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Hearing Systems – Part 1 of 2

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

TU Ilmenau – Audio Systems Technology

(Online) | 20. Januar 2021

Dr.-Ing. Tamas Harczos

•• Introduction

- Two lectures (with one short break, each) and one seminar.
- Useful links:
 - <https://hearingsystems.github.io/>,
 - <https://www.tu-ilmenau.de/mt/lehrveranstaltungen/lehre-fuer-master-mt/audio-systems-technology/>.
- Topics we will cover:
 - *Basics*: units, hearing, hearing loss, tonotopy, dynamic range & compression.
 - *Devices*: hearing aids, cochlear implants, optogenetic stimulation, hearables.
 - *Technologies*: audiological features, fitness & medical features, hardware & software.
 - *Current trends* in research & development.

•• Introduction

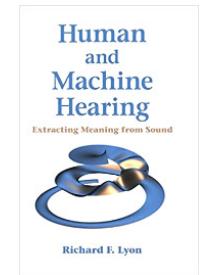
- audifon:
 - audifon GmbH & Co. KG develops, produces and sells hearing systems
 - Headquarter located in Kölleda, Thüringen (also place of production)
 - R&D offices in Köln and Ilmenau (System / Embedded SW Engineering)
 - About 200 employees
- myself:
 - First home computer generation
 - Programming as an early hobby
(Basic → Pascal → C/C++)
 - Interested in audio and audio signal processing
 - M.Sc. Information Technology (Veszprém, Hungary)
Ph.D. Biomedical Technology (Ilmenau)



•• 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)

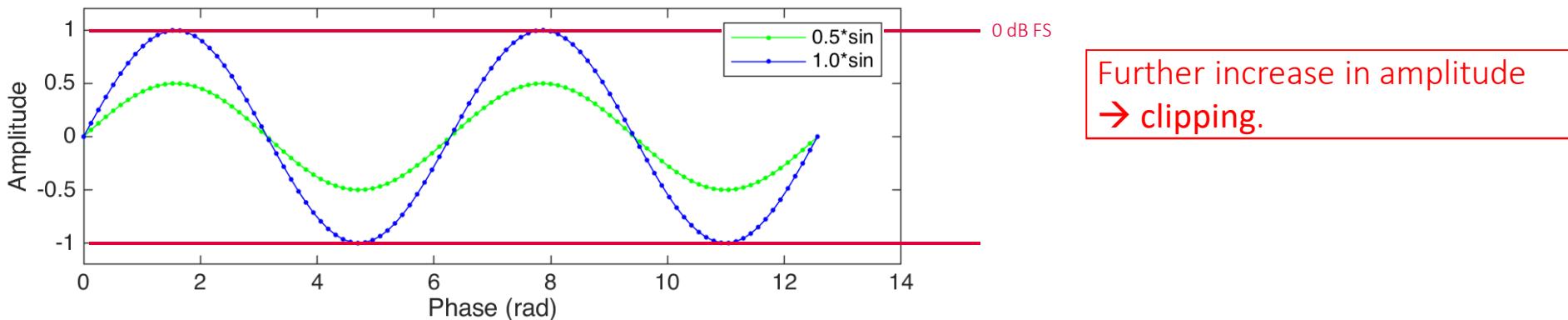


•• Ready?

- Face-off

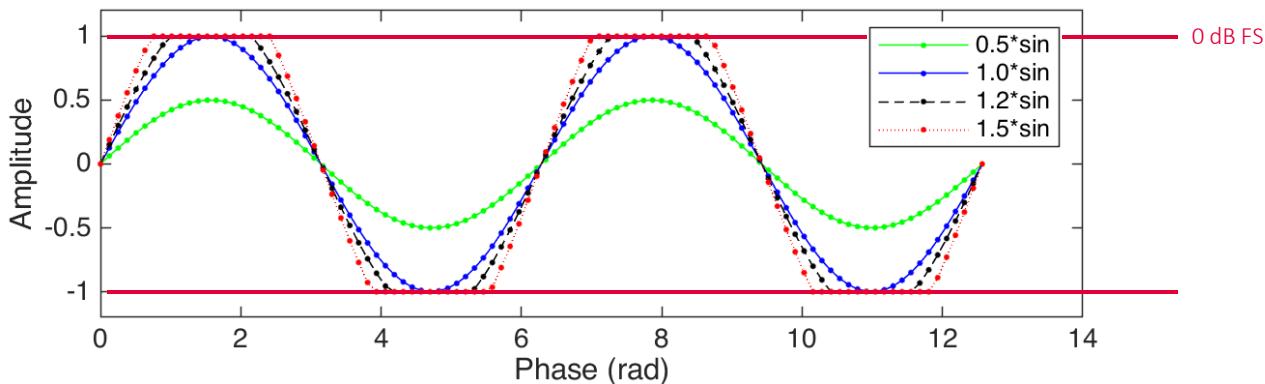
•• Scales and units in audio signal processing

- 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): relates to 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.



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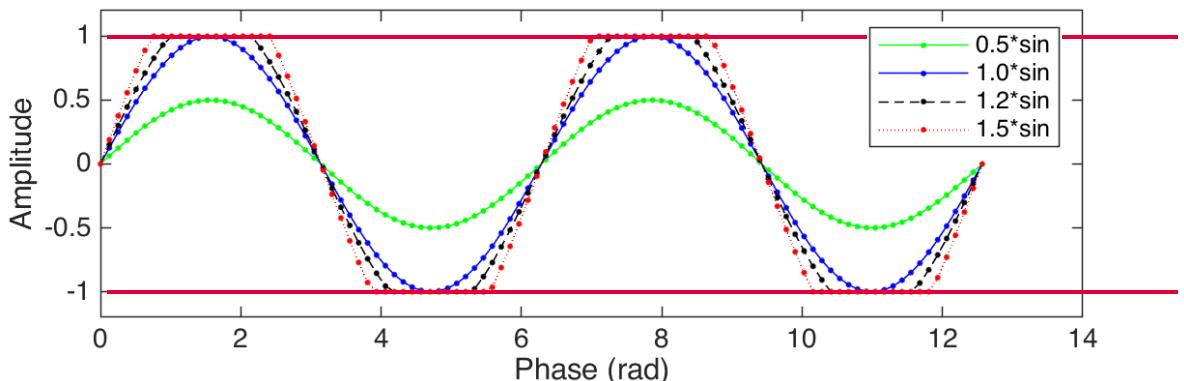


Further increase in amplitude
→ clipping.



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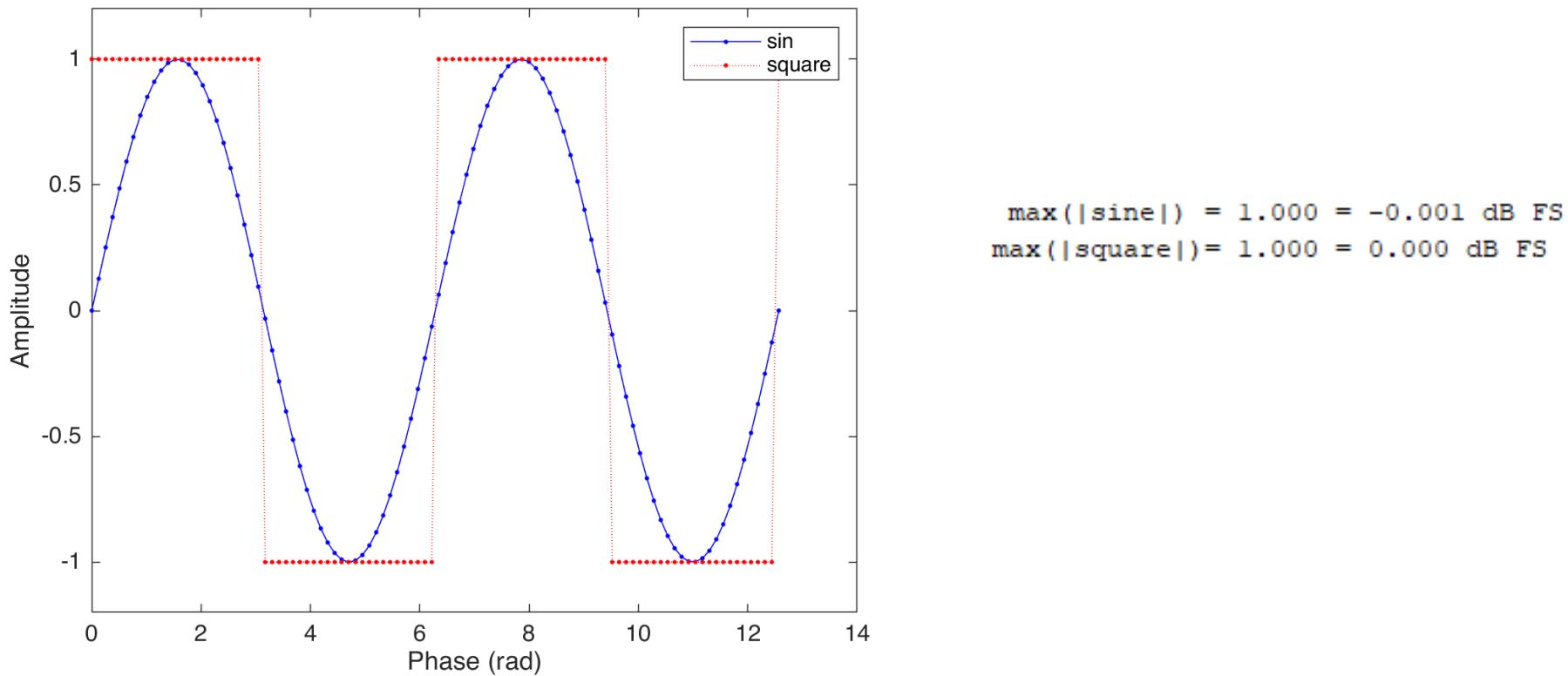


Further increase in amplitude
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Conversion:
 $dB = 20 \log_{10}(\text{mag}) \leftrightarrow \text{mag} = 10^{(dB/20)}$

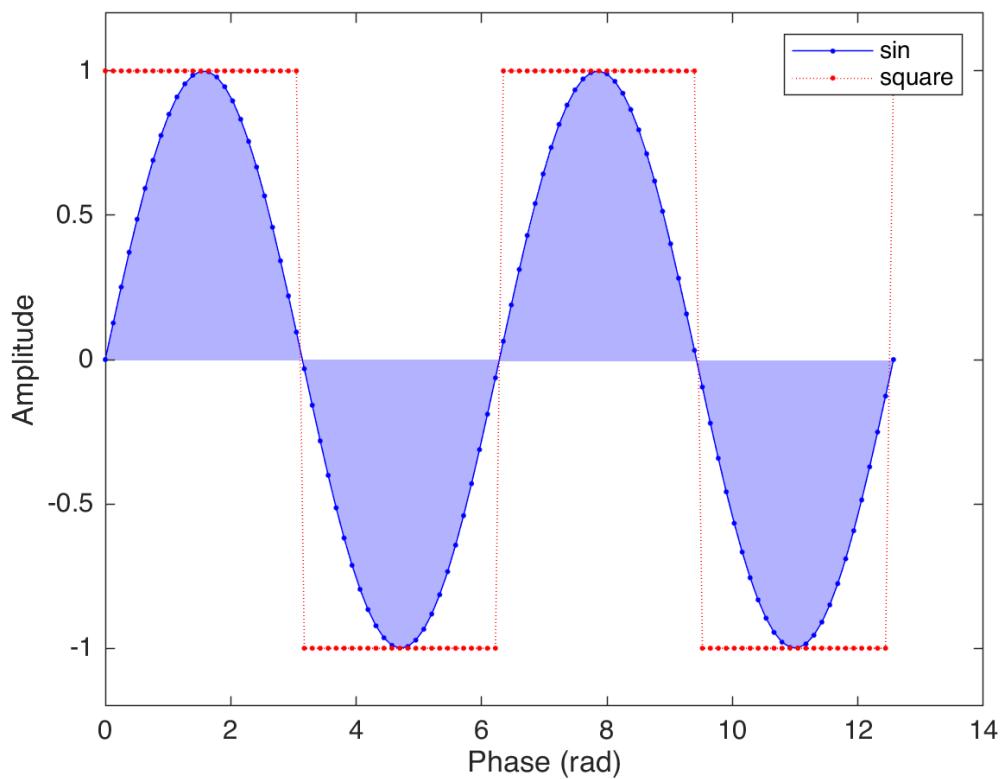
•• Scales and units in audio signal processing: dB FS

- 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!



