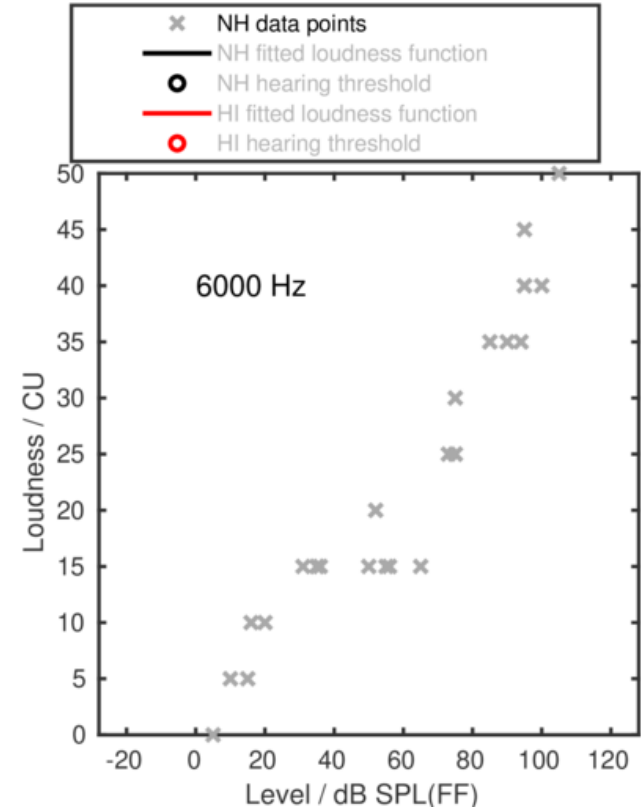
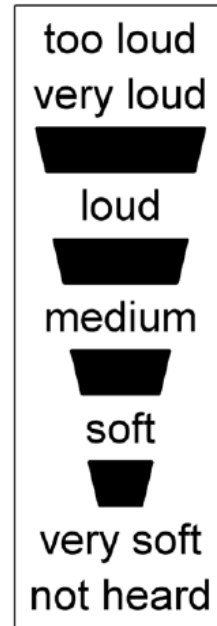
Source: <https://www.translatorscafe.com/unit-converter/Zh/sound-pressure-level/>



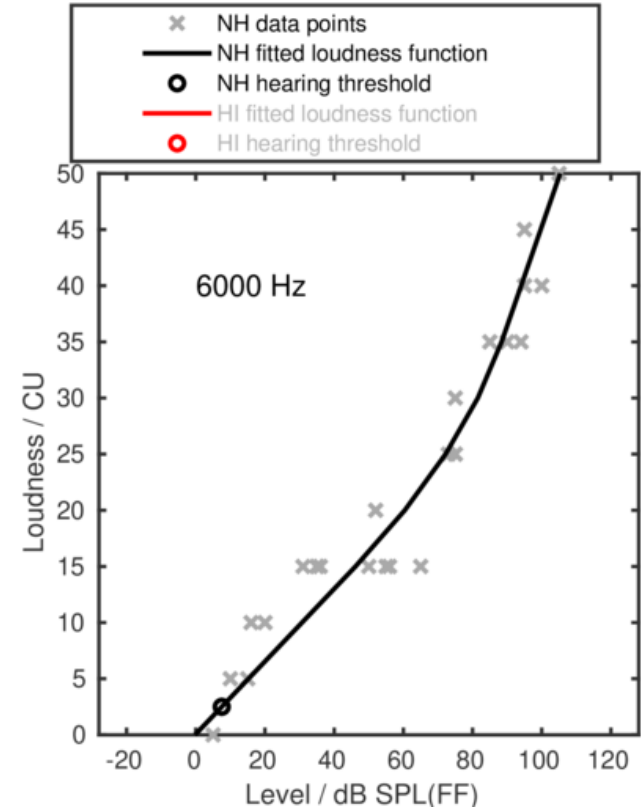
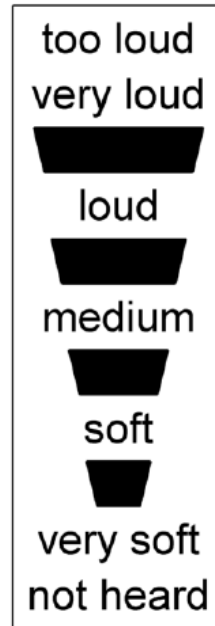
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 - Distance (source to receiver) is important, 1 m is frequently used as standard distance.
 - Doubling the distance halves the pressure in free field (-6 dB SPL).
 - Typical ranges:
 - 20-30 dB SPL: very calm room,
 - 40-60 dB SPL (1 m): normal conversation,
 - 70-90 dB SPL (10 m): nearby heavy traffic, > 90 dB SPL: Hearing damage over long-term exposure
 - 100-110 dB SPL (1 m): jack hammer / chain saw,
 - 120 dB SPL (100 m): jet engine, > 120 dB SPL: Instantaneous noise-induced hearing loss
 - 194 dB SPL: largest pressure fluctuation an undistorted sound wave can have in Earth's atmosphere.

•• Scales and units in audio signal processing: Categorical loudness scaling



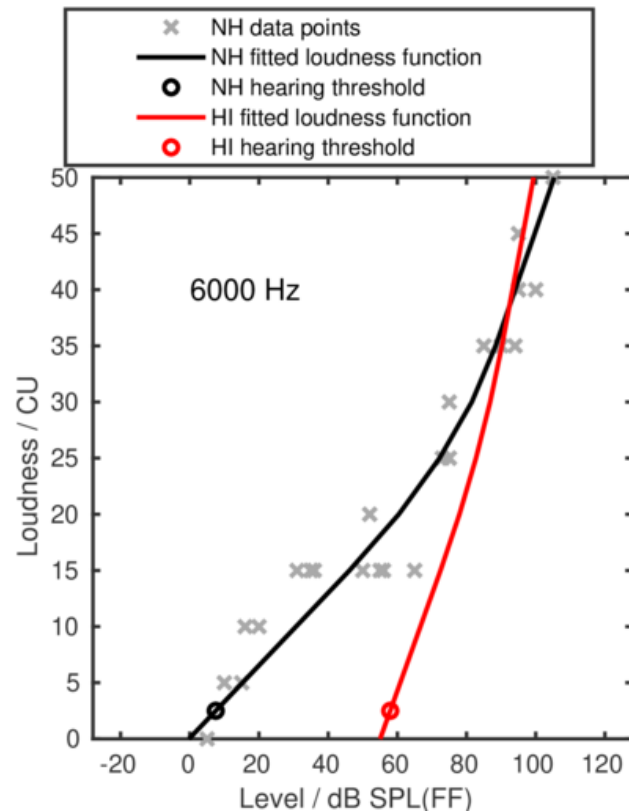
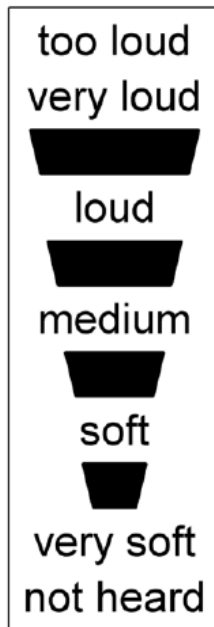
•• Scales and units in audio signal processing: Categorical loudness scaling



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Often observed in case of sensorineural hearing impairment:

- Hearing threshold shifted to higher sound pressure levels
- Uncomfortable level (perceived as too loud, 50 CU) not shifted

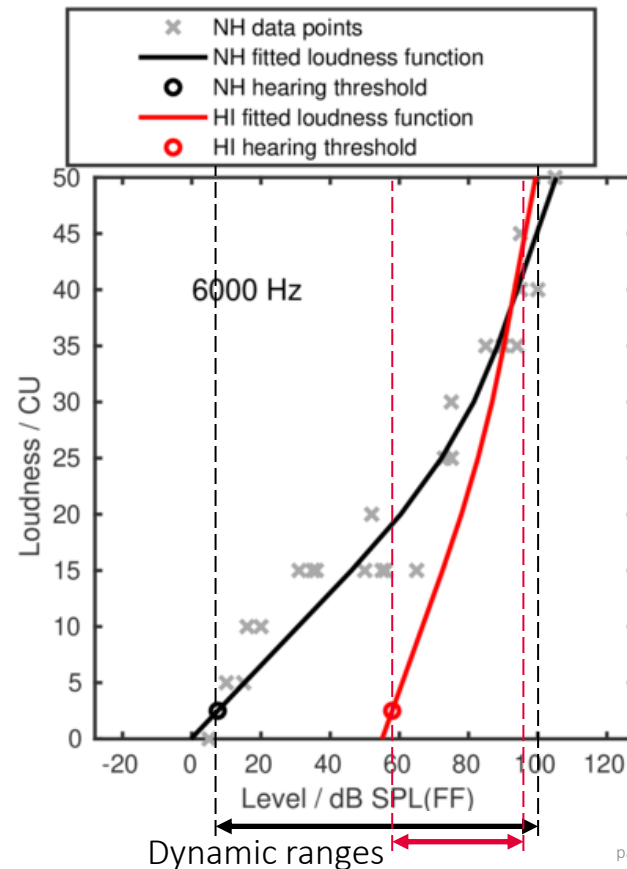
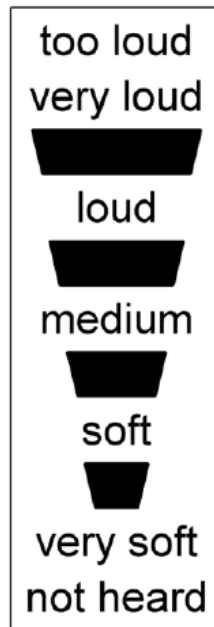


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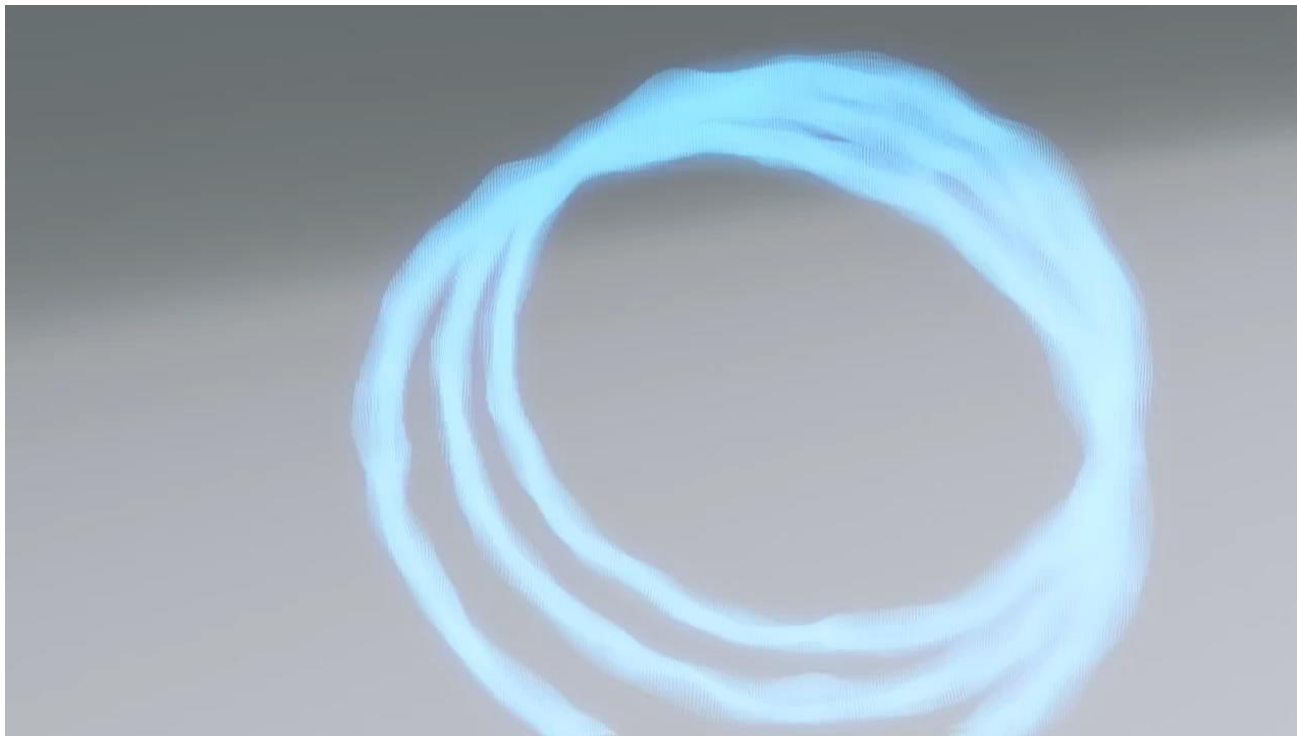
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⇒ Reduced dynamic range



- How hearing works



•• Overview

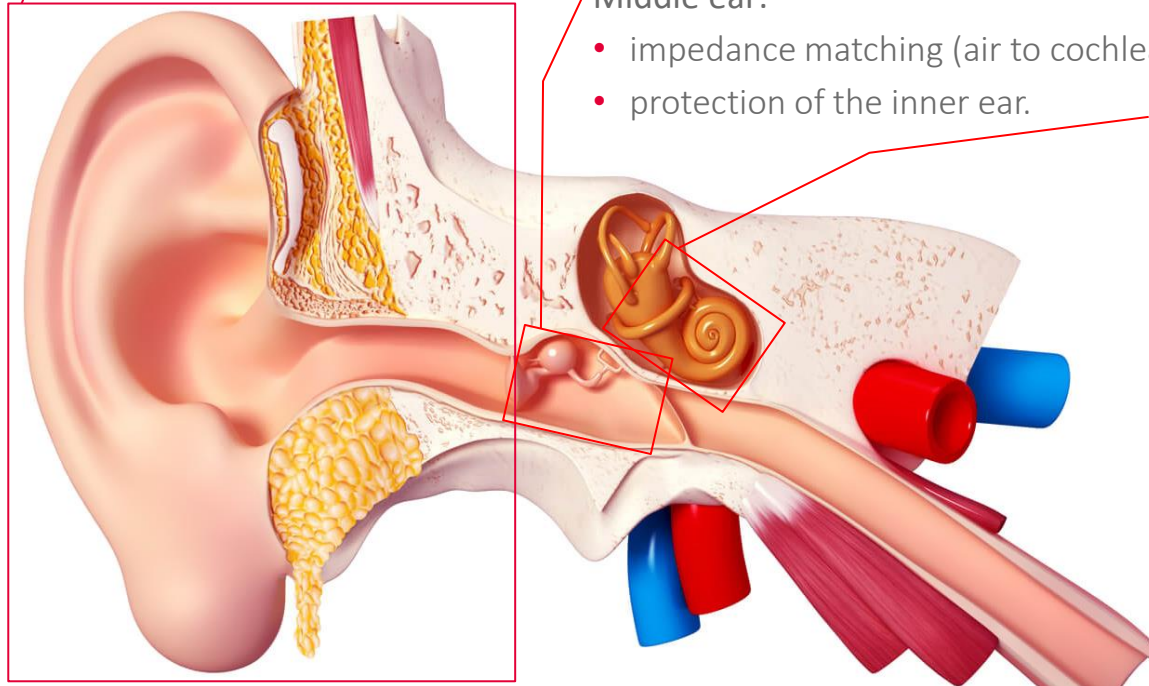
Outer ear: amplification,
direction-dependent filtering.

Middle ear:

- impedance matching (air to cochlea),
- protection of the inner ear.