•• Scales and units in audio signal processing: dB FS (RMS)

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

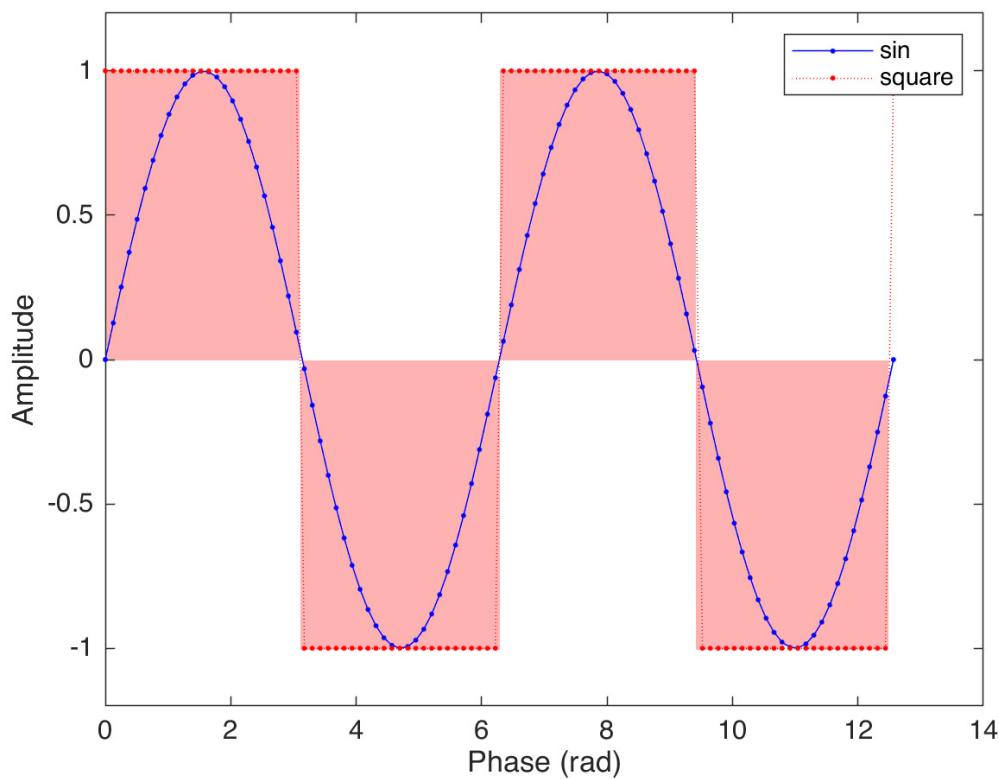
`max(|sine|) = 1.000 = -0.001 dB FS`
`max(|square|) = 1.000 = 0.000 dB FS`

`max(|sine/2|) = 0.500 = -6.022 dB FS`
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`RMS(sine) = 0.704 = -3.054 dB FS (RMS)`

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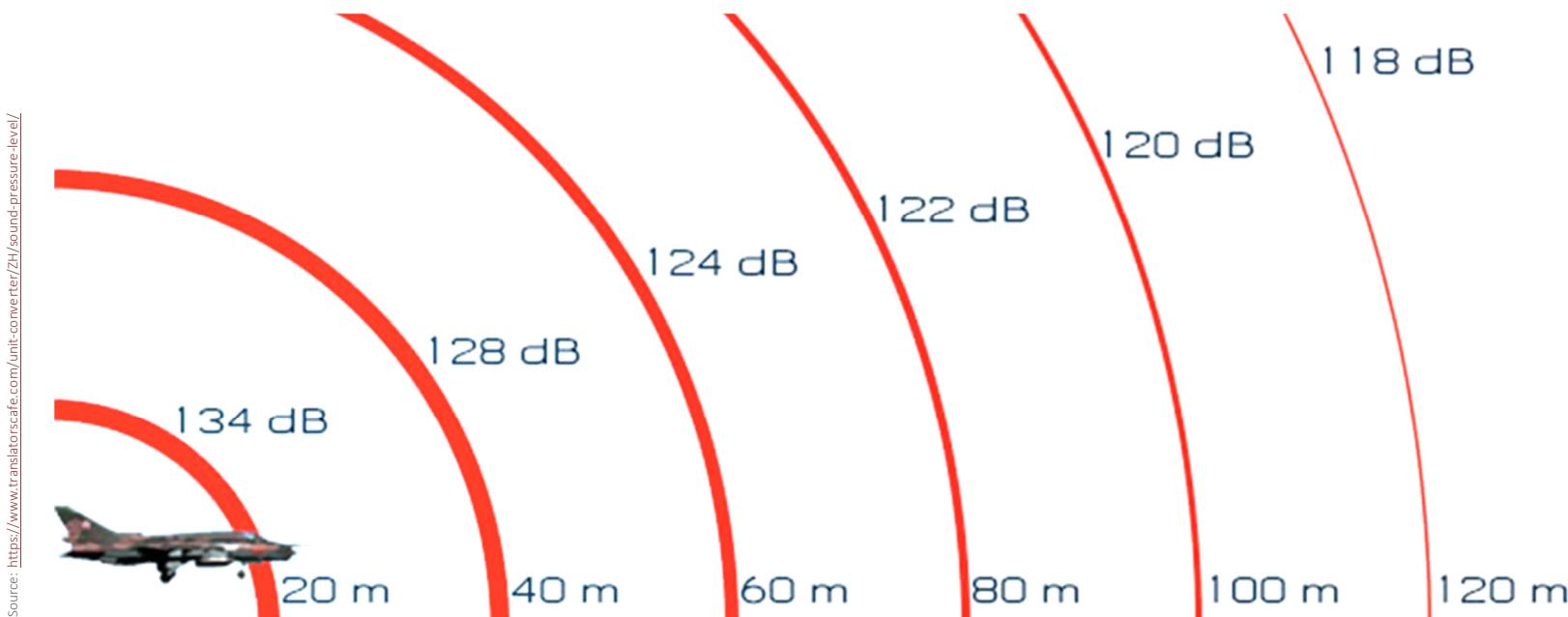
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- The unit **dB SPL** (Decibel sound pressure level): relates to the reference sound pressure $p_0 = 20 \mu\text{Pa}$ in air (often considered as the threshold of human hearing). Definition: $B_{\text{dB SPL}} = 20 \log_{10} (p / p_0)$.
 - Distance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

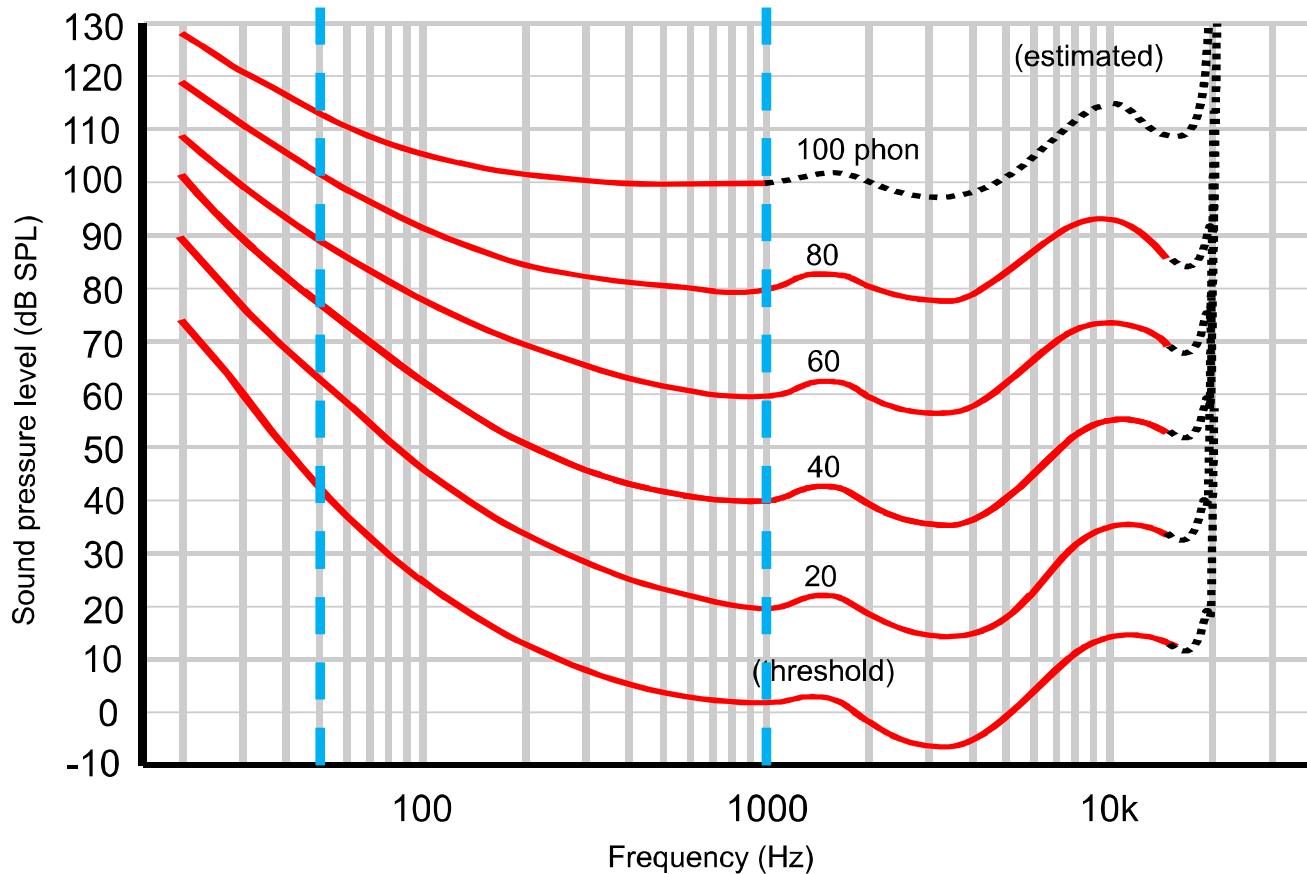


Source: <https://www.translator-scale.com/unit-converter/ZH/sound-pressure-level/>

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 - Distance (source to receiver) is important, 1 m is frequently used as standard distance.
 - Doubling the distance halves the SPL (in free field).
 - Typical ranges:
 - 20-30 dB SPL: very calm room,
 - 40-60 dB SPL (1m): normal conversation,
 - 70-90 dB SPL (10m): nearby heavy traffic, **>85 dB SPL: Hearing damage over long-term exposure**
 - 100-110 dB SPL (1m): jack hammer / chain saw,
 - 120 dB SPL (100m): jet engine, **>120 dB SPL: Instantaneous noise-induced hearing loss**
 - 194 dB SPL: largest pressure variation an undistorted sound wave can have in Earth's atmosphere.