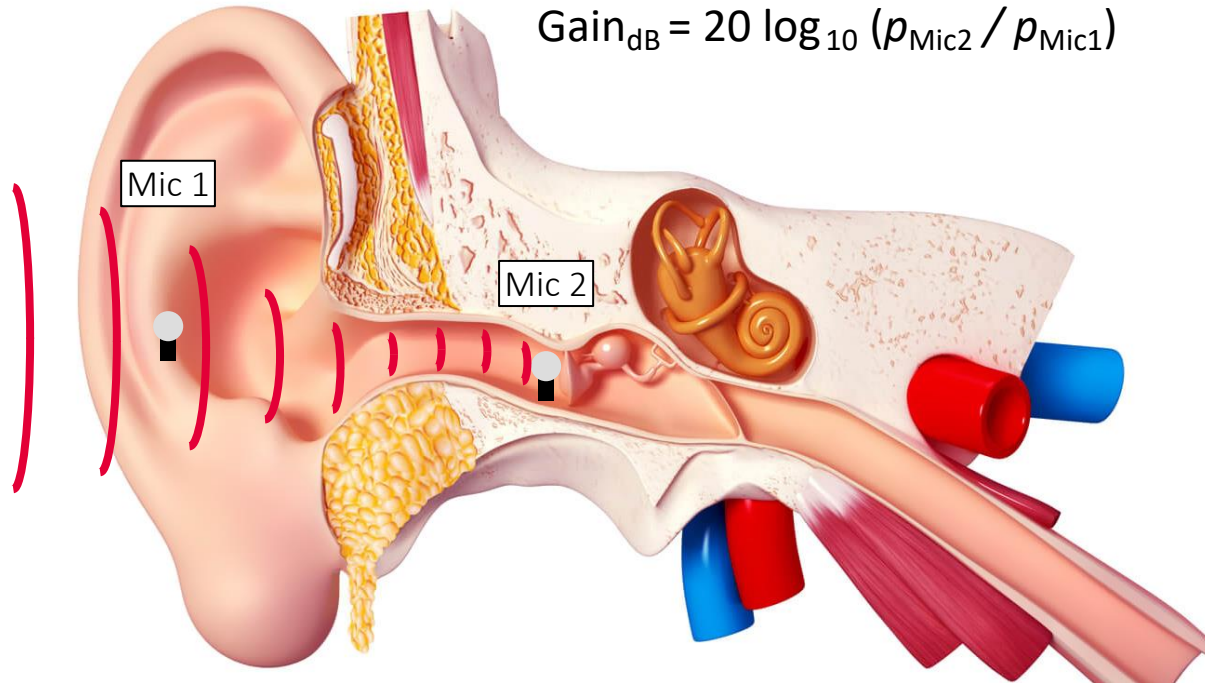
Inner ear (cochlea):

- spectral decomposition of signal (~filter bank),
- extension of dynamic range (compressive nonlinearity),
- transformation into electrical signals.

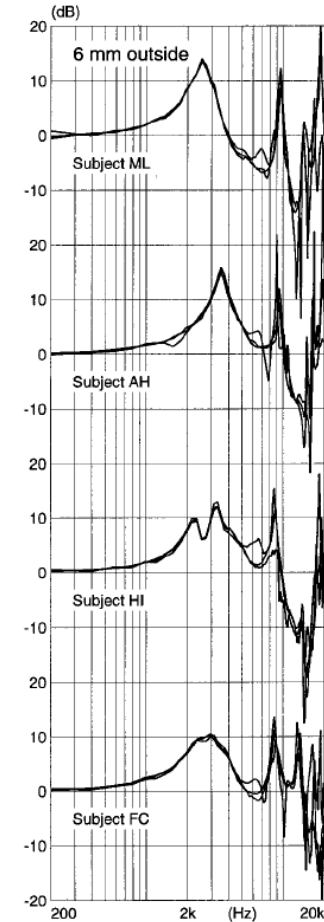


Source: www.lobe.ca, 2021.

•• Outer ear: Transfer function



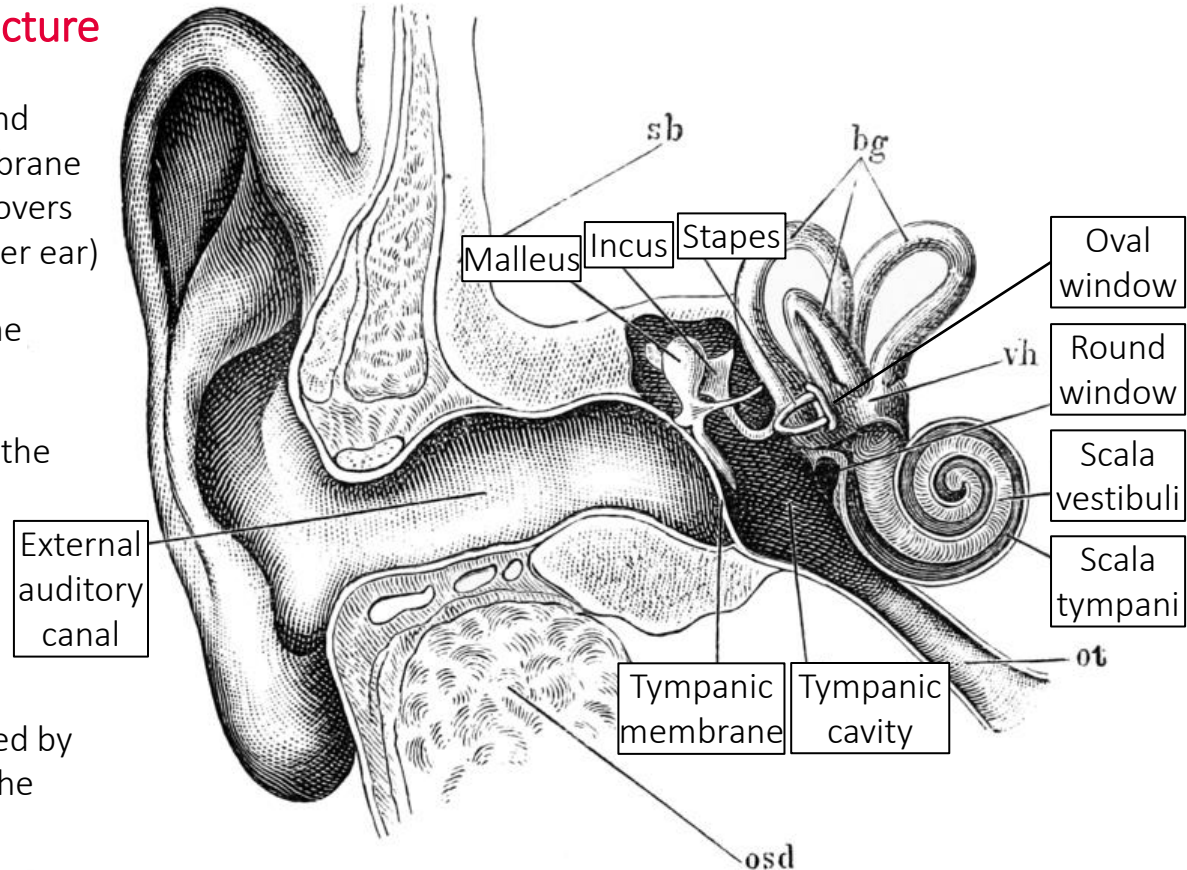
$$\text{Gain}_{\text{dB}} = 20 \log_{10} (p_{\text{Mic2}} / p_{\text{Mic1}})$$



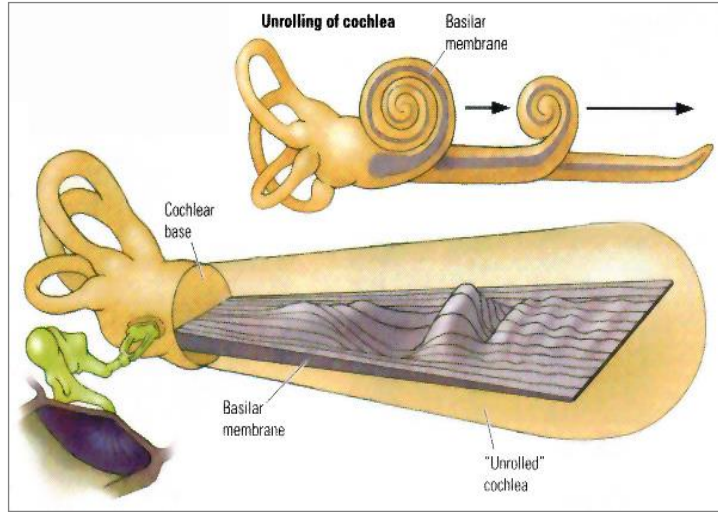
Source: Hammershoi, D. and Møller, H.: Sound transmission to and within the human ear canal, 1995

•• Middle ear and Inner ear: Structure

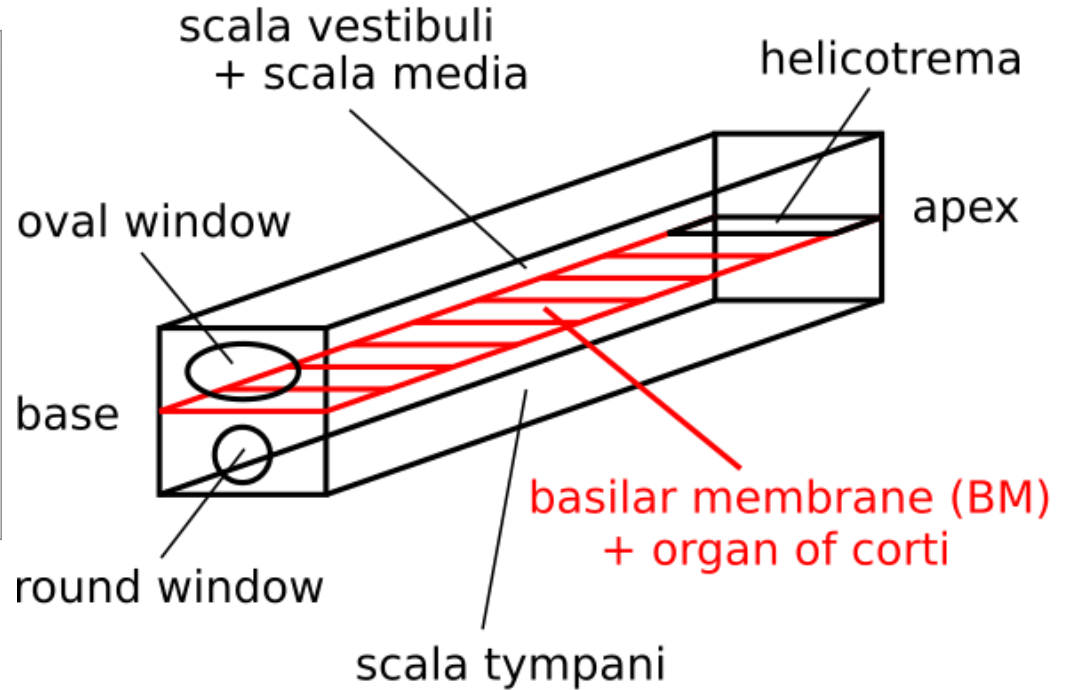
- The three ossicles (malleus, incus, and stapes) connect the tympanic membrane (ear drum) to the membrane that covers the oval window of the cochlea (inner ear)
- The oval window is an opening of the scala vestibuli
- The round window is an opening of the scala tympani, and covered with a membrane as well
- The cochlea scales are filled with fluids
- The cochlea scales are only separated by the basilar membrane that carries the inner and outer hair cells



•• Inner ear (cochlea): Simplified geometry

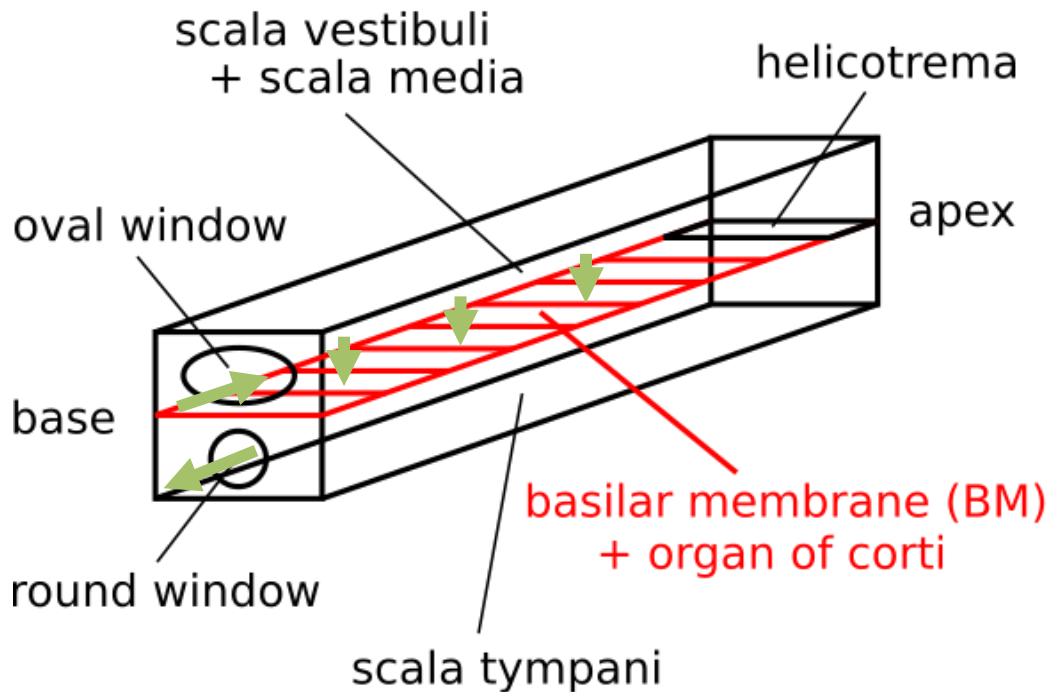


Source: <http://www.pc.rhul.ac.uk>



•• Inner ear (cochlea): Impedance

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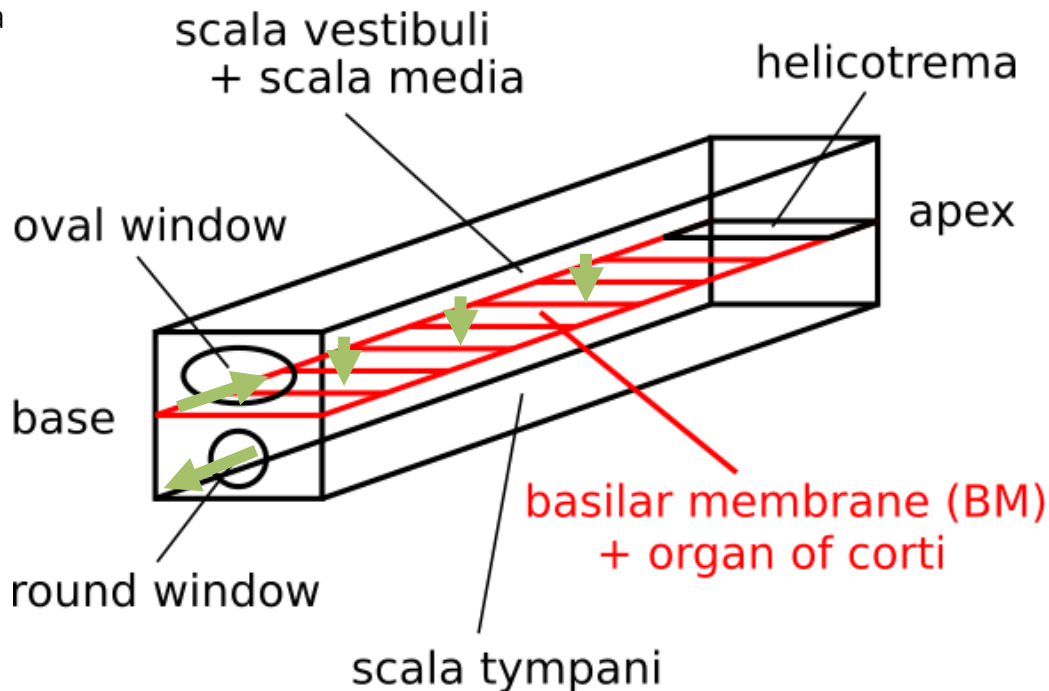
•• Inner ear (cochlea): Impedance

- The mechanical impedance of the cochlea is a combination of...

... the stiffness of the membranes inside the cochlea and the membranes covering the oval and round window,
 ... the inertia of the fluids,
 ... the compressibility of the fluids (negligible),
 ... some damping here and there.

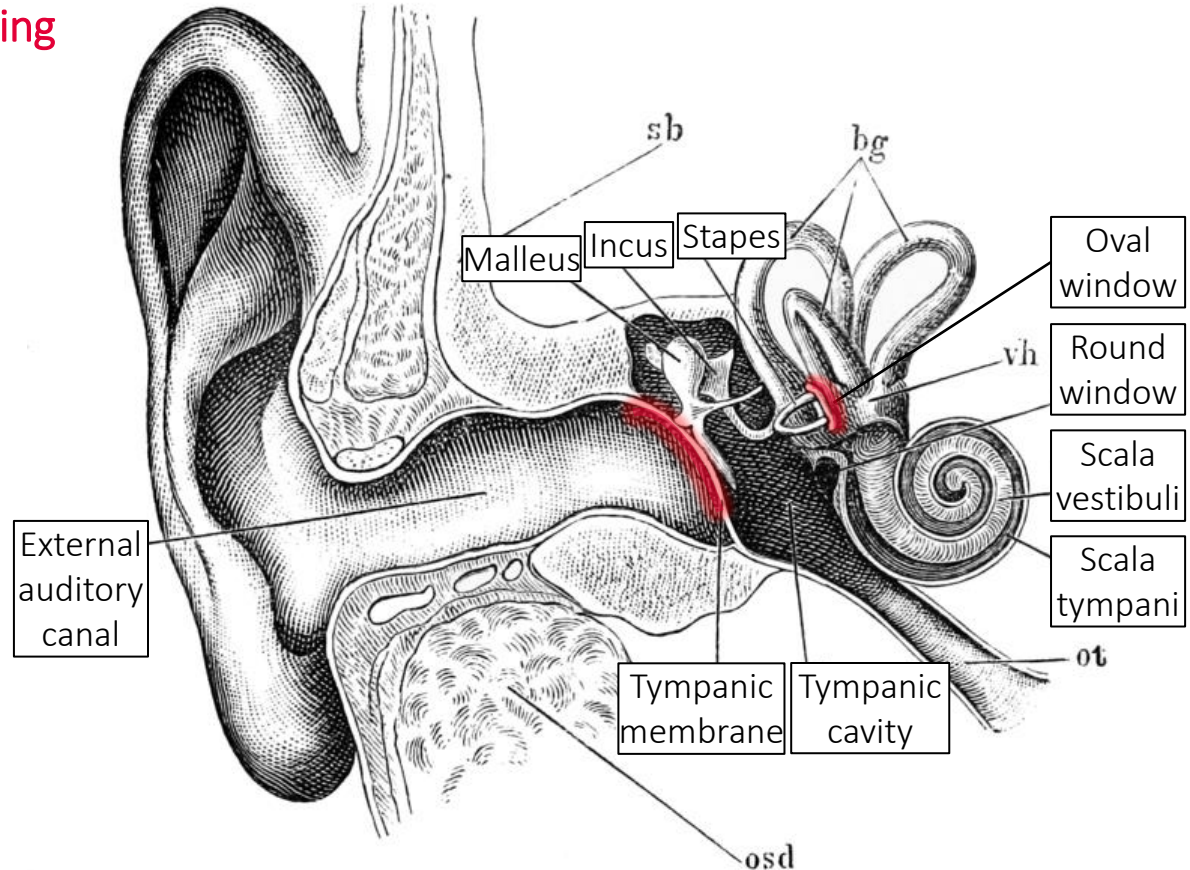
- The impedance of this system is lower than the impedance of fluids but still higher than the impedance of air

⇒ Impedance matching between air and cochlea is required to avoid reflection of sound waves at the oval window



•• Middle ear: Impedance matching

- The sound pressure (force / area) needs to be increased
 - A lever could increase the force, but the leverage ratio of the ossicles seems to be small
 - The area of the oval window is smaller than the area of the ear drum
- ⇒ Force is concentrated on a smaller area
- ⇒ Pressure (force / area) is increased



•• Middle ear: Transfer function

Simple theoretical calculation:

- Area of ear drum: 80 (mm)^2
- Area of oval window: 3 (mm)^2

$$\Rightarrow \text{Gain} = \frac{80}{3} = 27 \triangleq 20 \log_{10}(27) \text{ dB} = 29 \text{ dB}$$

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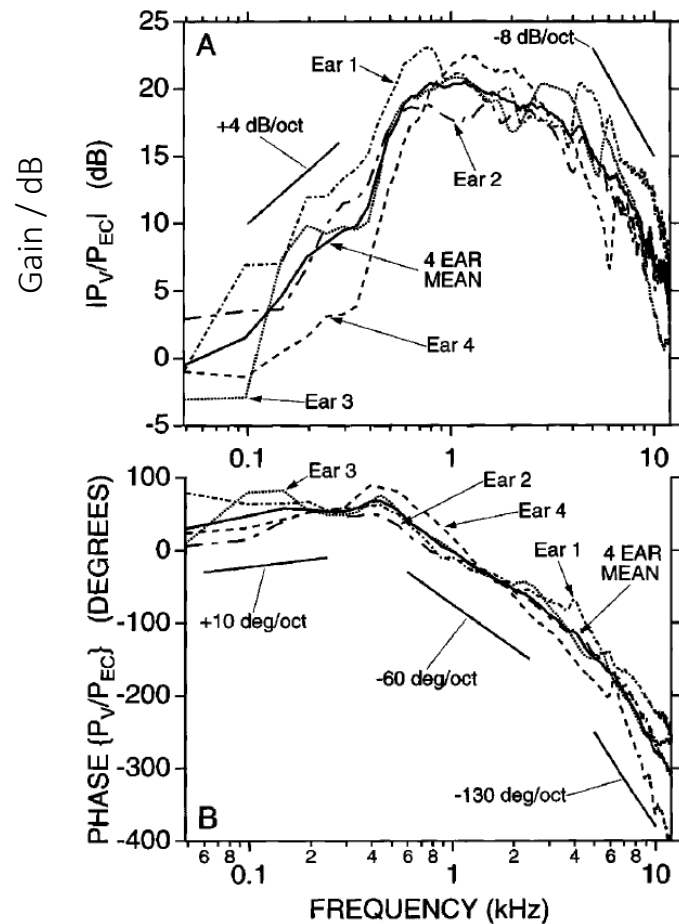
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Measured transfer function by Puria et al. (1997):

- About 20 dB gain at medium frequencies



Source: Puria et al.: Sound-pressure measurements in the cochlear vestibule of human-cadaver ears, 1997

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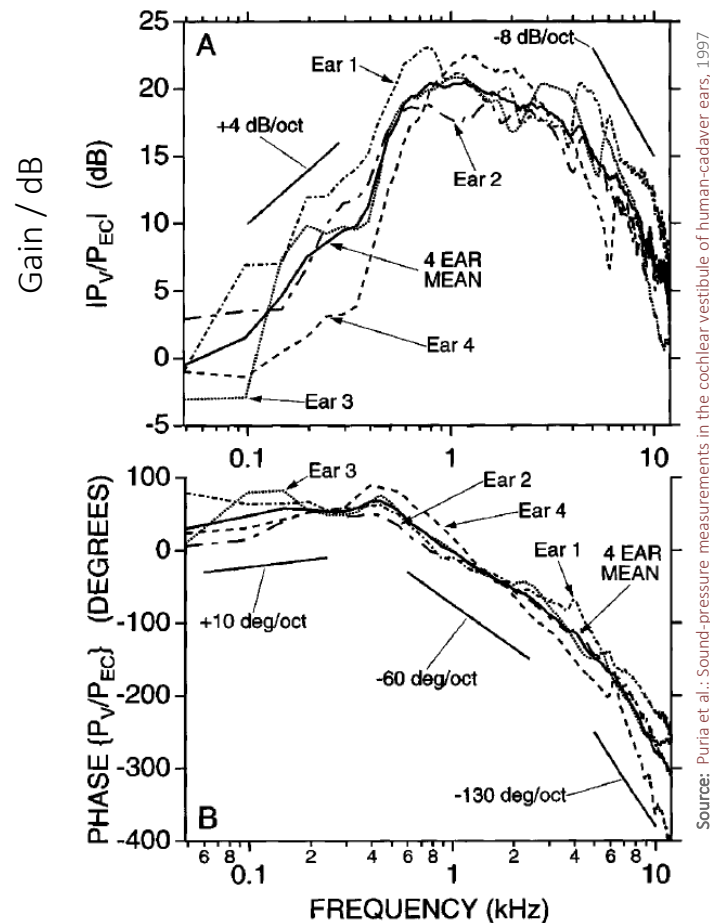
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Reasons for 9 dB lower gain than in calculation:

- Movements of membranes more complicated
- Joints between ossicles are flexible
- Friction (damping) in ossicular joints and ligaments

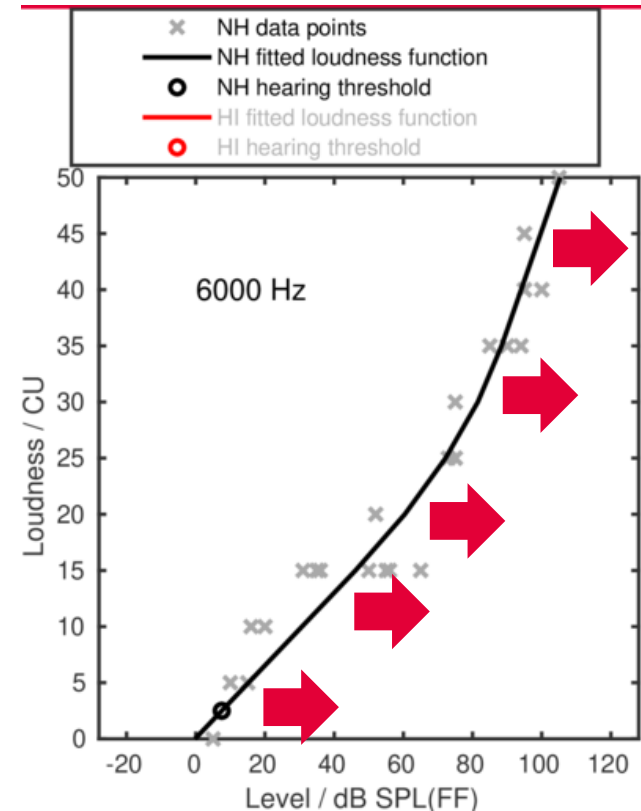


•• Conductive hearing loss

- Outer or middle ear transfer function altered
- ⇒ Sound pressures that enter the inner ear (cochlea) are decreased
- ⇒ Higher levels are required to reach the “normal” datapoints

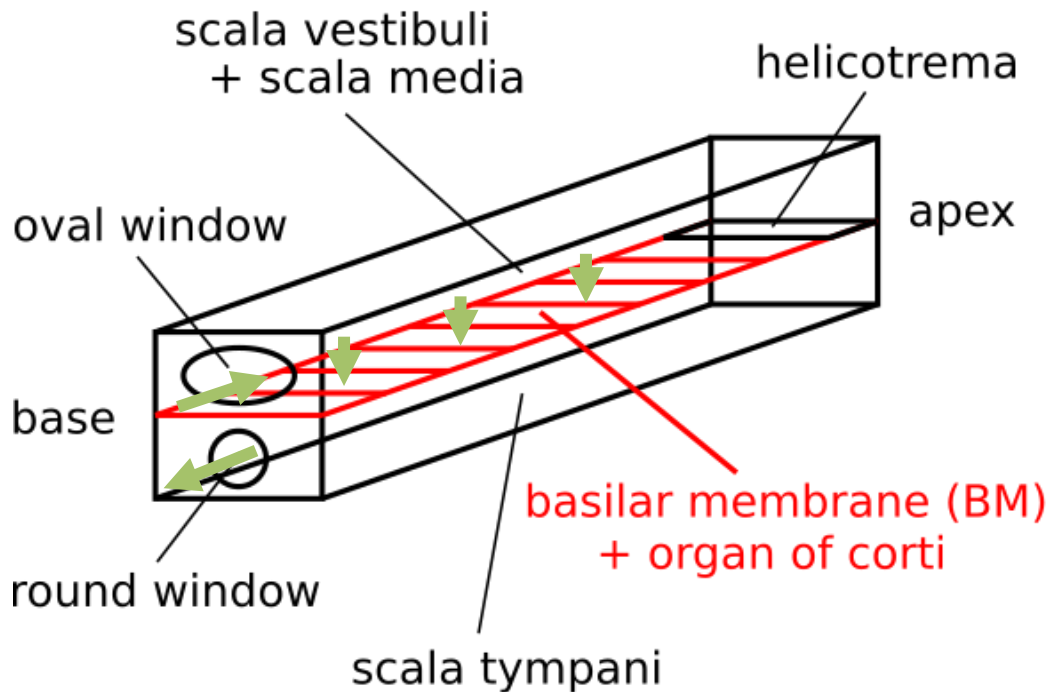
Example:

- Loudness function (including hearing threshold and uncomfortable level) shifted to higher levels, but the shape of the function is not altered



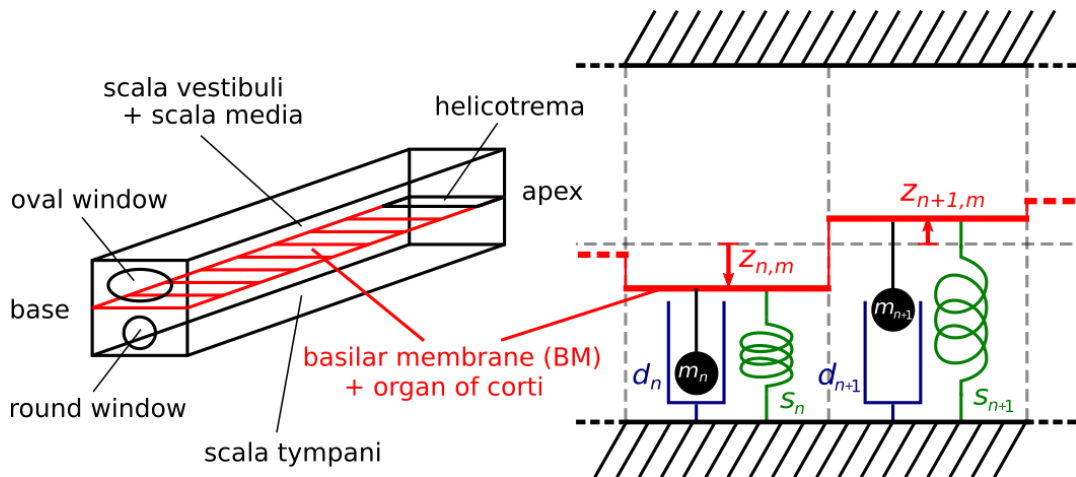
•• Inner ear (cochlea): Frequency-place transformation

- Stiffness of basilar membrane (BM) decreases from base to apex
 - Mass of fluid that needs to be moved increases from base to apex
- ⇒ Resonance frequency decreases from base to apex
- ⇒ High frequency components excite the BM closer to the base, low frequency components closer to the apex
- ⇒ The inner ear is a mechanical spectral analyzer



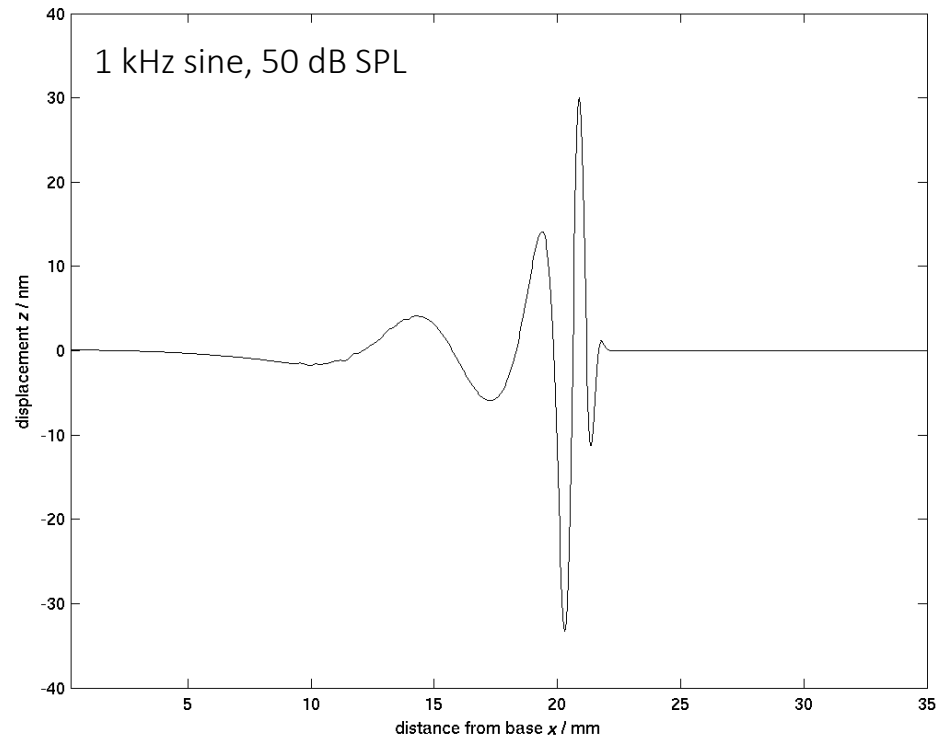
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Békésy György, 1899-1972
Biophysicist
Nobel-prize 1961 awardee