•• Scales and units in audio signal processing: Equal-loudness contours

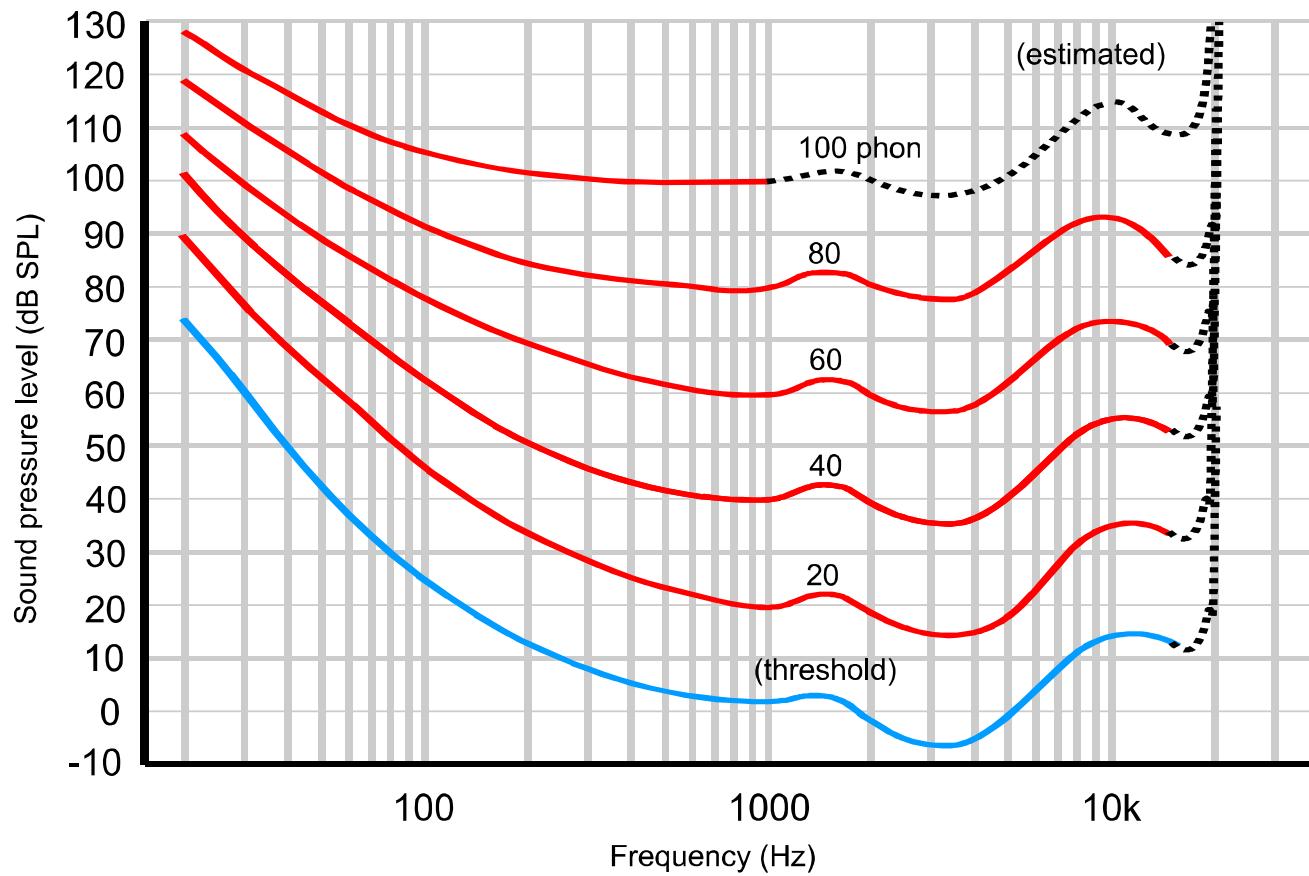


- 1933: Fletcher & Munson (*JASA*)
- 1956: Robinson & Dadson (*BJAP*)
- 2003: Multisite study → ISO 226
- Averaged over many normal hearing (NH) listeners
- At 1000 Hz: dB SPL ≈ loudness.
- At other frequencies, e.g. at 50 Hz (mainly at higher levels) not.

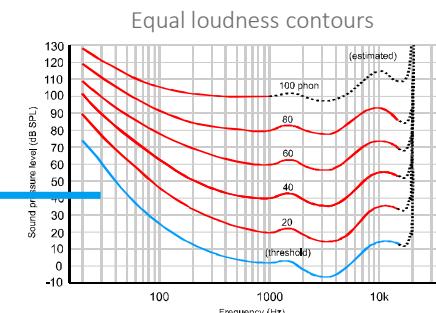
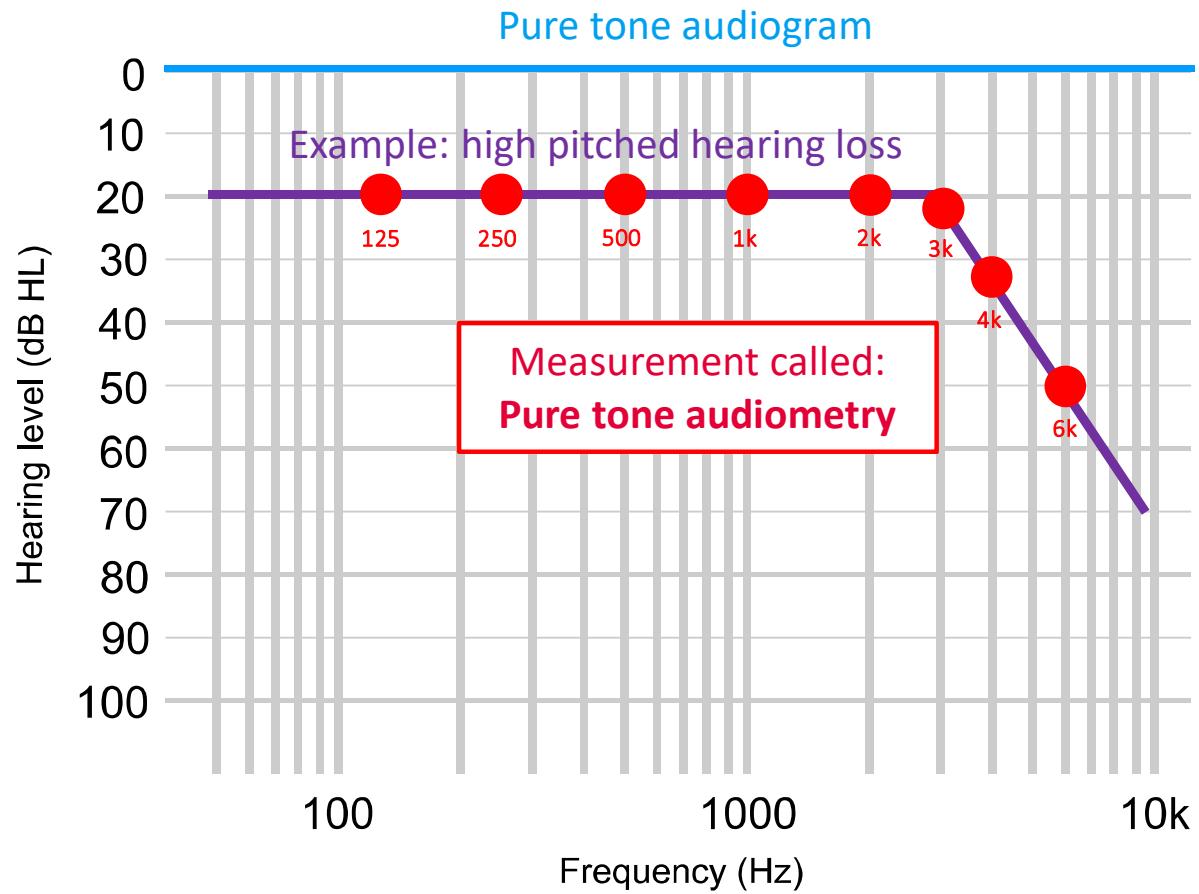
Loudness perception is
frequency dependent
and **non-linear**.

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

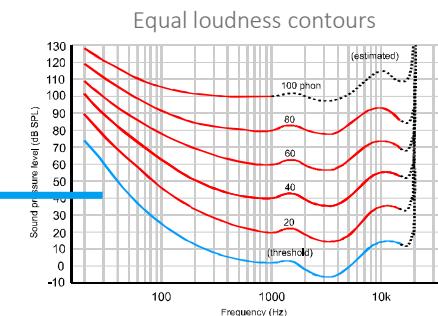
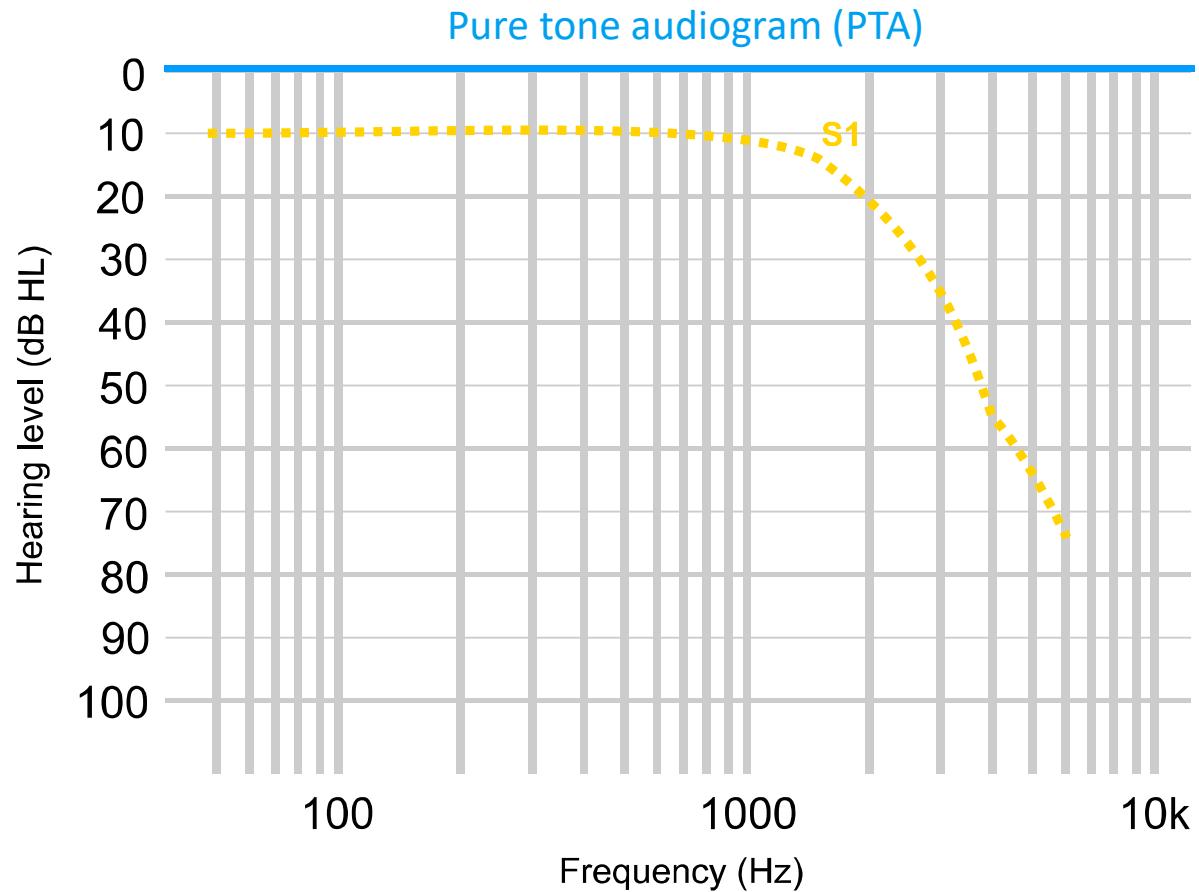
Equal loudness contours