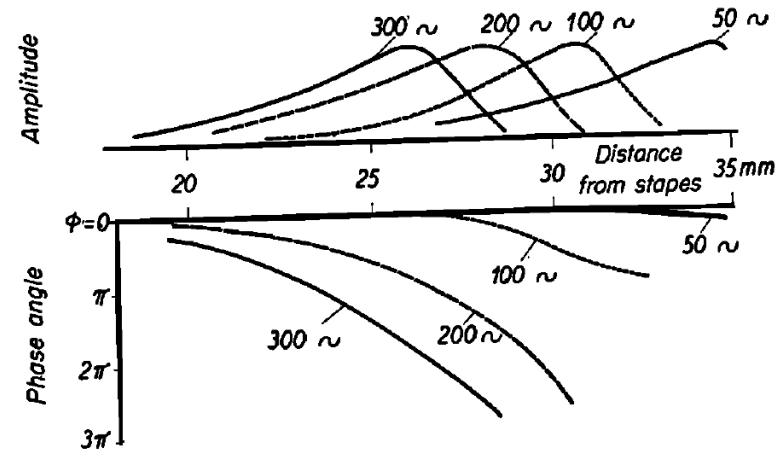
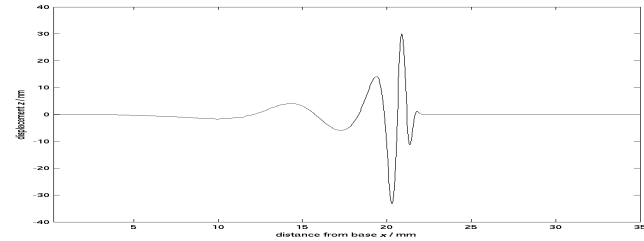
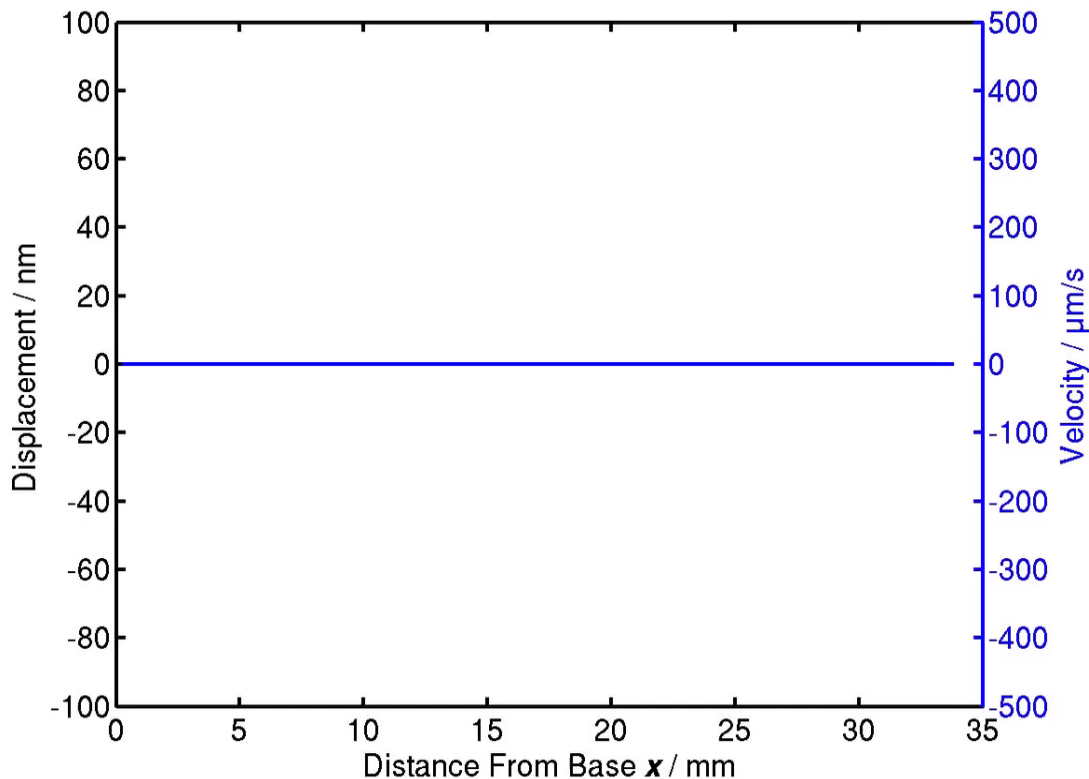


FIG. 5. Amplitude and phase angle at various distances along the cochlear partition. Distance is given from the stapes. Measurements are shown for four frequencies.

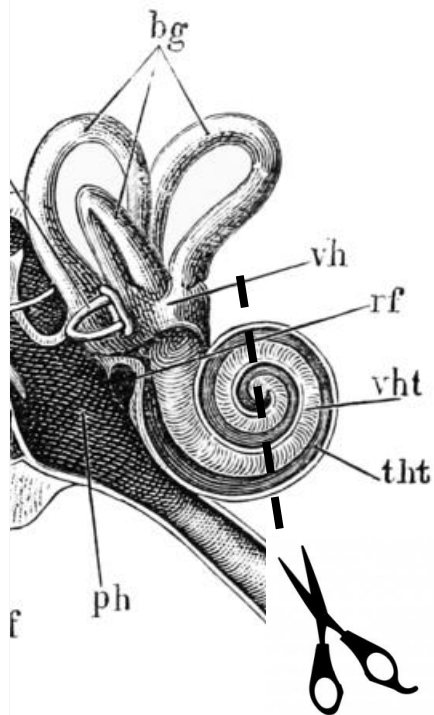
Source: Georg V. Békésy: *The Variation of Phase Along the Basilar Membrane with Sinusoidal Vibrations*, 1947

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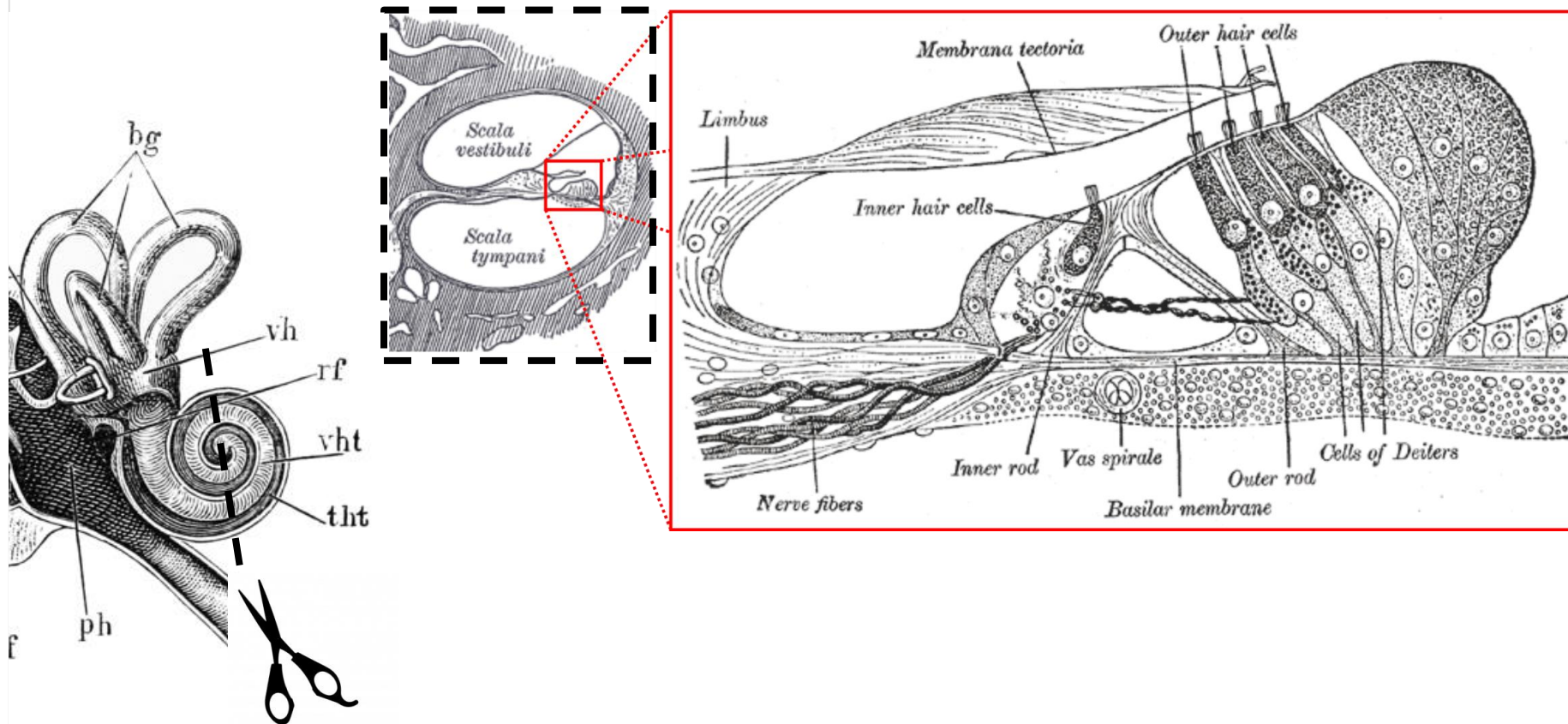
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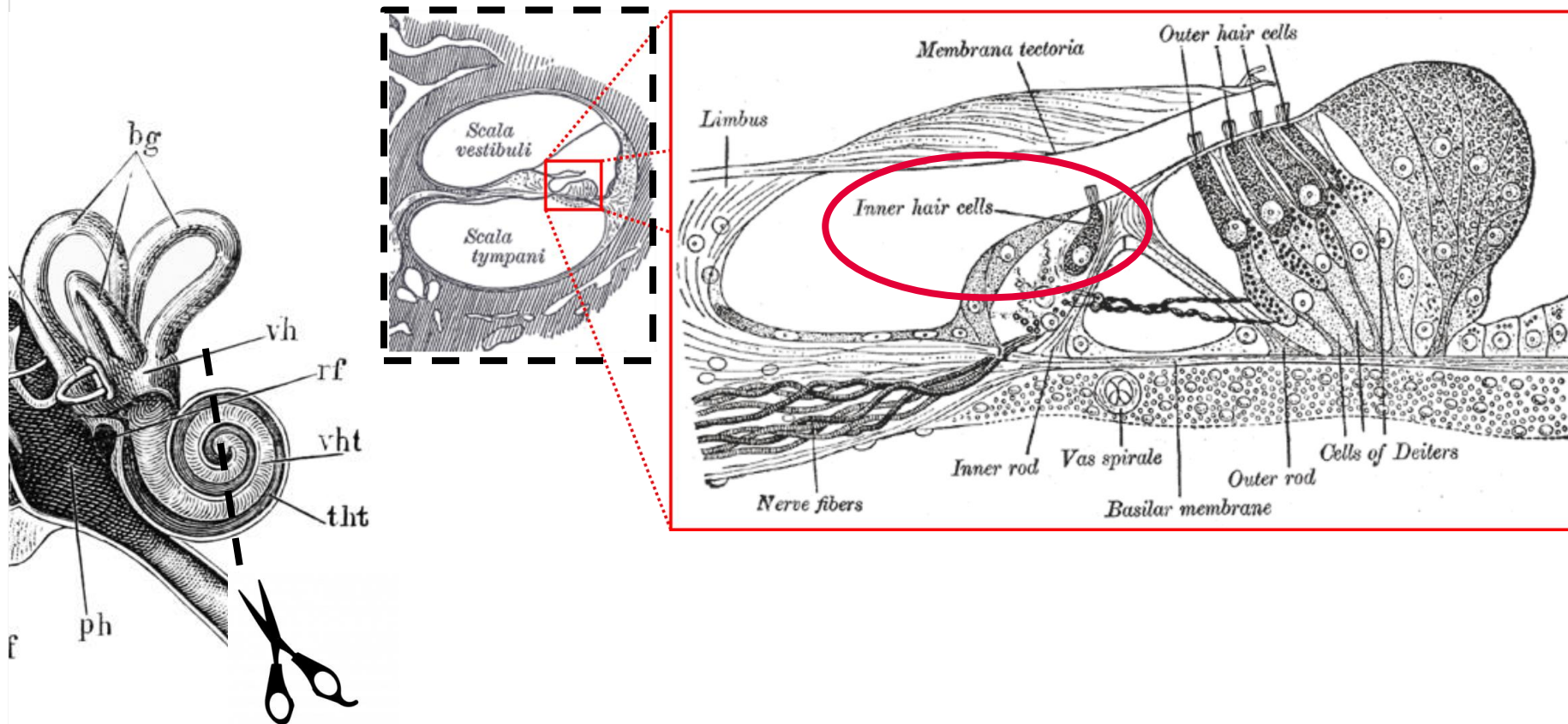
- Inner ear (cochlea)



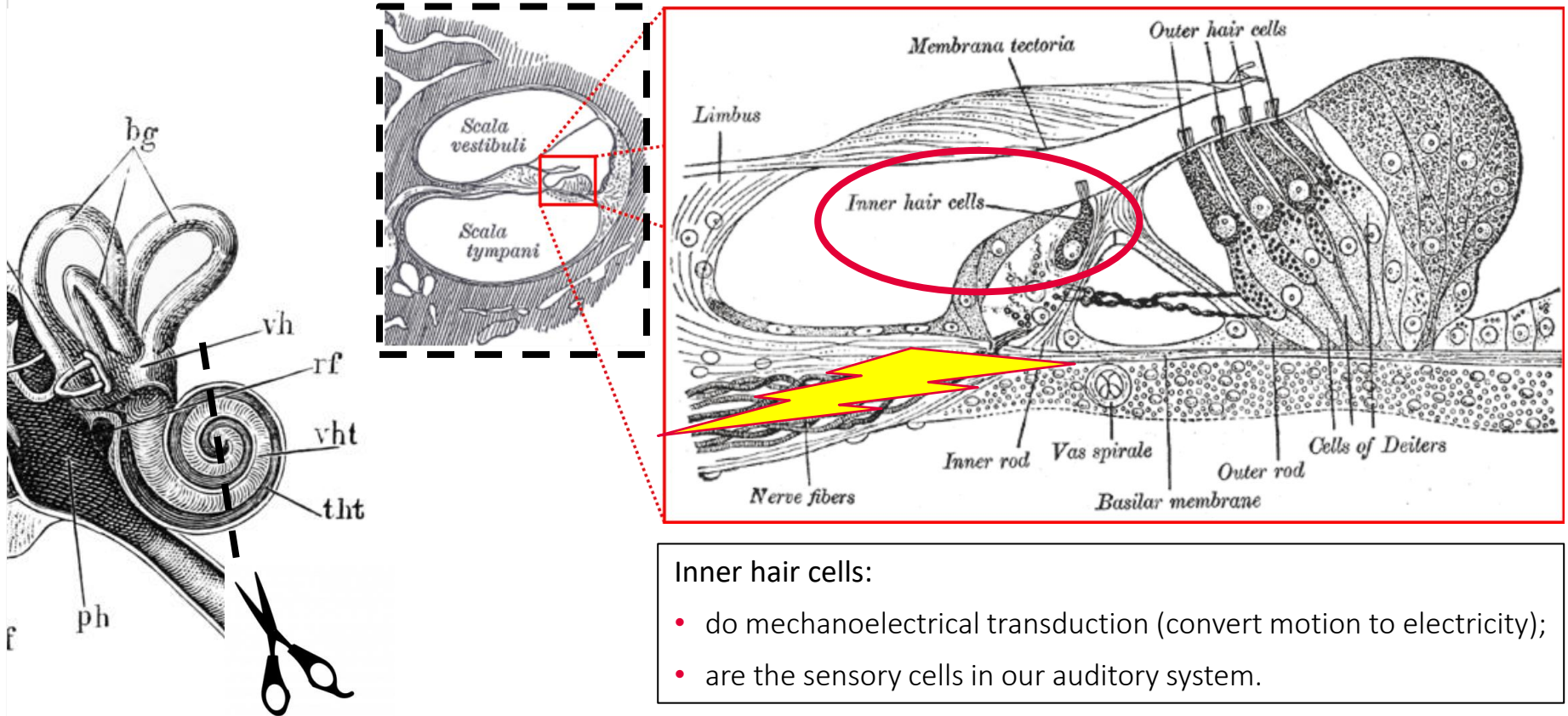
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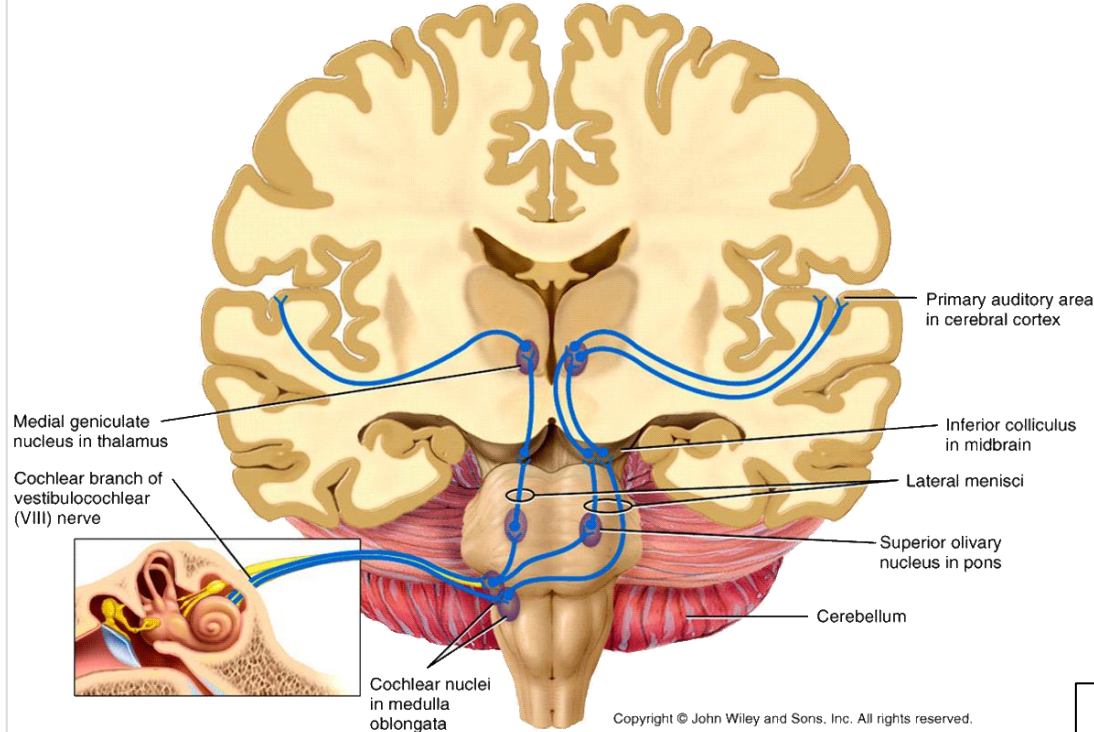
•• Inner ear (cochlea)



•• Inner ear (cochlea): Inner hair cells



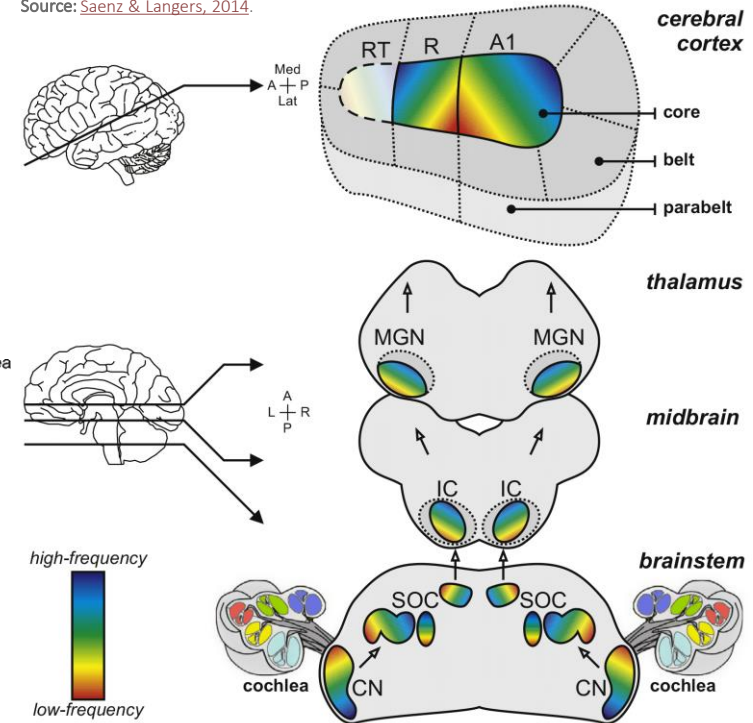
•• Auditory nervous system: Tonotopy



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Source: [Tortora & Derrickson: Principles of Anatomy and Physiology, 2016](#)

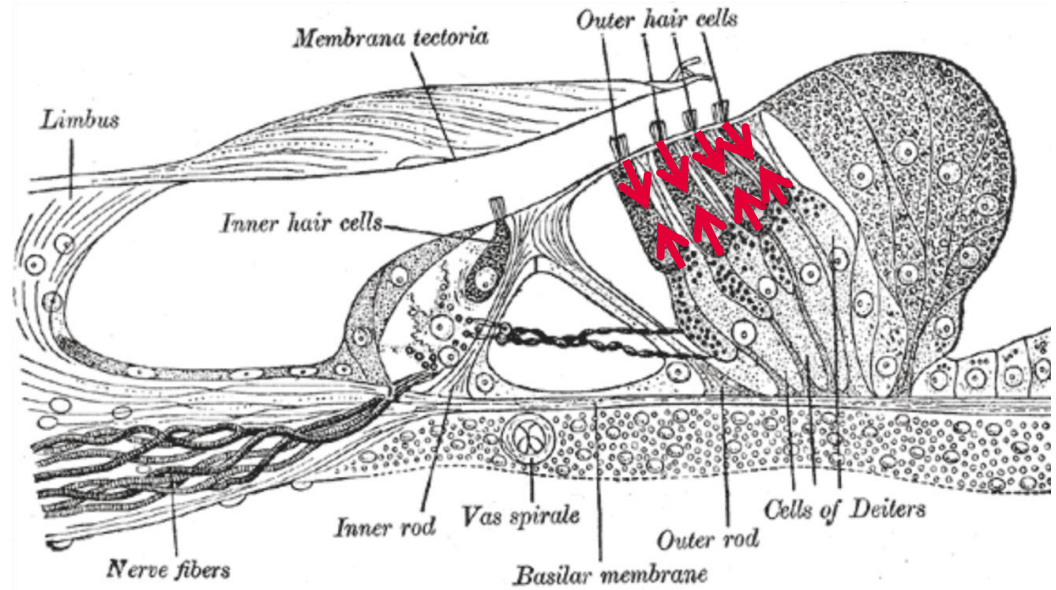
Source: [Saenz & Langers, 2014](#).



Tonotopy is the spatial arrangement of where sounds of different frequencies are processed in the auditory nervous system.

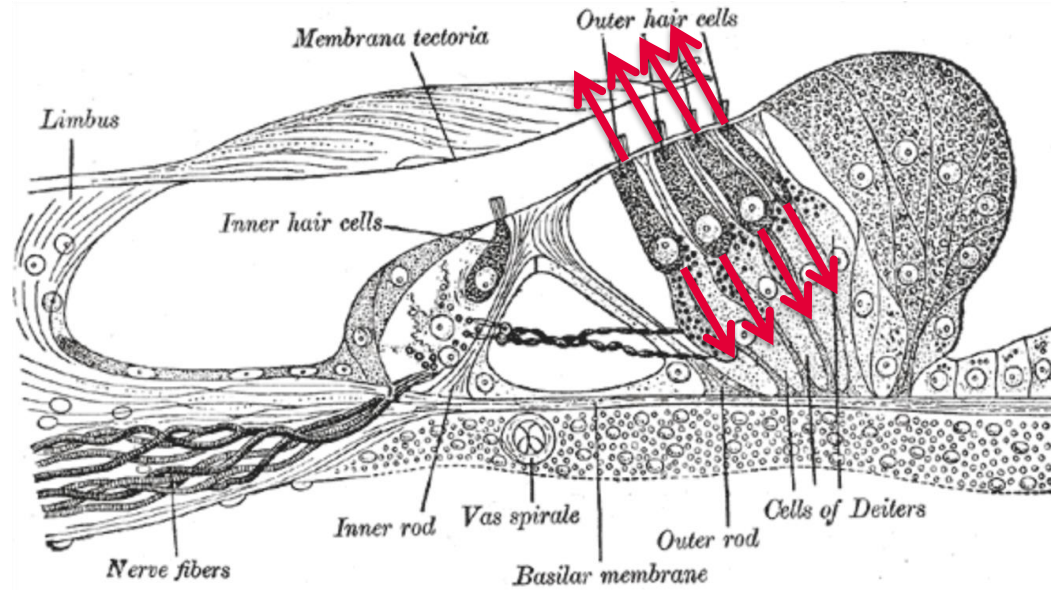
- Inner ear (cochlea): Cochlear gain

Contraction



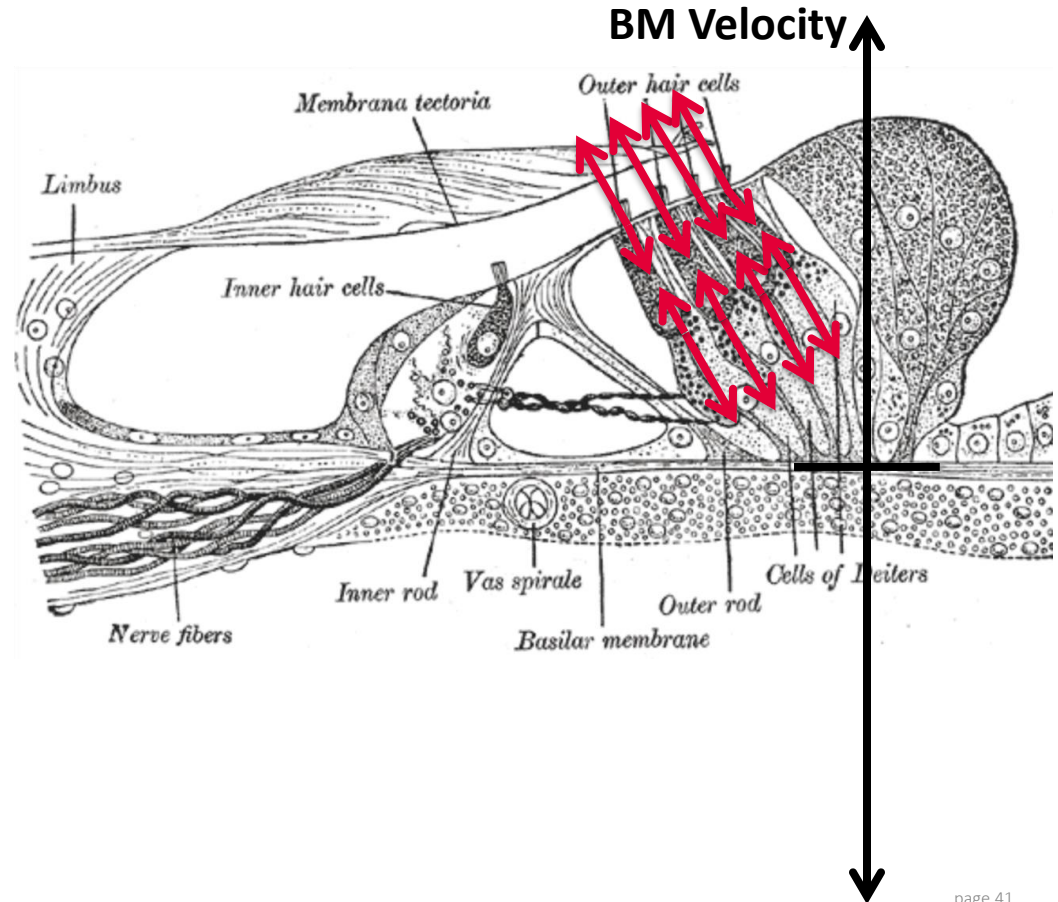
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Expansion



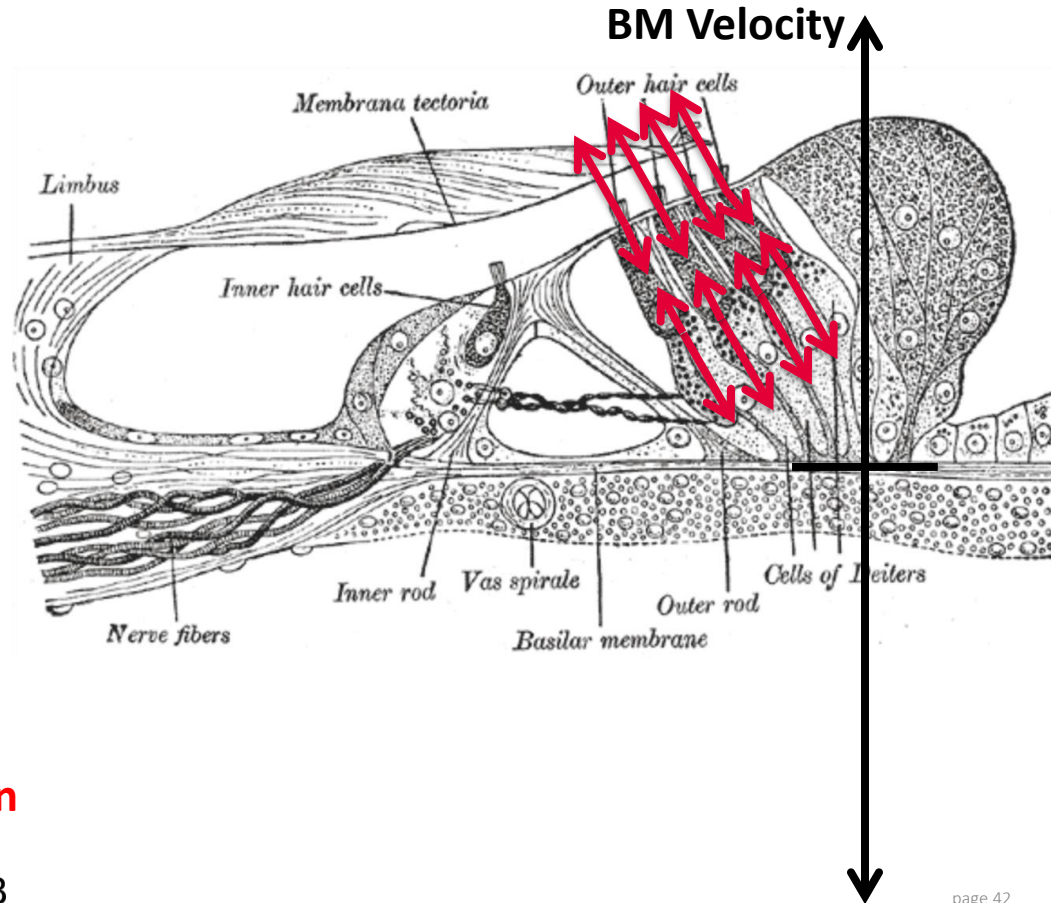
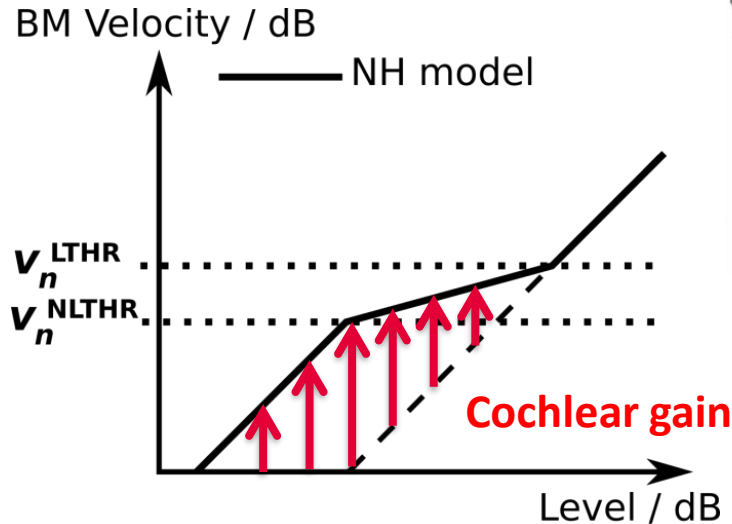
•• Inner ear (cochlea): Cochlear gain

- Outer hair cells (OHC) amplify movements of the basilar membrane (BM)



•• Inner ear (cochlea): Cochlear gain

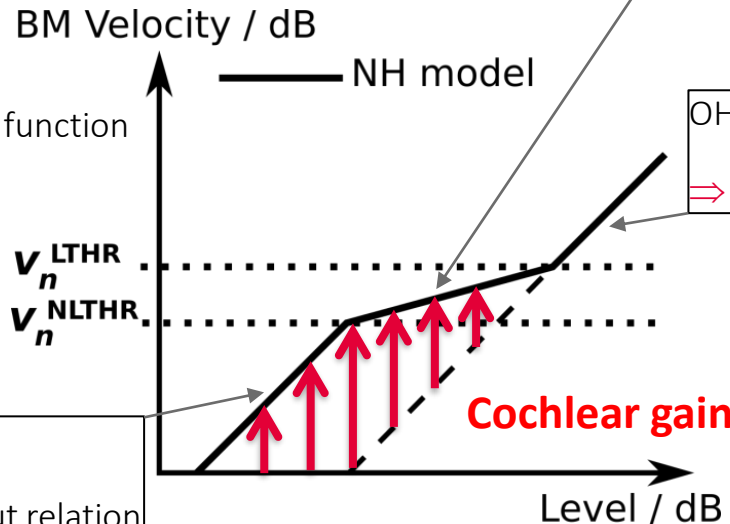
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- OHC force is limited but mechanical damping force increases with velocity (which increases with level)