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



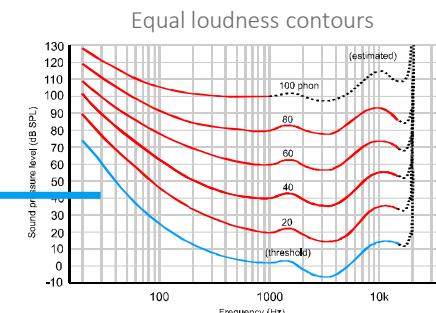
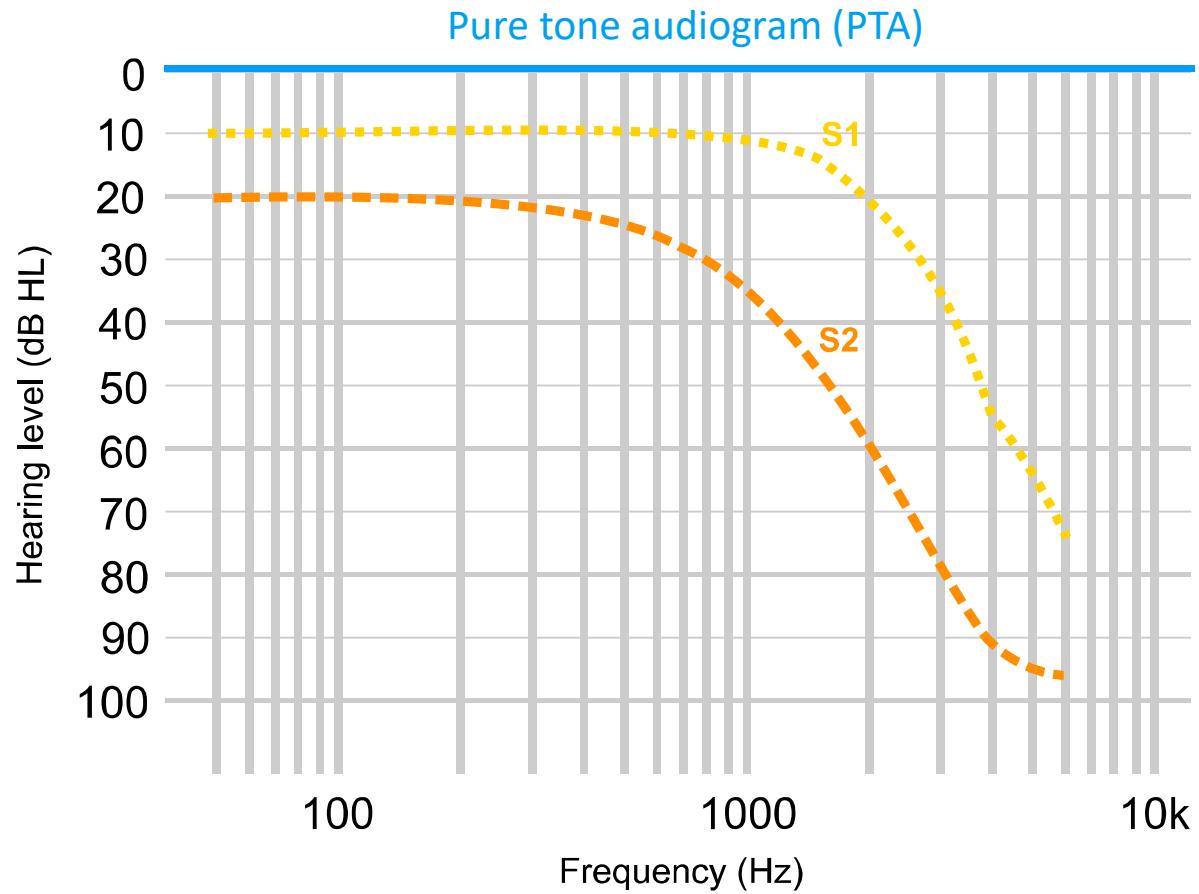
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Bisgaard standard audiograms:

- S1: very mild (*degree of hearing loss*)

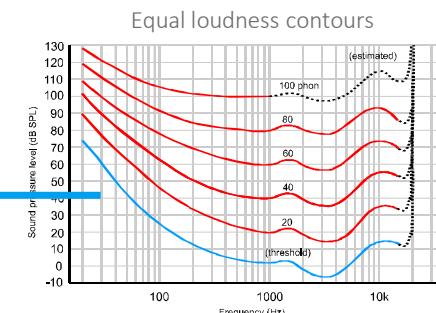
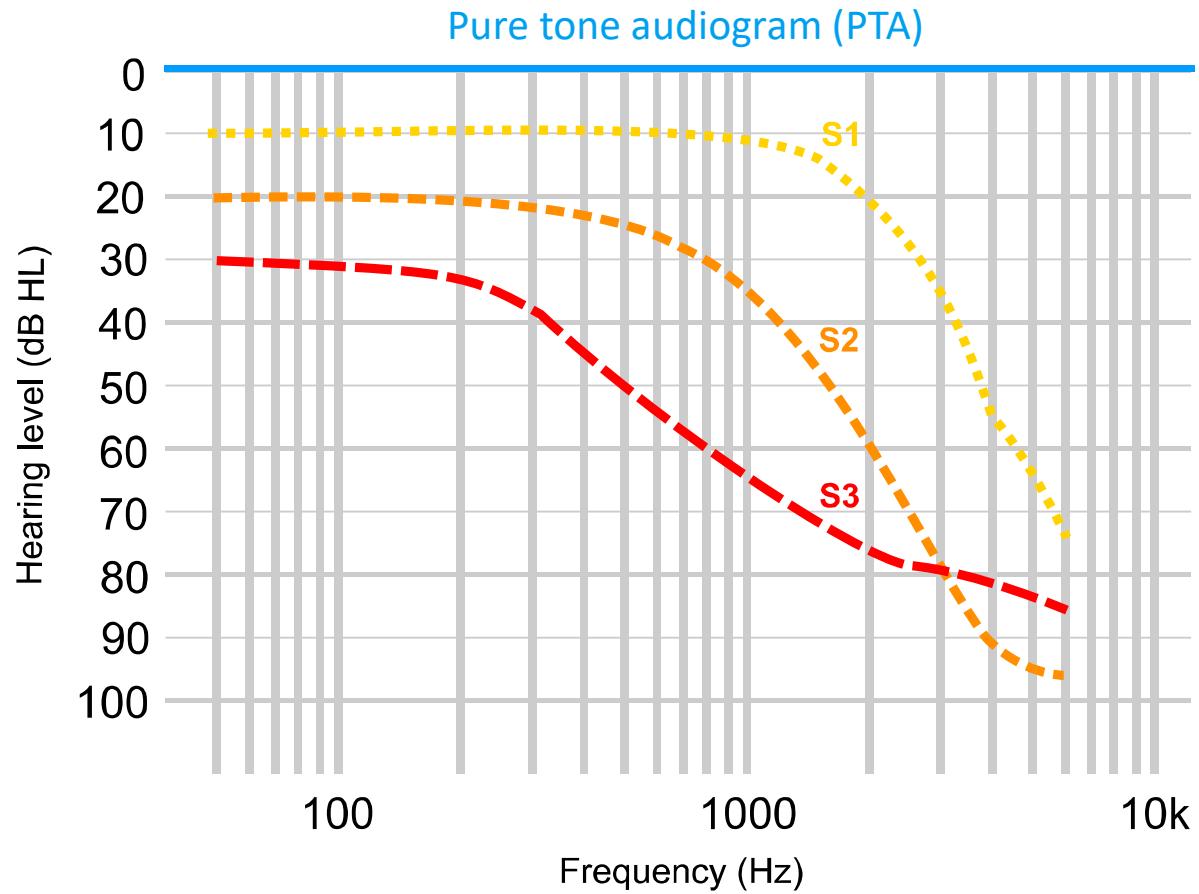
•• Scales and units in audio signal processing: dB HL



Bisgaard standard audiograms:

- S1: very mild (*degree of hearing loss*)
- S2: mild

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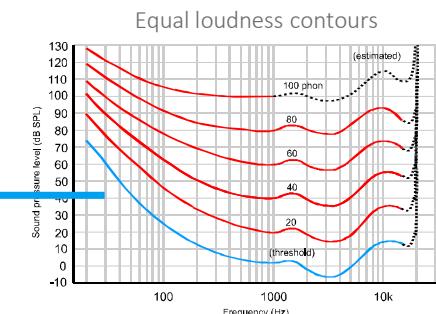
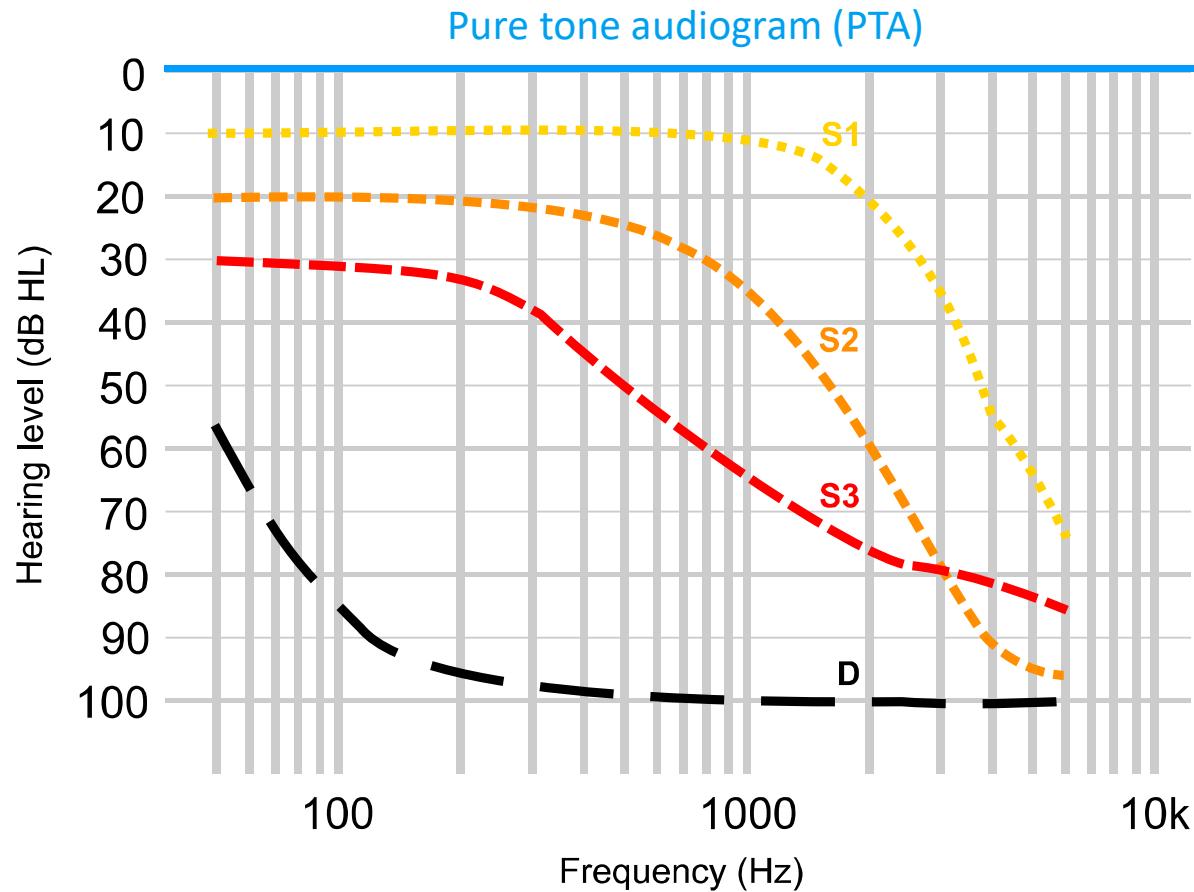