•• Inner ear (cochlea): Cochlear gain

- Outer hair cells (OHC) amplify movements of the basilar membrane (BM)
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⇒ “Broken Stick” – input-output function



OHC force \approx damping force

⇒ compressive input-output relation

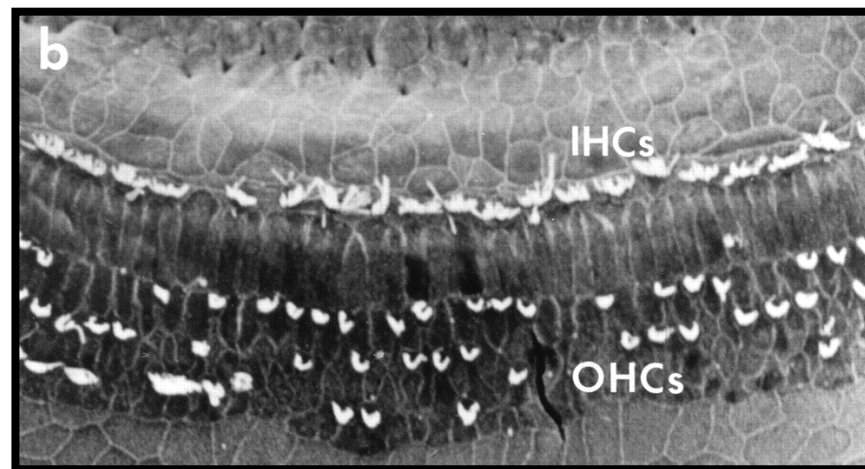
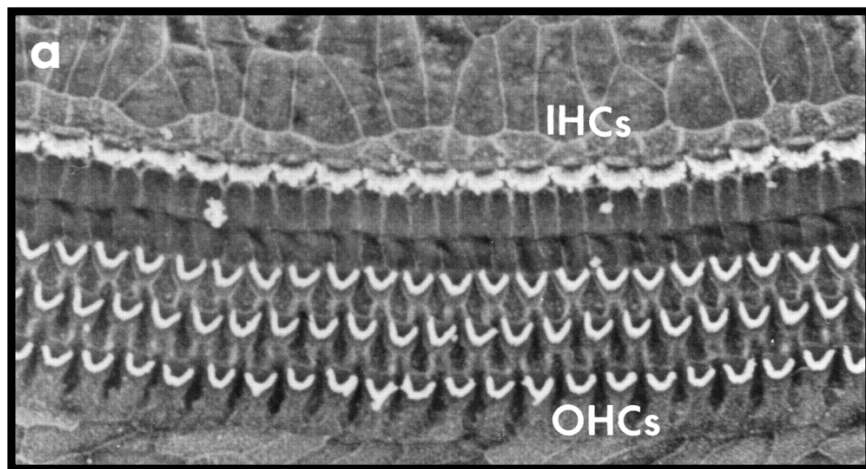
OHC force \ll damping force

⇒ damped linear input-output relation

OHC force \gg damping force

⇒ amplified linear input-output relation

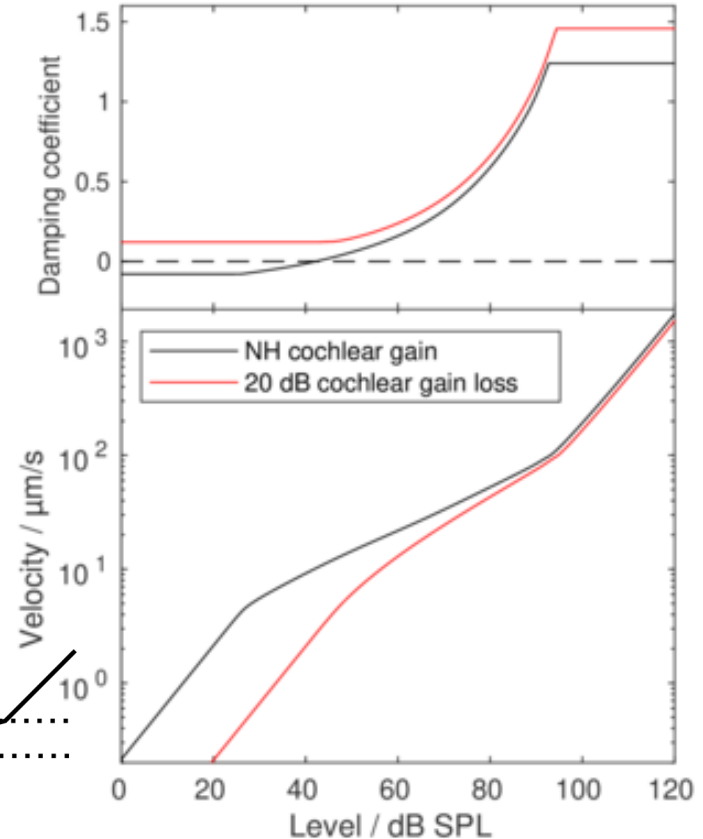
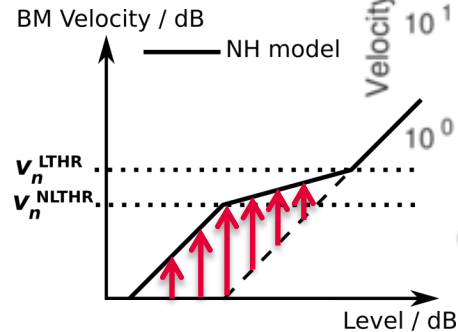
- Inner ear (cochlea): Sensorineural hearing loss



Source: [Ryan, 2000](#)

•• Inner ear (cochlea): Sensorineural hearing loss

- Outer hair cells (OHC) amplify movements of the basilar membrane (BM)
- OHC force is limited but mechanical damping force increases with velocity (which increases with level)
- In models, OHC force and damping force are often combined to a single force with velocity dependent damping coefficient
- Damage to OHCs reduces cochlear gain

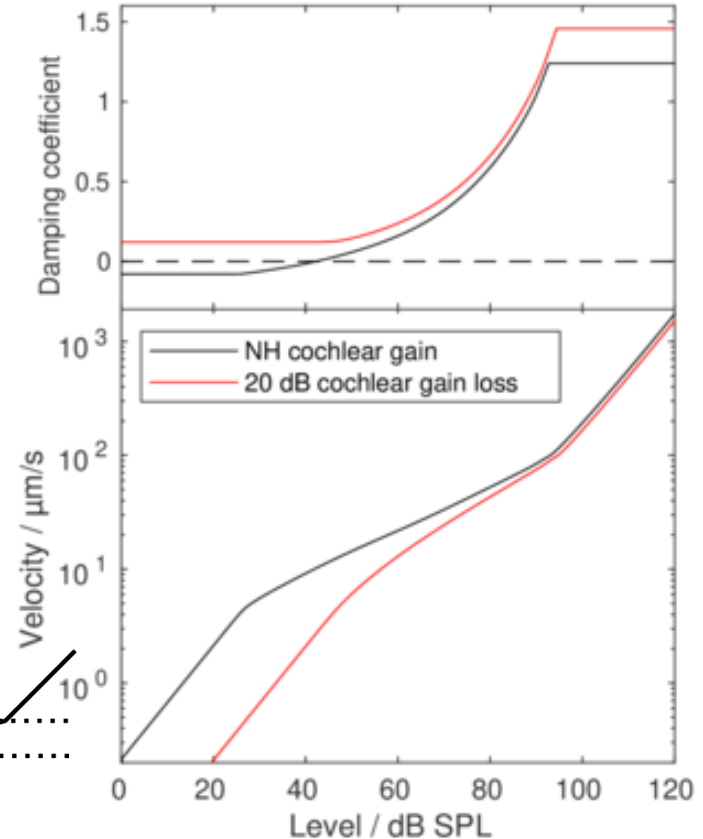
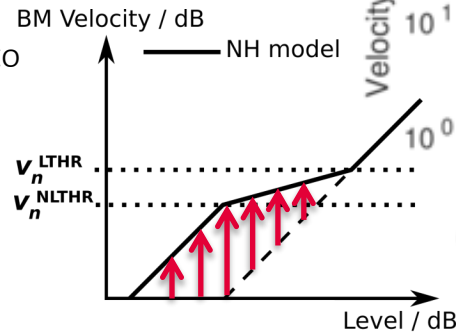


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⇒ Higher sound pressure levels required to reach certain BM velocities

⇒ Not much differences at high levels



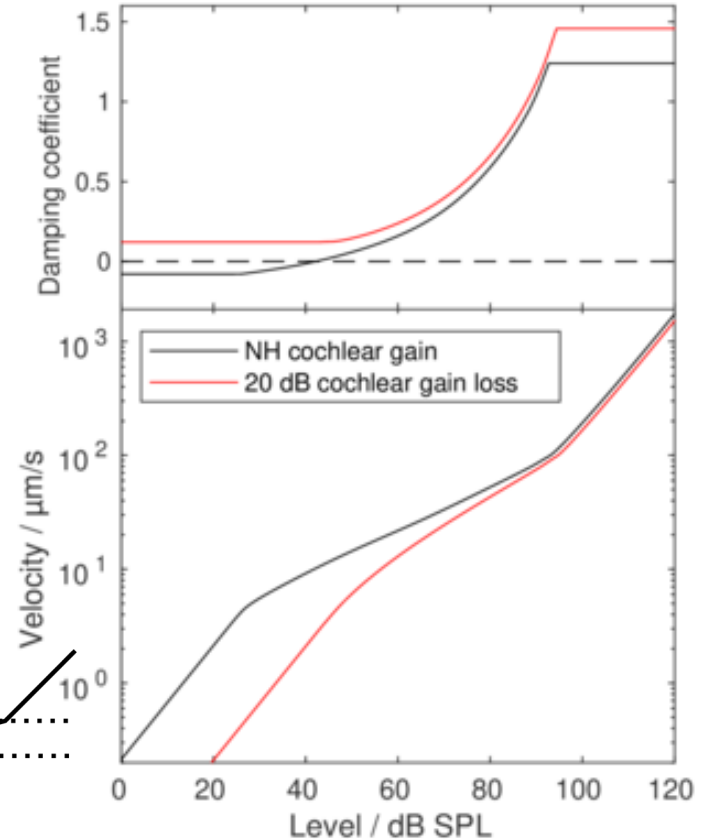
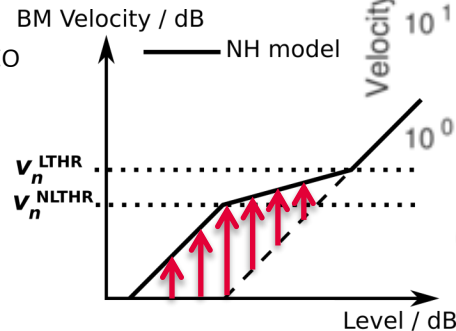
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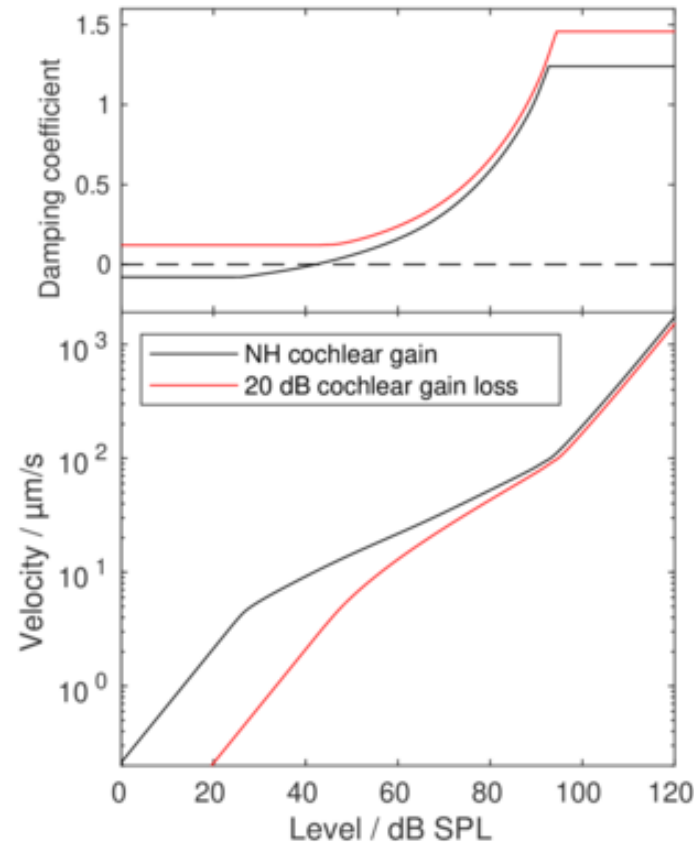
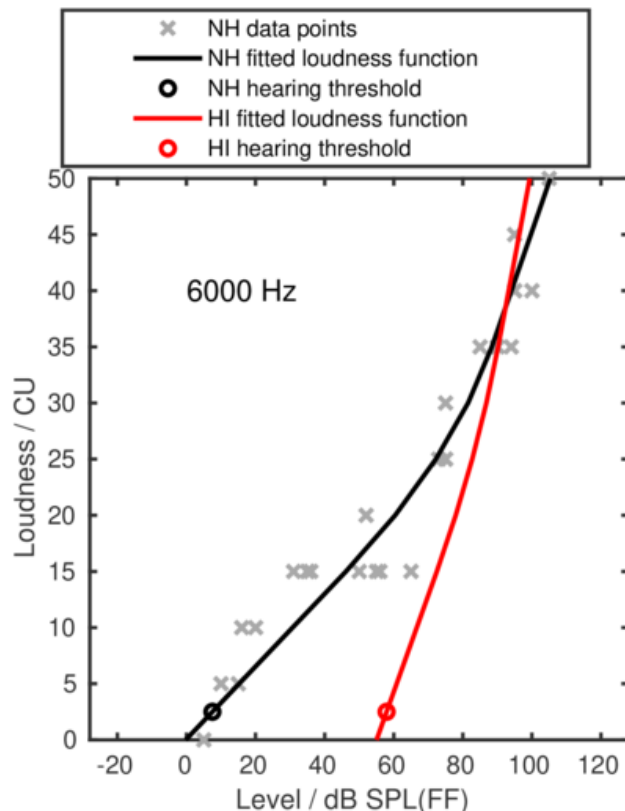
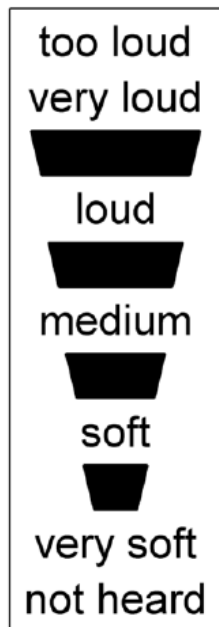
⇒ Higher sound pressure levels required to reach certain BM velocities

⇒ Not much differences at high levels

⇒ Reduced dynamic range

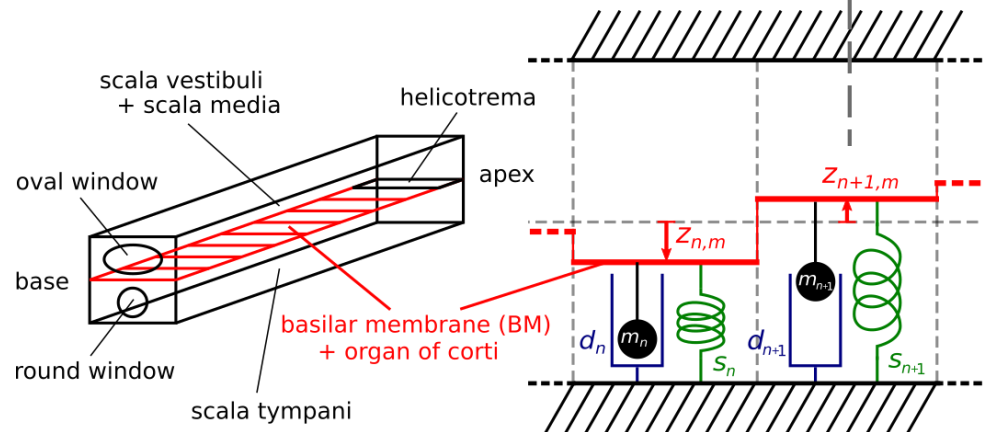
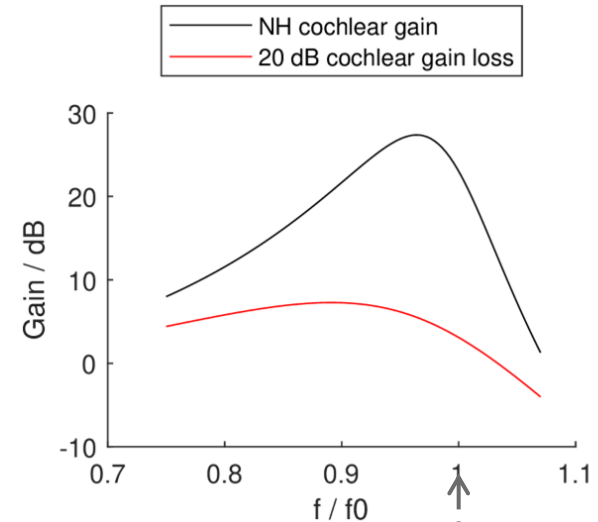


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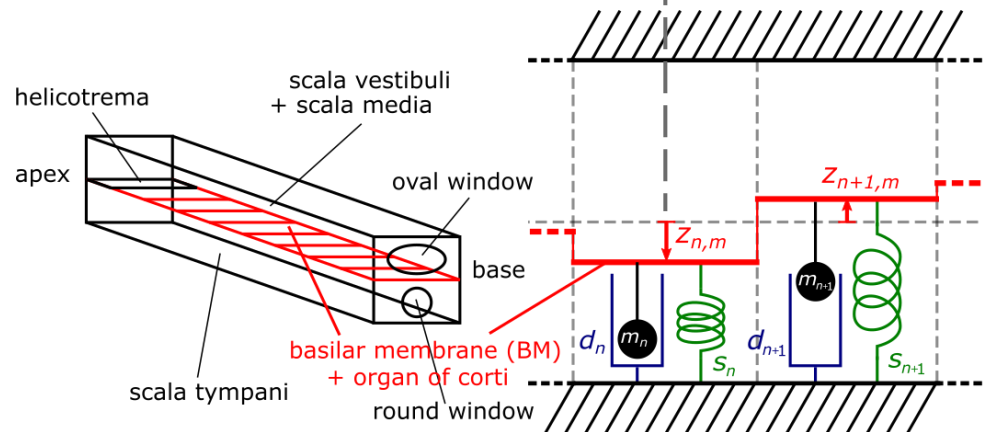
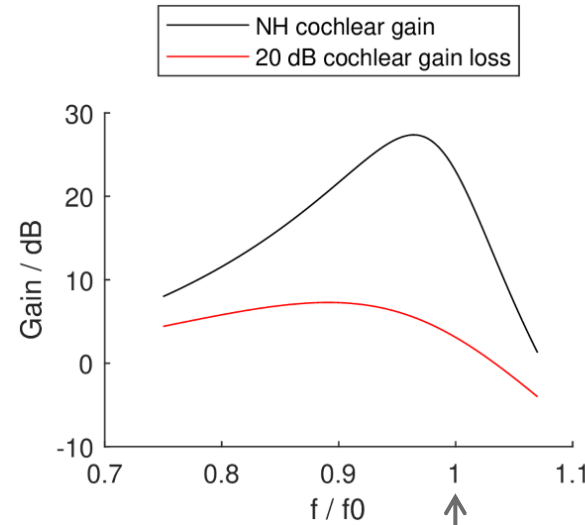
•• Inner ear (cochlea): Frequency discrimination

- Outer hair cells push the basilar membrane
- ⇒ damping is effectively reduced
- ⇒ sharper tuning of places to their resonance frequency



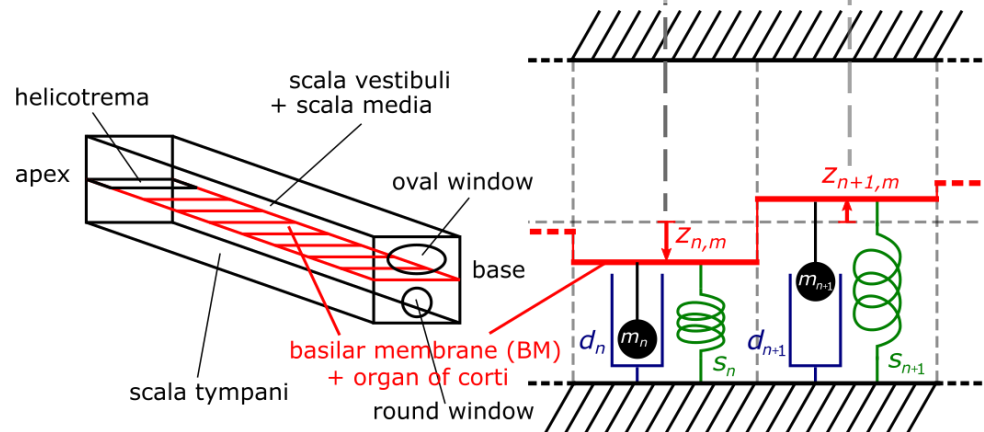
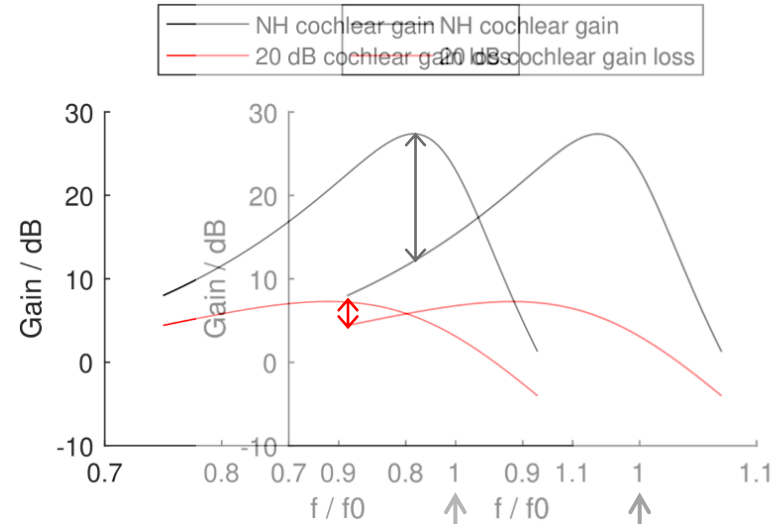
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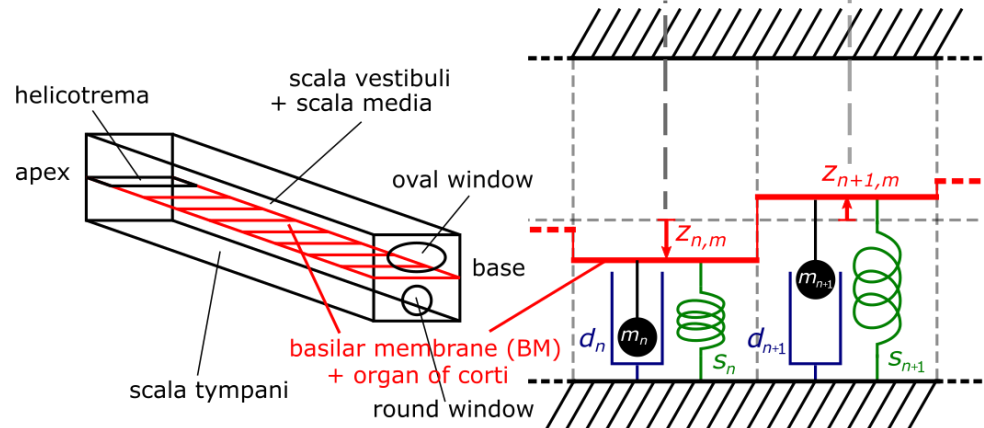
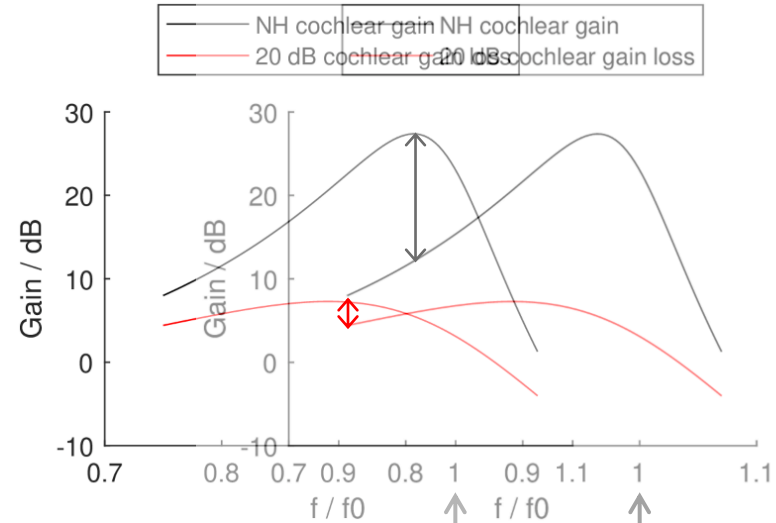
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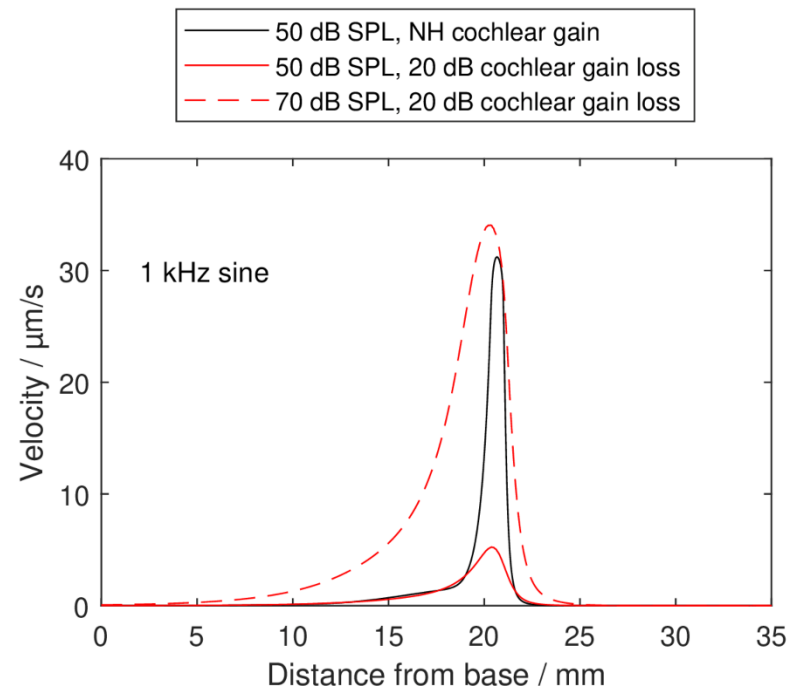
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- ⇒ higher gain differences at neighboring places for single frequency components
- ⇒ better frequency discrimination



•• Inner ear (cochlea): Frequency discrimination

- Outer hair cells push the basilar membrane
 - ⇒ damping is effectively reduced
 - ⇒ sharper tuning of places to their resonance frequency
 - ⇒ higher gain differences at neighboring places for single frequency components
 - ⇒ better frequency discrimination
- Damage to outer hair cells (sensorineural hearing loss)
 - ⇒ worsened frequency discrimination



•• Short recap

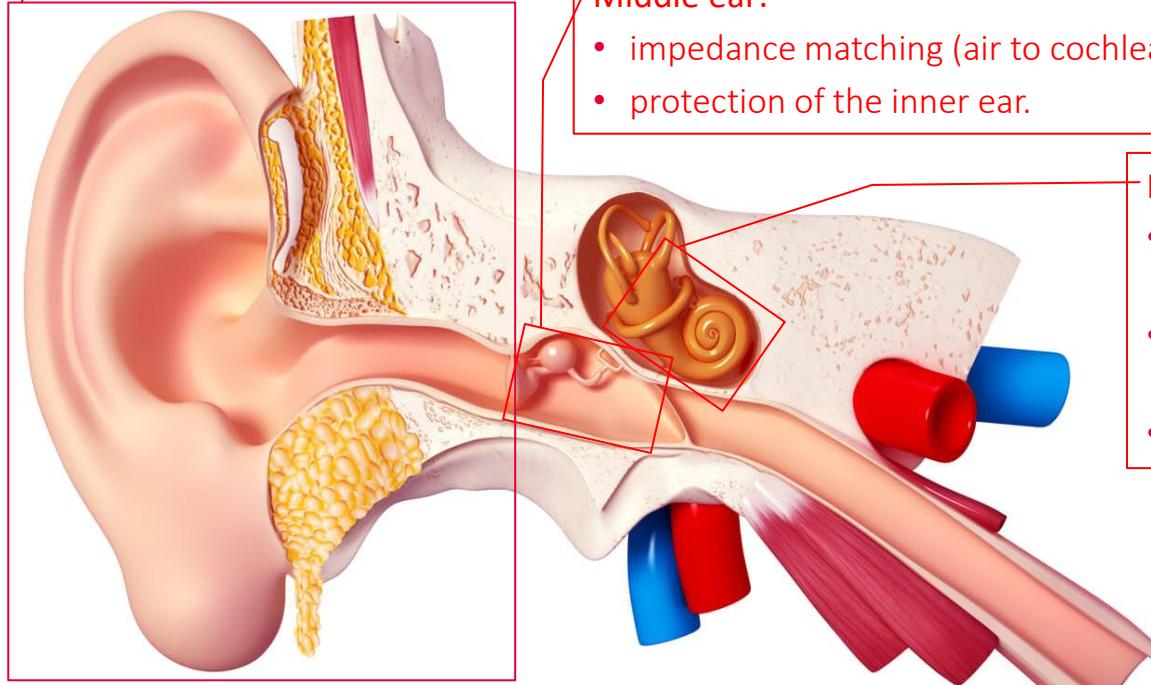
Outer ear: amplification,
direction-dependent filtering.

Middle ear:

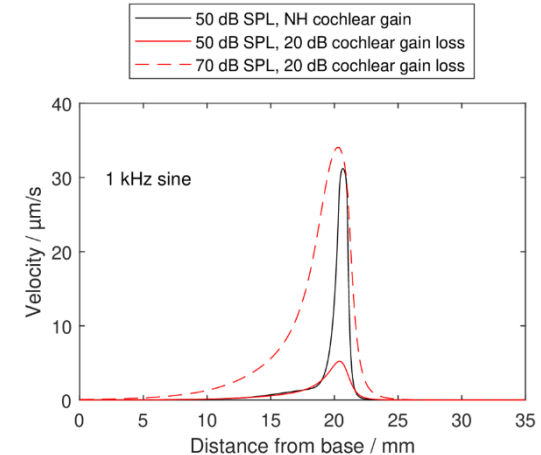
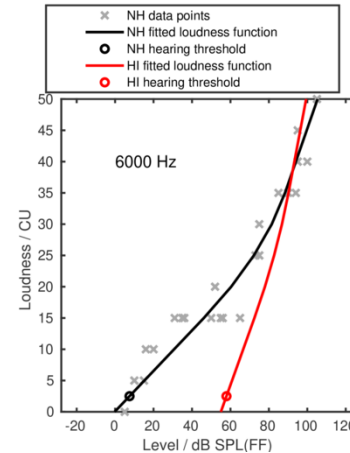
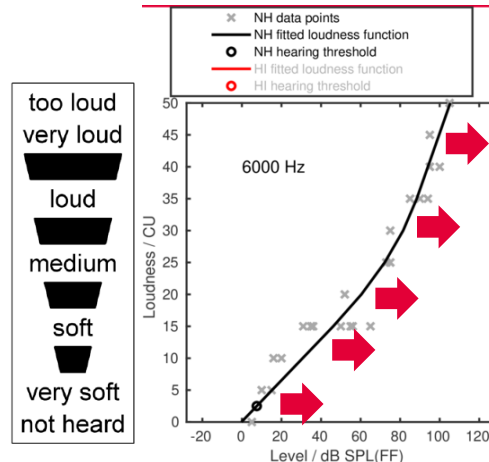
- impedance matching (air to cochlea),
- protection of the inner ear.

Inner ear (cochlea):

- spectral decomposition of signal (~filter bank),
- extension of dynamic range (compressive nonlinearity),
- transformation into electrical signals.