Bisgaard standard audiograms:

- S1: very mild (*degree of hearing loss*)
- S2: mild
- S3: severe

Source: [Bisgaard et al. \(2010\)](#)

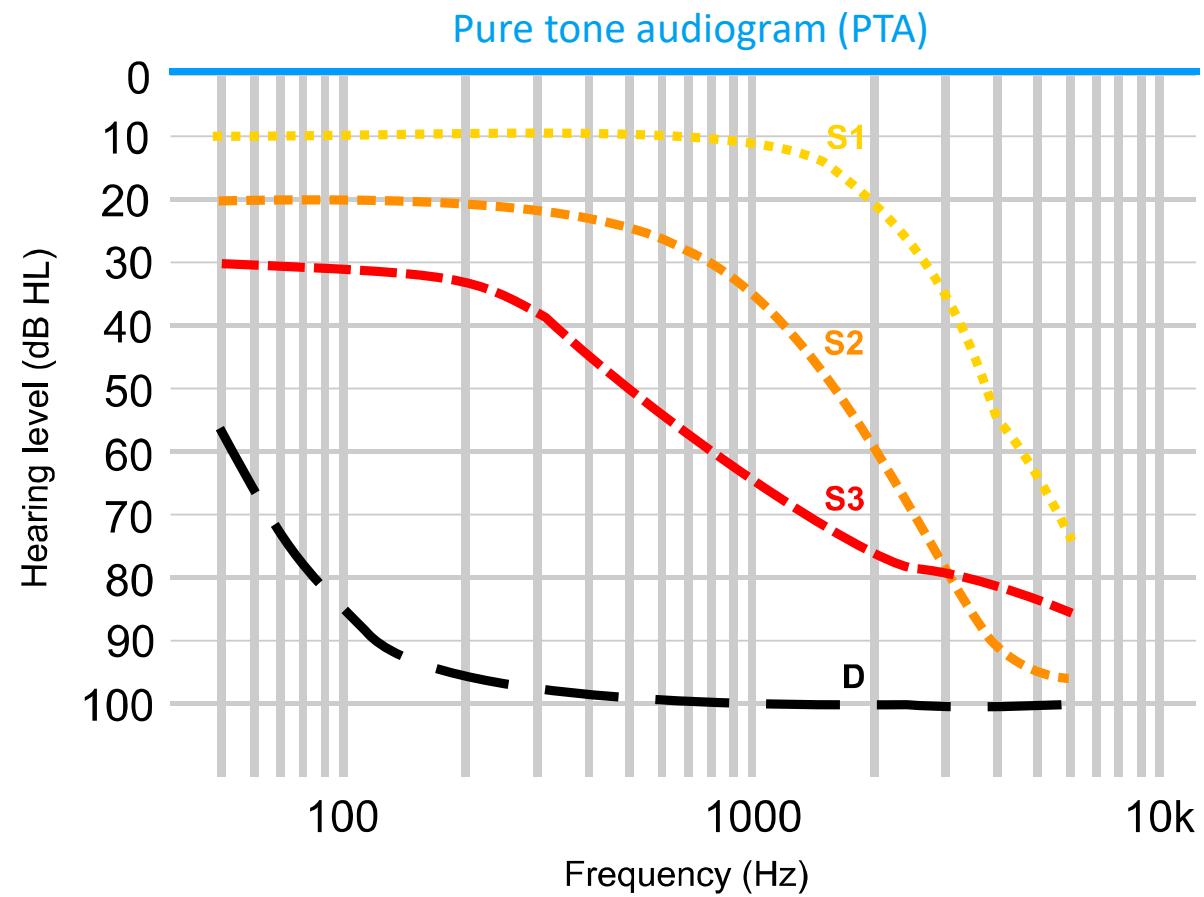
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Bisgaard standard audiograms:

- S1: very mild (*degree of hearing loss*)
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 - S3: severe
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- D: hearing loss bordering on deafness

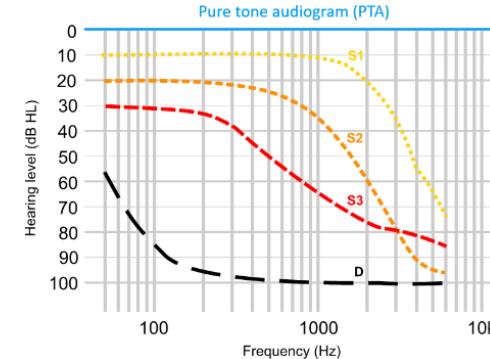
•• Hearing and hearing impairments



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Questions:

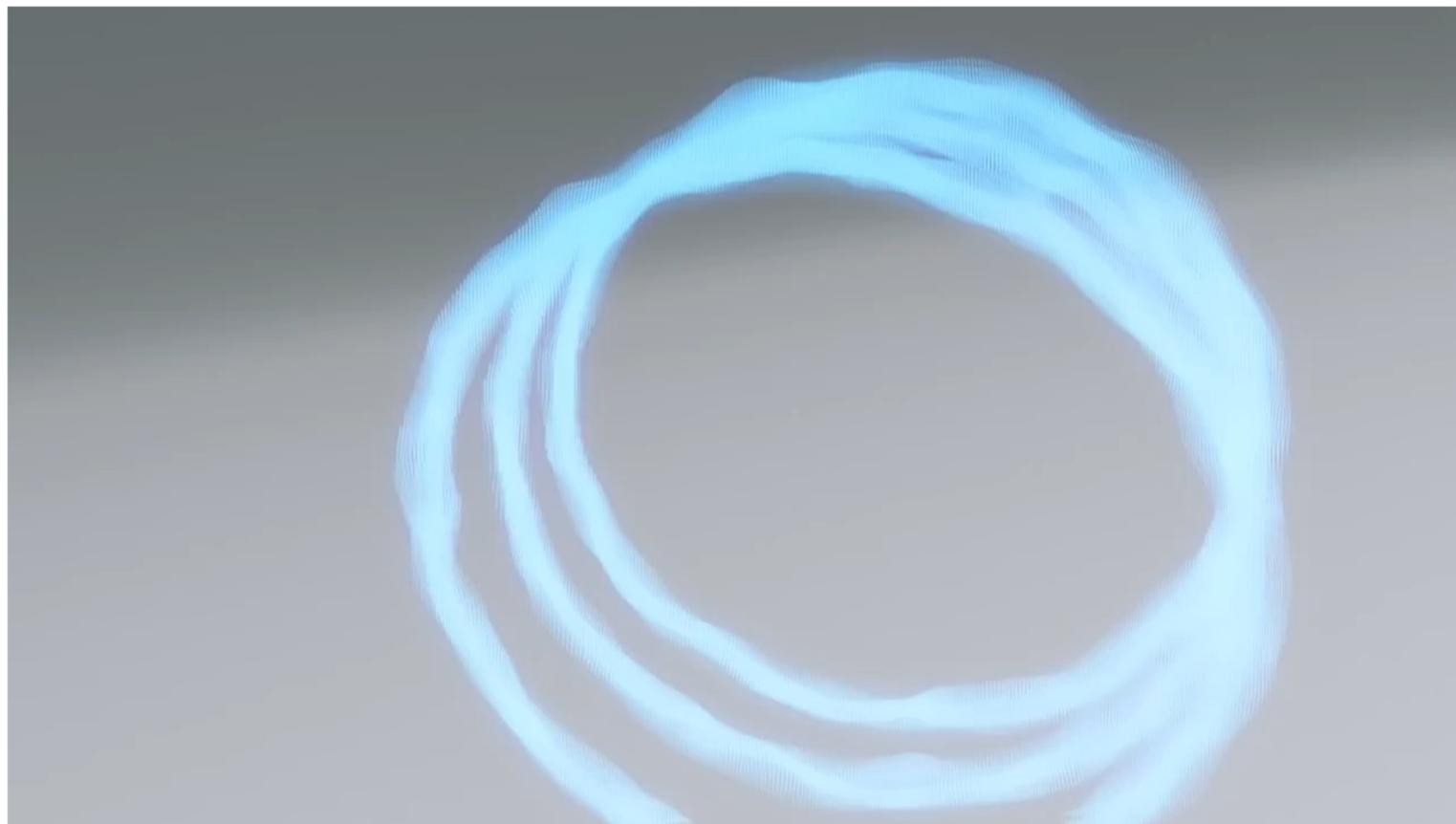
- How many are affected?
 - [WHO 2020](#): worldwide ca. 466M people with disabling hearing loss.
- How bad is impaired hearing?
 - It is bad, especially in background noise. Try for yourself → see **slide 4**: hearing loss simulators.  
- What are the causes of the impairments?
 - Genetic causes, complications at birth, infectious diseases, chronic ear infections, certain drugs, ageing, and exposure to excessive noise (1.1B young people under 35 due to high SPLs in recreational settings).
- What can be done to help people?
 - Hearing protection and education, access to early and on-demand screening;
 - access to hearing systems: hearing aids, cochlear implants, and other assistive devices ([WHO 2020](#): currently only 17% of those who could benefit from use of a hearing aid actually use one);
 - sign language and social support.



•• Short recap

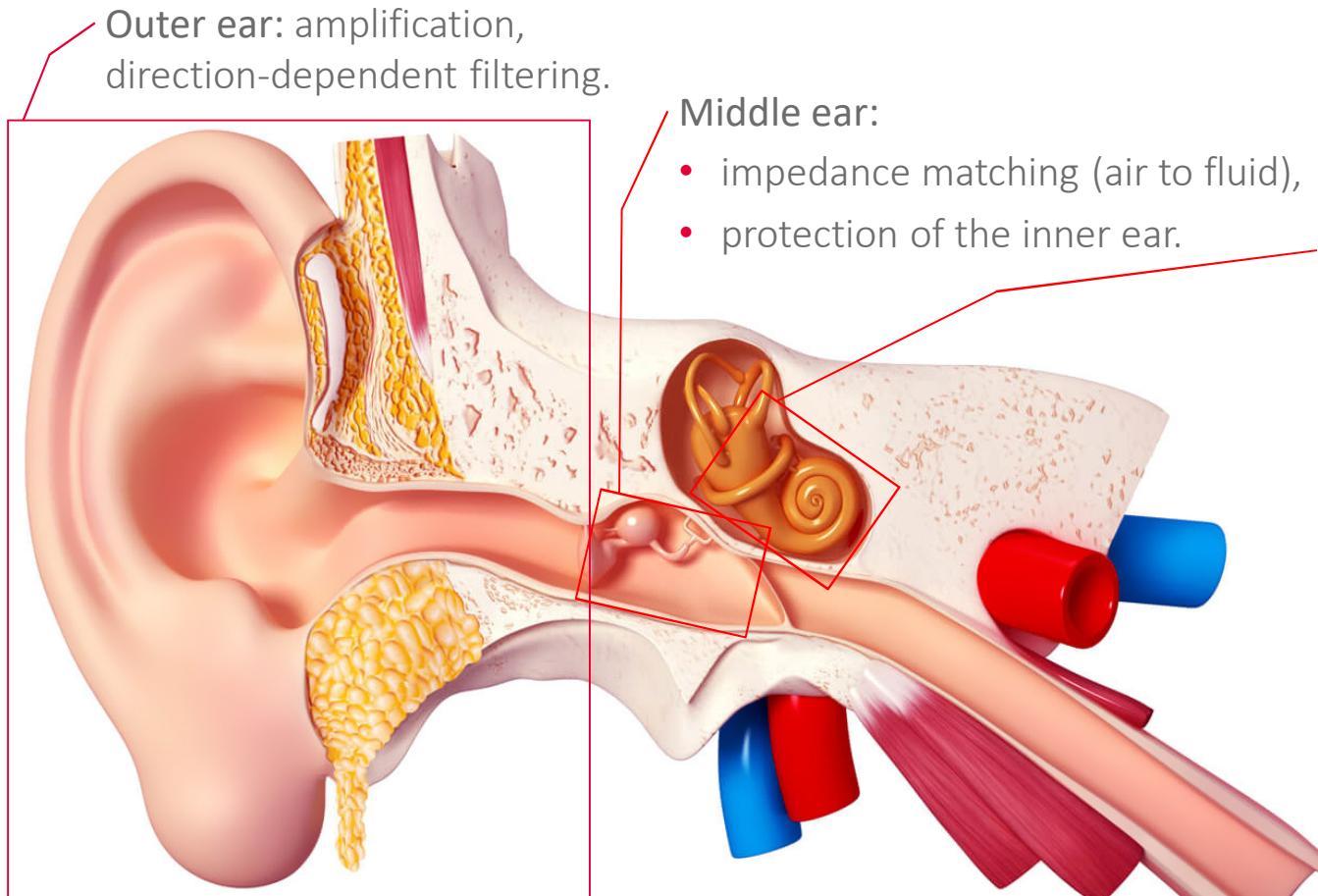
- Scales (\rightarrow dB) and main units (\rightarrow dB FS) in audio signal processing,
conversion: $dB = 20 \log_{10}(mag) \leftrightarrow mag = 10^{(dB/20)}$.
- Importance of signal form (\rightarrow dB RMS) and distance (\rightarrow dB SPL) and how they influence
loudness (\rightarrow equal loudness contours).
- Hearing level (\rightarrow dB HL) and pure tone audiogram.
- Facts about hearing impairments.

•• How hearing works



Source: <https://www.youtube.com/watch?v=4AcS2AfJ9OM>

•• Overview



Outer ear: amplification,
direction-dependent filtering.

Middle ear:

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

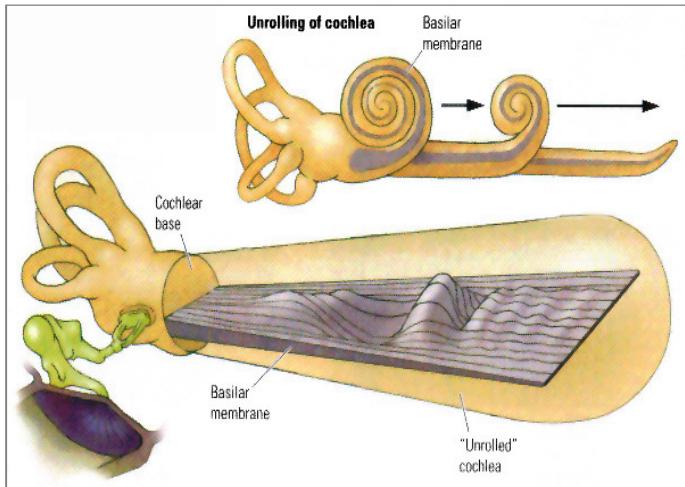
Inner ear:

- spectral decomposition of signal (~filter bank),
- transformation into electrical signals (neural spikes).

Source: www.lobe.ca, 2021.

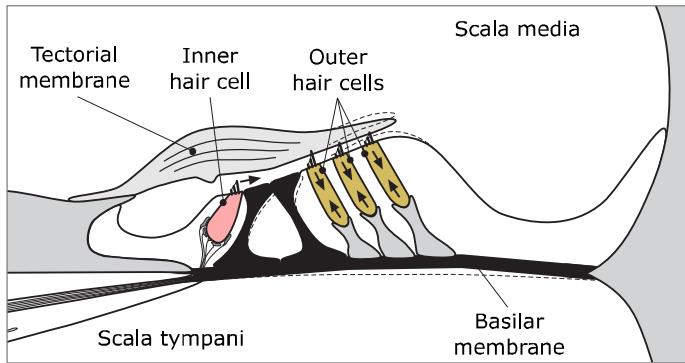
•• How hearing works

Unrolled cochlea



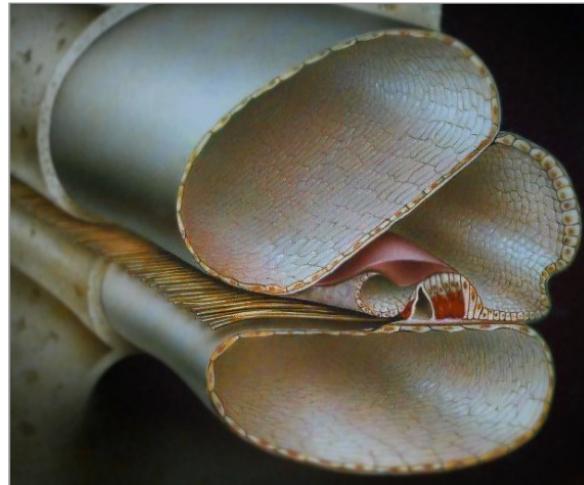
Source: <http://www.pc.rhul.ac.uk>

Organ of Corti



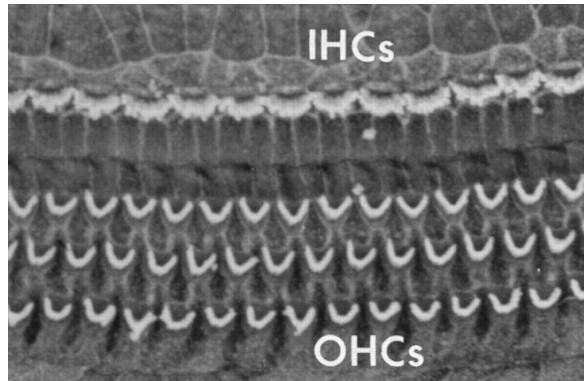
Adapted from: [Baumgarte, 2000](#)

Cochlear cross-section



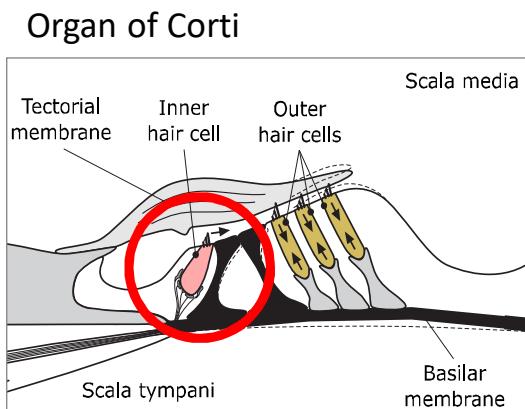
Source: www.meniett.com

Hair cell rows

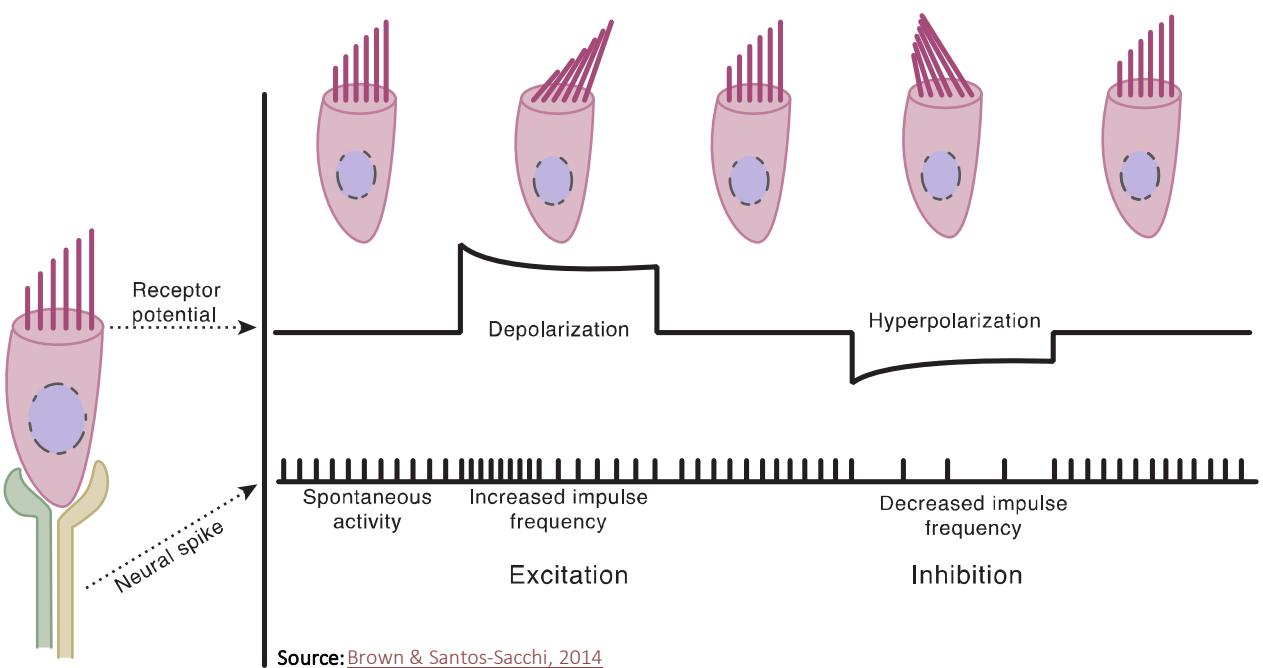


Source: [Ryan, 2000](#)

•• How hearing works: Inner hair cells



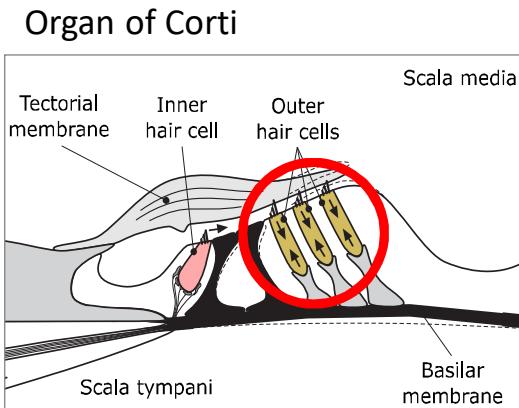
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Inner hair cells:

- do mechanoelectrical transduction (convert motion to electricity);
- are the sensory cells in our auditory system.