•• Manifestations of hearing loss



Conductive:

Cause: Gain reduction in outer and/or middle ear

Manifestation: Accordingly increased hearing threshold and uncomfortable level

Sensorineural:

Cause: Damage to OHCs, IHCs and/or auditory nerves

Manifestation: Reduced dynamic range and frequency selectivity

Mixed:

Conductive and sensorineural hearing loss

•• Introduction of A, C, and Z-weighted decibel scales

Sound Level Meter:

- Calculates RMS level for the last period
- But mean value replaced with first order low-pass filter
- Slow integration time:
Time constant $\tau = 1 \text{ s}$ \Leftrightarrow cut-off frequency $f_c = 1/(2\pi\tau) = 0.16 \text{ Hz}$
- Fast integration time:
Time constant $\tau = 0.125 \text{ s}$ \Leftrightarrow cut-off frequency $f_c = 1/(2\pi\tau) = 1.27 \text{ Hz}$

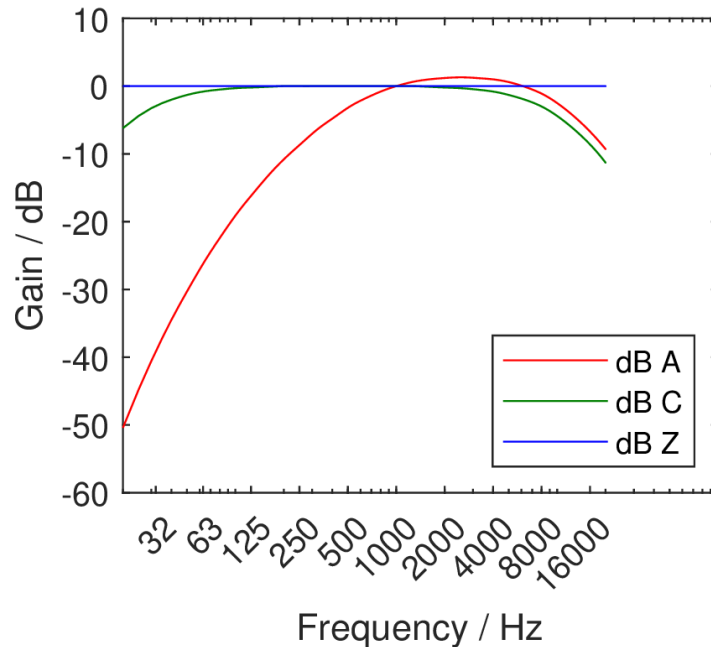


Source: <https://www.highlite.com/de/91004-digital-sound-level-meter.html>

•• Introduction of A, C, and Z-weighted decibels scales

Sound Level Meter:

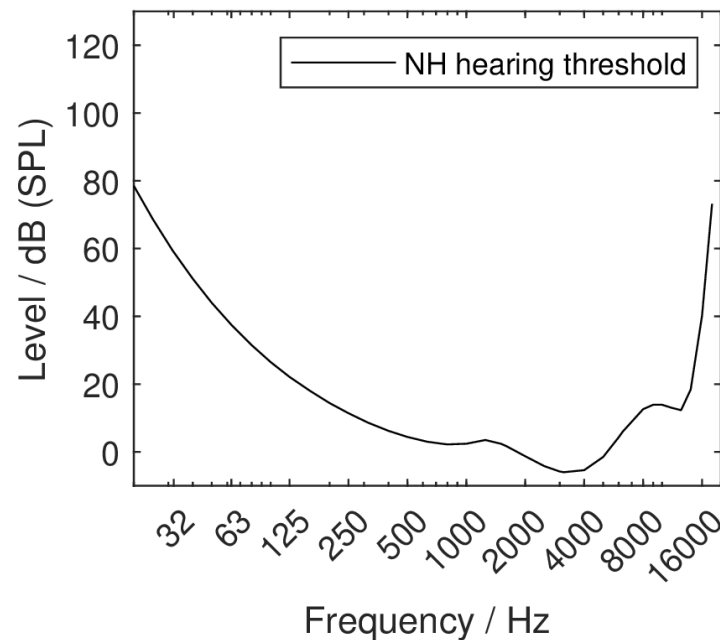
- Different frequency weightings (A, C, and Z) are used



Source: <https://www.highlite.com/de/91004-digital-sound-level-meter.html>

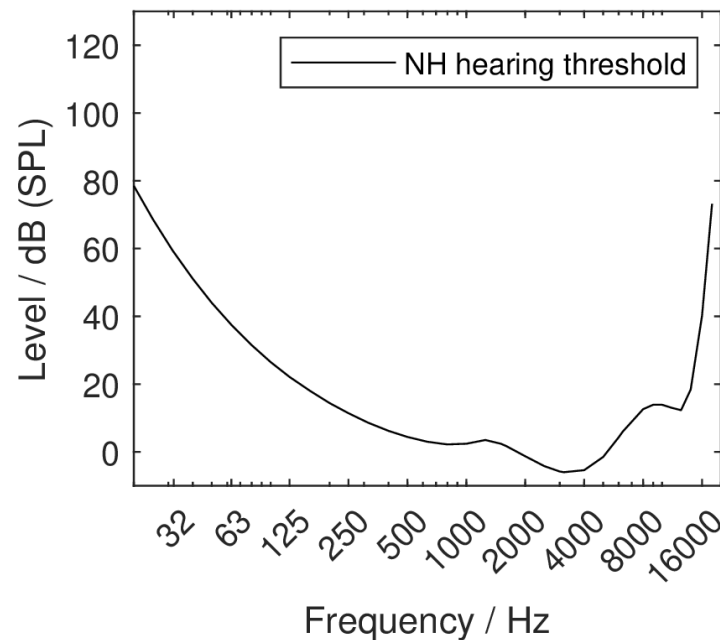
•• Hearing threshold for normal hearing NH

- Hearing threshold for NH: Lowest level (dB SPL) at which a pure tone is audible for young adults
- Low and high frequencies require high sound pressure levels to be audible
- In general, human hearing is less sensitive to low and high frequencies



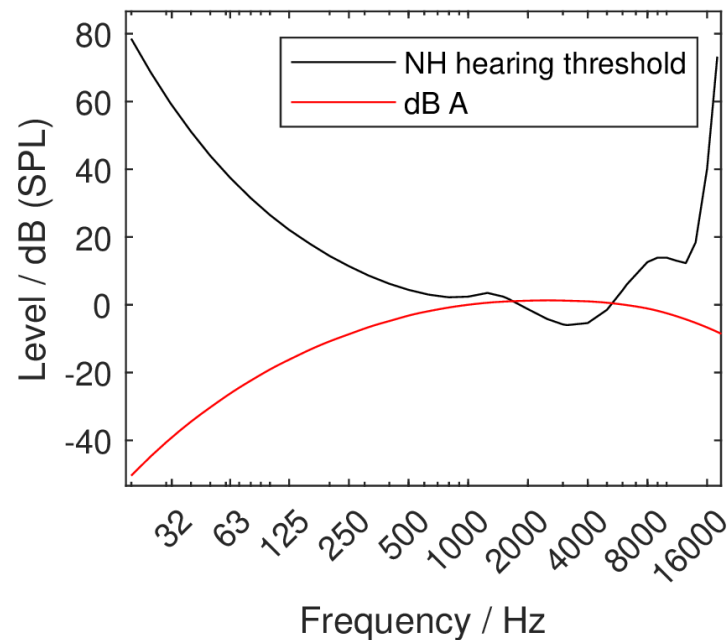
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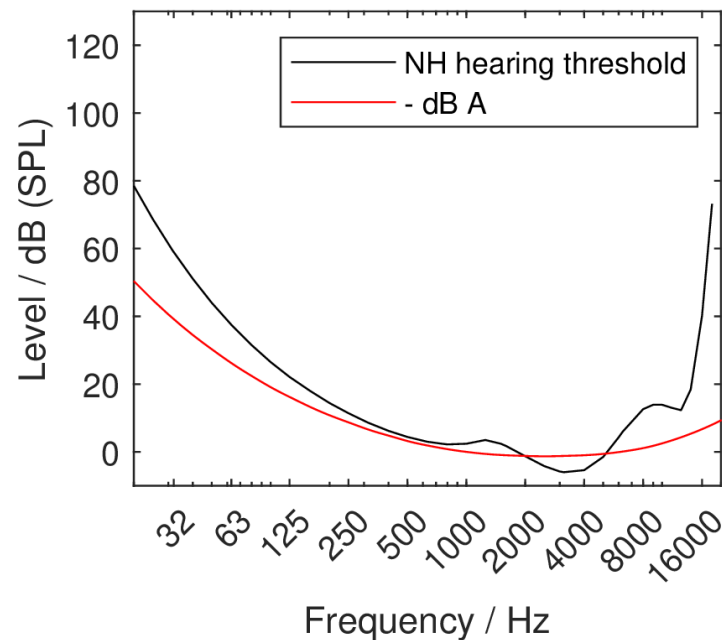
•• Hearing threshold for normal hearing NH / A-weighting

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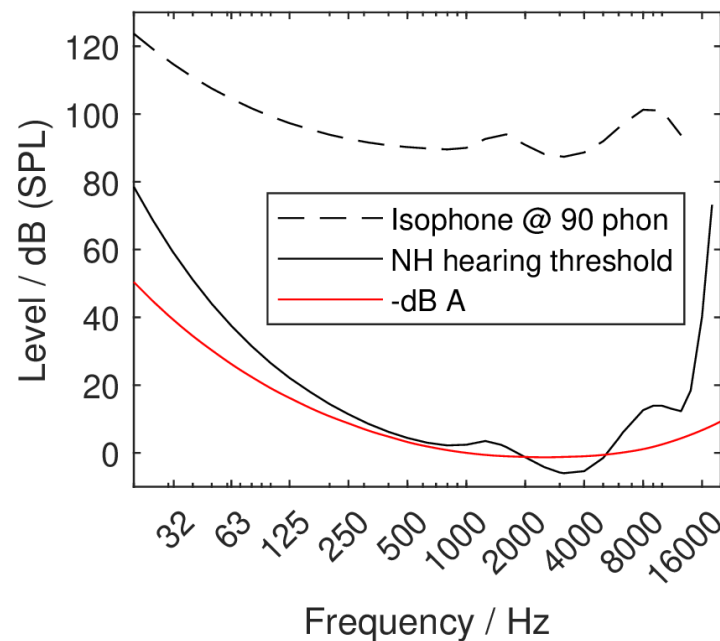
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- By attenuating low and high frequencies, the A-weighting accounts for human perception at low to medium sound pressure levels
- Negative dB A values show similarity with hearing threshold



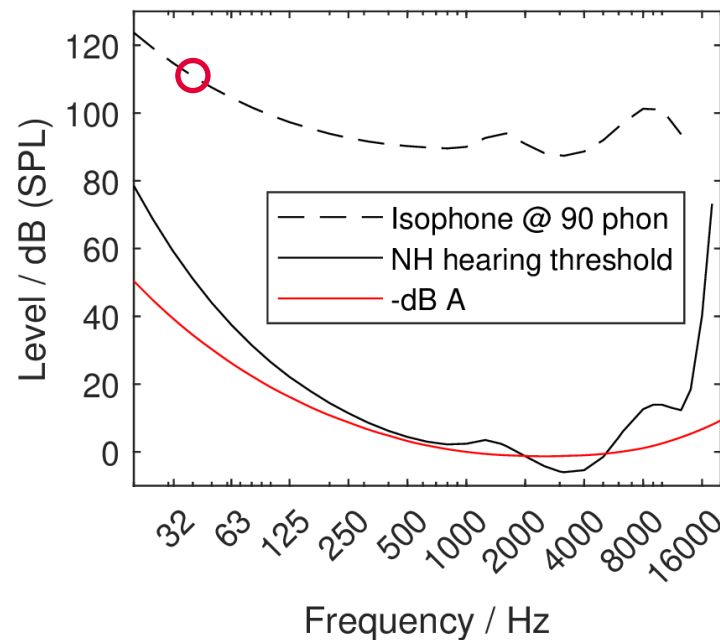
•• Isophones (equal loudness contours for pure tones)

- Levels (dB SPL) at which a pure tone is perceived as loud as a 1000 Hz tone with a given reference level (dB SPL)
- The loudness of an isophone is called <reference level @ 1000 Hz> phon



•• Isophones (equal loudness contours for pure tones)

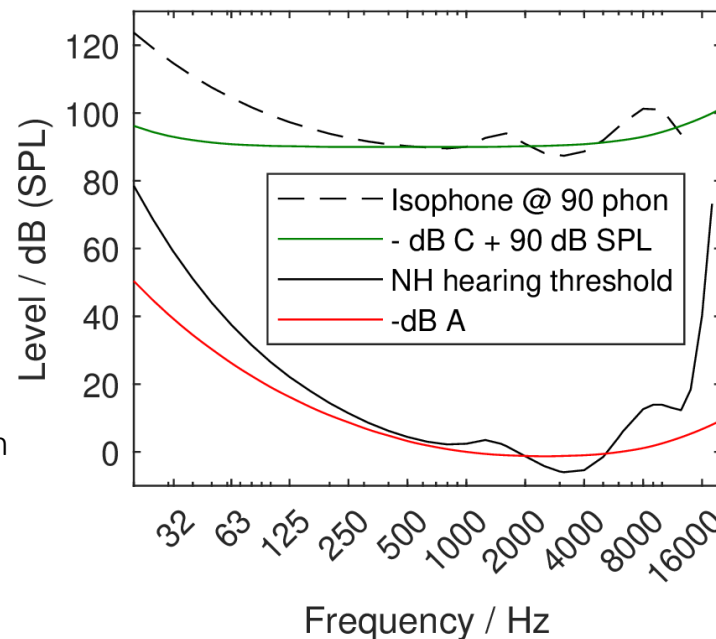
- Levels (dB SPL) at which a pure tone is perceived as loud as a 1000 Hz tone with a given reference level (dB SPL)
- The loudness of an isophone is called <reference level @ 1000 Hz> phon
- Example:
A 40 Hz tone with a level of 111 dB SPL has a loudness of 90 phon



•• Isophones (equal loudness contours for pure tones) / C-weighting

Equal loudness contour (Isophone):

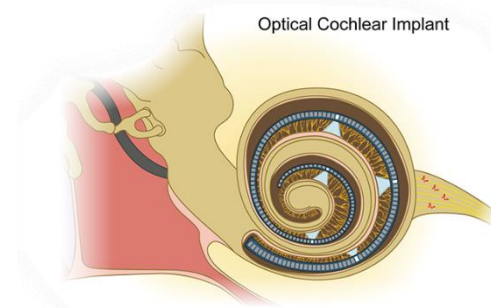
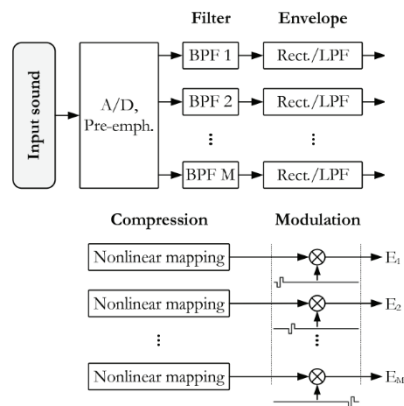
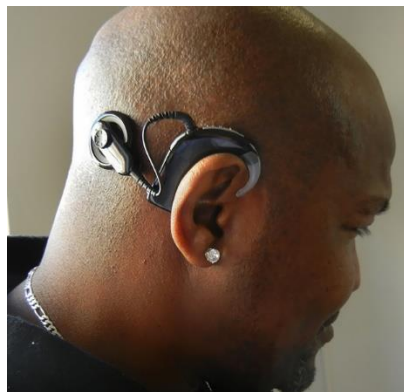
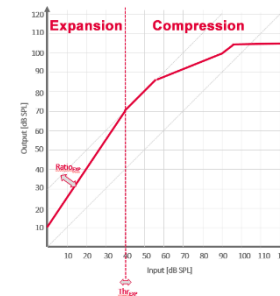
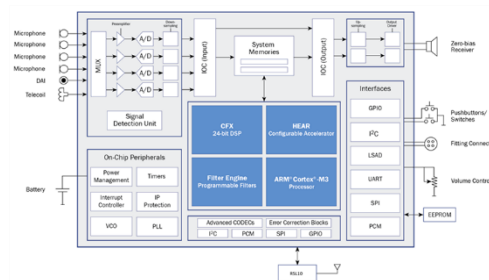
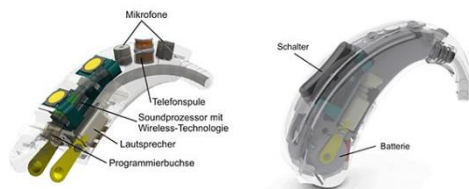
- Levels (dB SPL) at which a pure tone is perceived as loud as a 1000 Hz tone with a given reference level (dB SPL)
- The loudness of an isophone is called <reference level> phon
- Example:
A 40 Hz tone with a level of 111 dB SPL has a loudness of 90 phon
- C-weighting roughly accounts for the loudness perception at high levels



•• Introduction of A, C, and Z-weighted decibel scales

- Z-weighting:
Sound pressure measurement
- A-weighting:
Human perception of low to medium sound pressures
(e.g., environmental noise measurements)
- C-weighting:
Human perception of high sound pressures
(e.g., concerts)

•• Next week





Thank you very much!
Questions?

Dr. rer. nat. Iko Pieper
iko.pieper@audifon.com

audifon GmbH & Co. KG