•• How hearing works: Outer hair cells



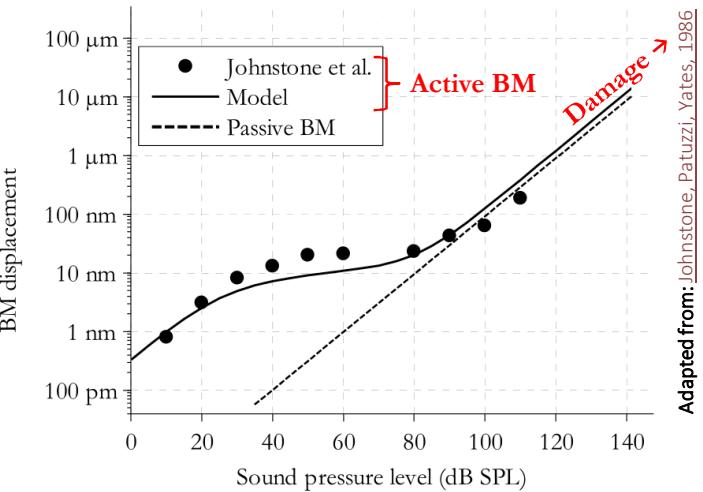
Adapted from: [Baumgarte, 2000](#)

OHC motility



Source: [J. Ashmore for BBC 'Ear we go', 1987](#)

BM nonlinearity



Adapted from: [Johnstone, Patuzzi, Yates, 1986](#)

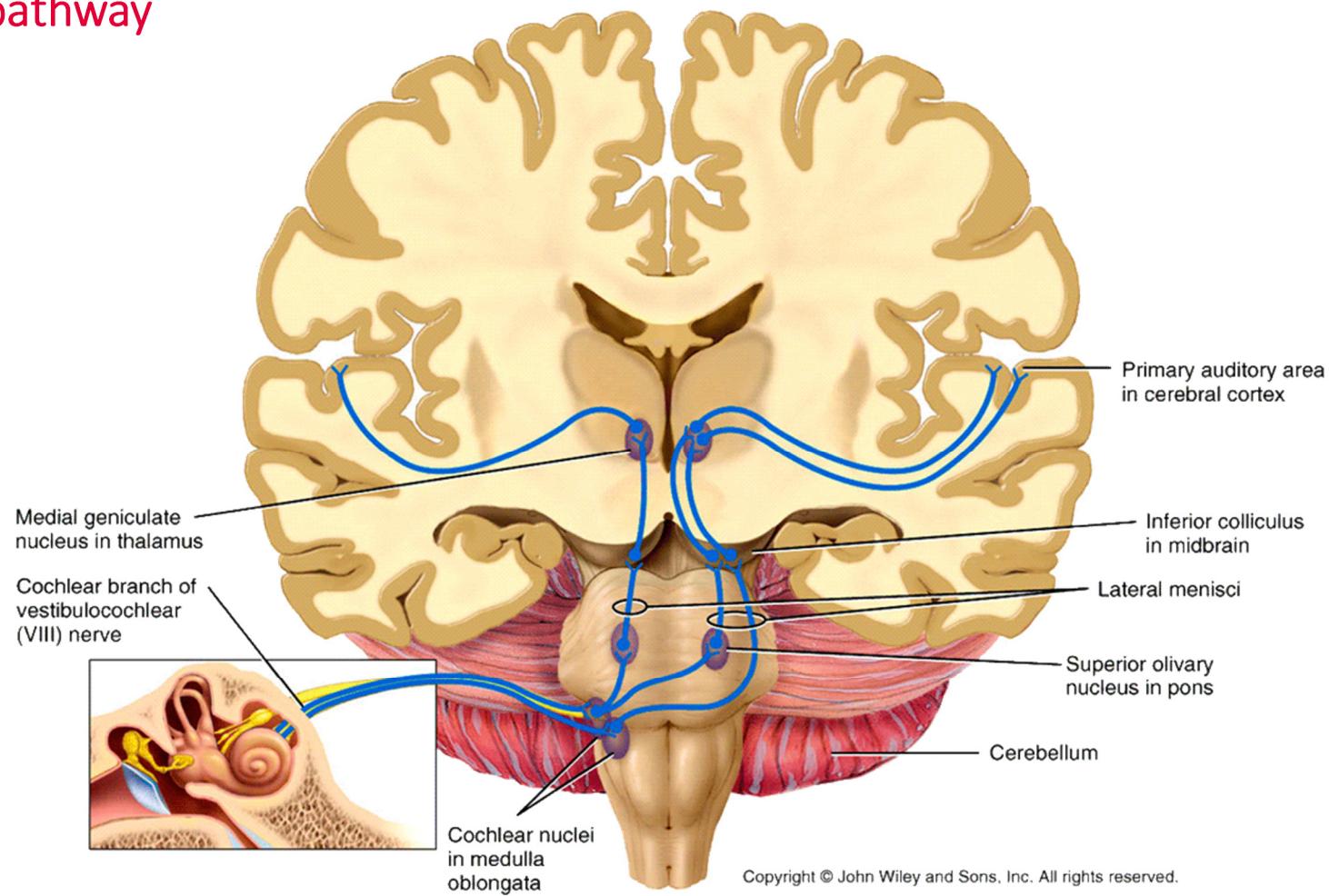
Outer hair cells (OHCs):

- actively amplify/dampen the movement of the basilar membrane (BM), thus increase the loudness range (dynamic range) of the ear;
- increase frequency selectivity at the basilar membrane;
- protect inner hair cells by stiffening upon loud signals (until damaged).



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

•• Auditory pathway



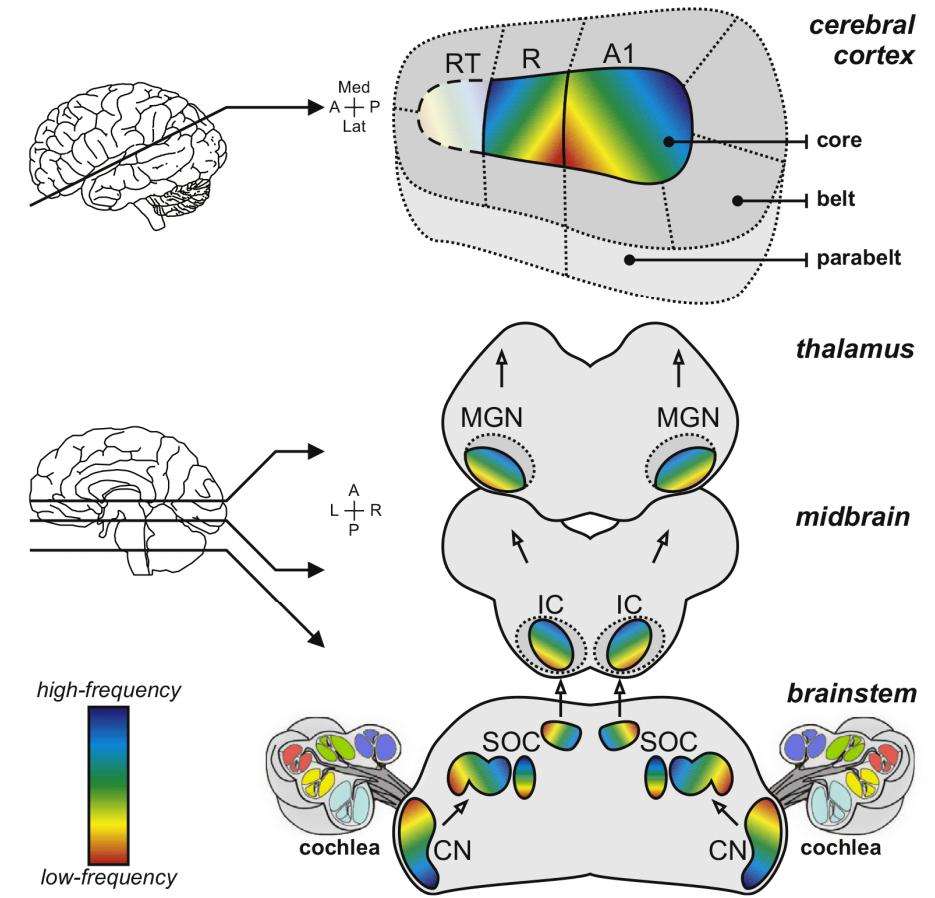
Source: [Tortora & Derrickson: Principles of Anatomy and Physiology, 2016](#)

•• Tonotopy



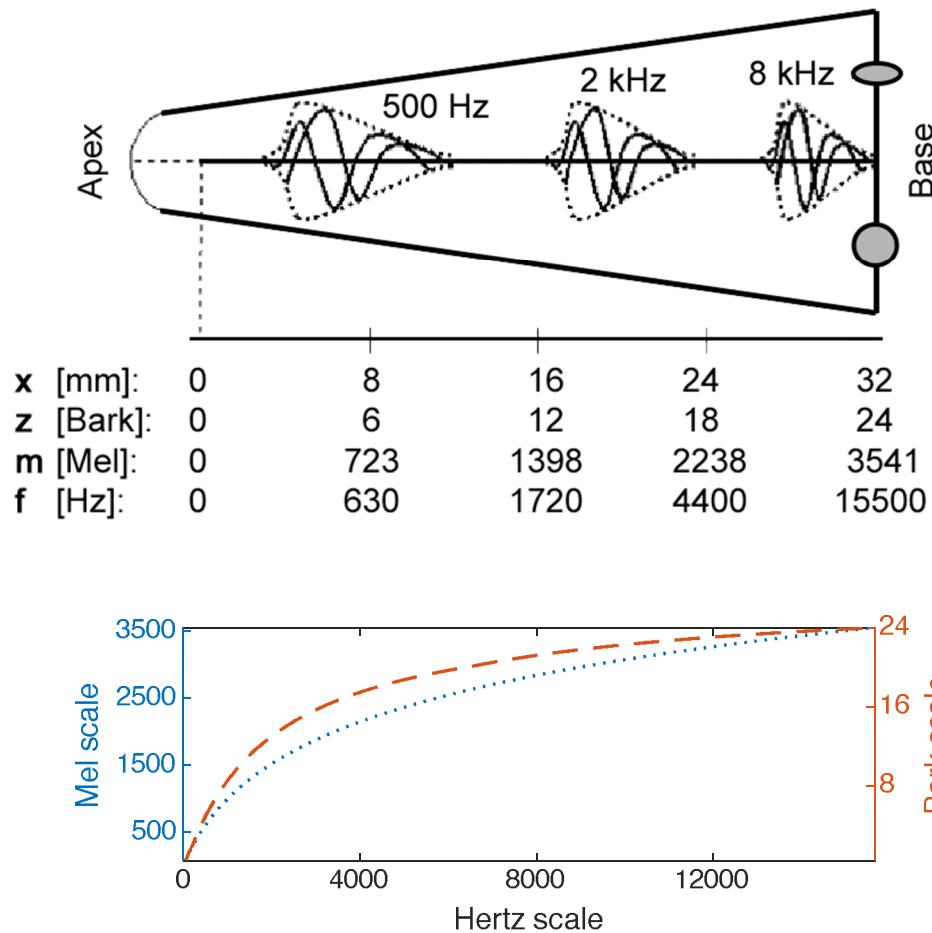
Source: [HHMI, 2000](#).

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



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

•• Tonotopy



Frequency scale of the ear :

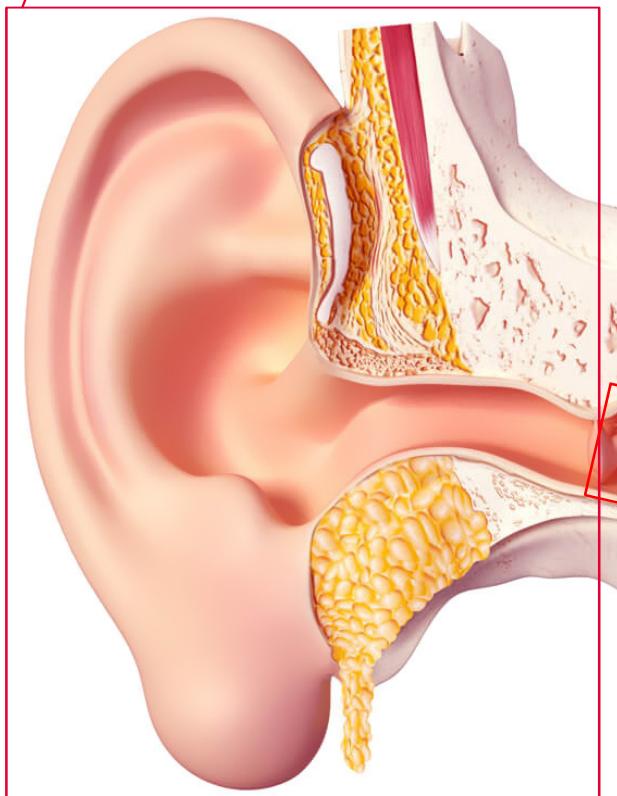
- The human basilar membrane (BM) is approx. 32-35 mm long. Along the BM ca. 3500 IHCs and 12000 OHCs are distributed.
- Regardless of whether we take Bark or Mel scale, it is important to remember that place pitch is not distributed linearly along the cochlea;
 - 210 ± 10 Hz we can discriminate well, but
 - 4410 ± 10 Hz will cause difficulties.



- Pitch difference of 1 Bark roughly equals to 1.3 mm on the BM; you only have around 150 IHCs along that cochlear section.

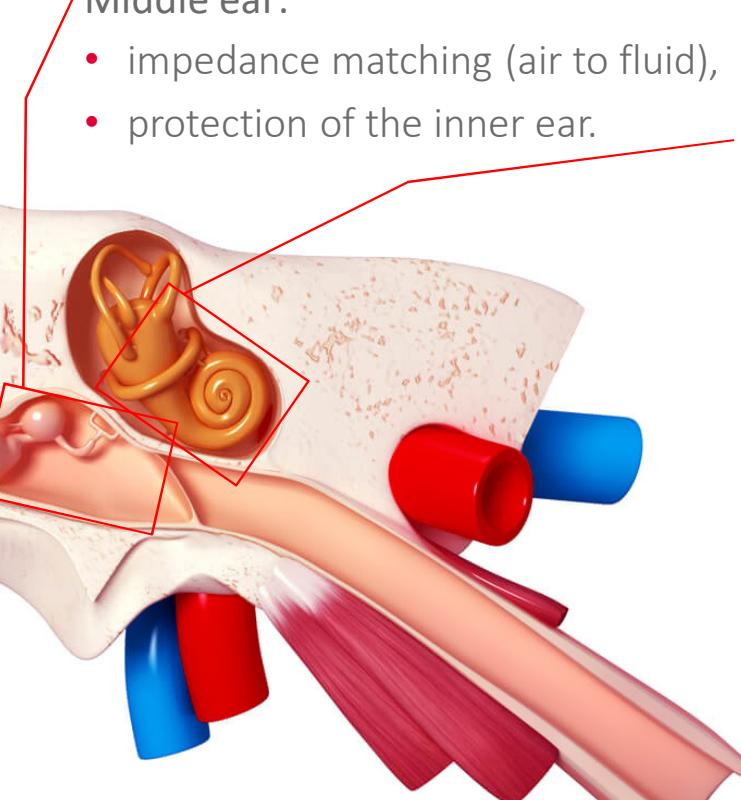
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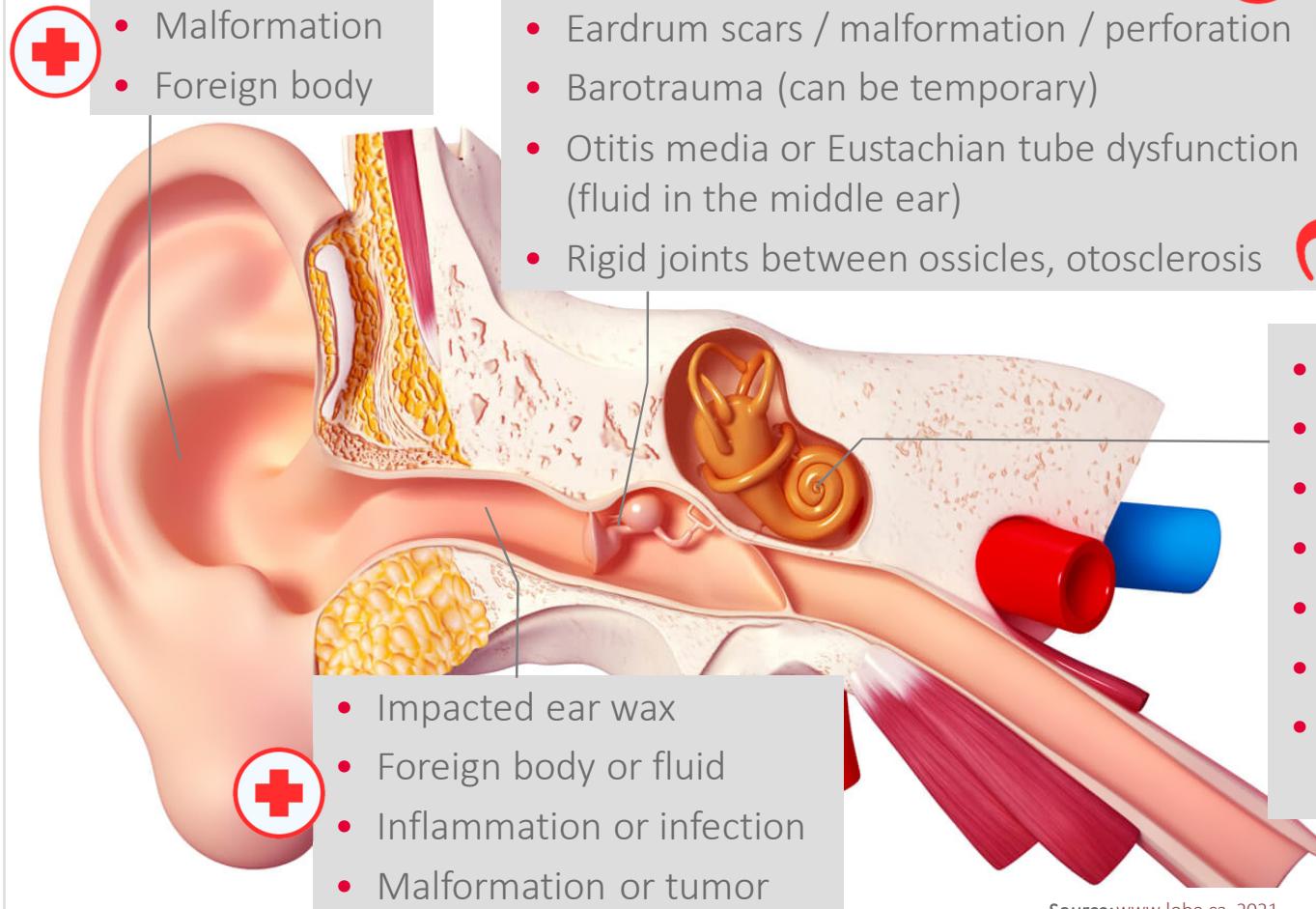
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Properties:

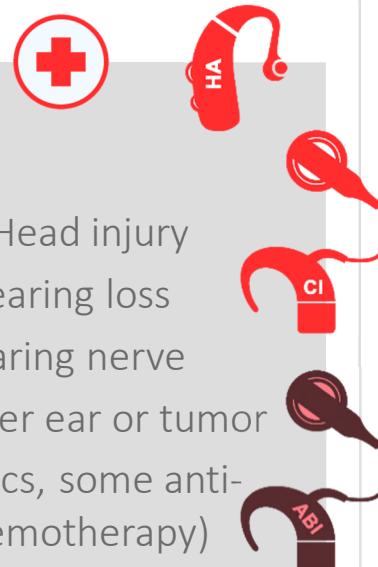
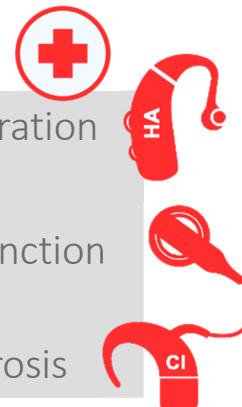
- Frequency: non-linear (log-like) map.
- Amplitude: compressive nonlinearity.

Source: www.lobe.ca, 2021.

•• Causes of hearing impairment



Source: www.lobe.ca, 2021.

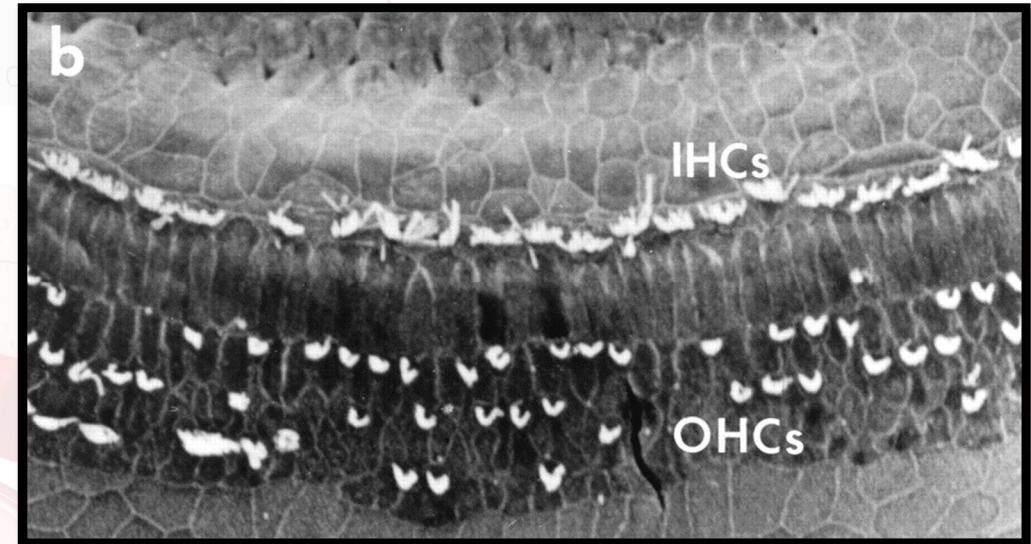
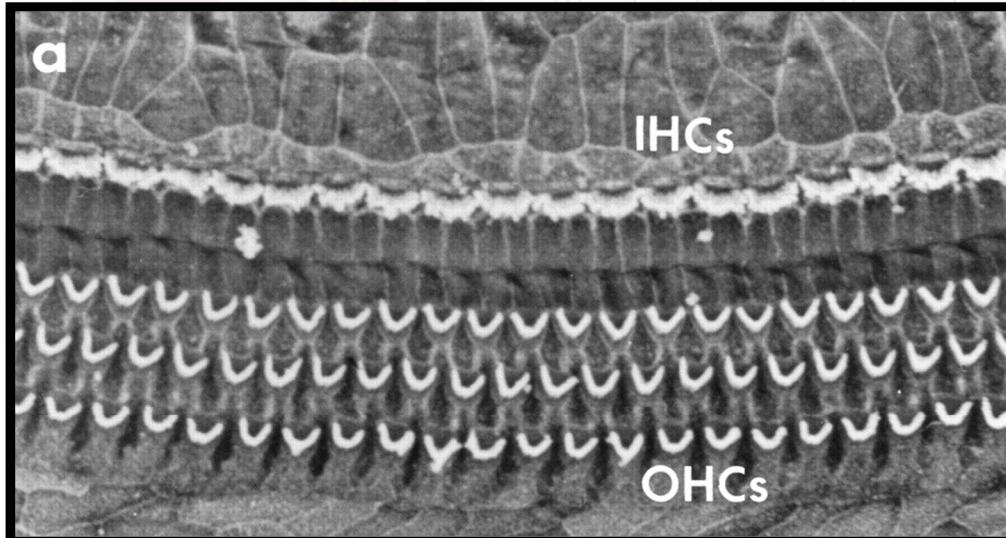


•• Causes of hearing impairment

- Malformation
- Foreign body

- Eardrum scars / malformation / perforation
- Barotrauma (can be temporary)
- Otitis media or Eustachian tube dysfunction

Hair cell damage



- Foreign body or fluid
- Inflammation or infection
- Malformation or tumor

- Ototoxic drugs (antibiotics, some inflammatory drugs, chemotherapy)

Source: [Ryan, 2000](#)

Source: [www.lobe.ca, 2021](#).

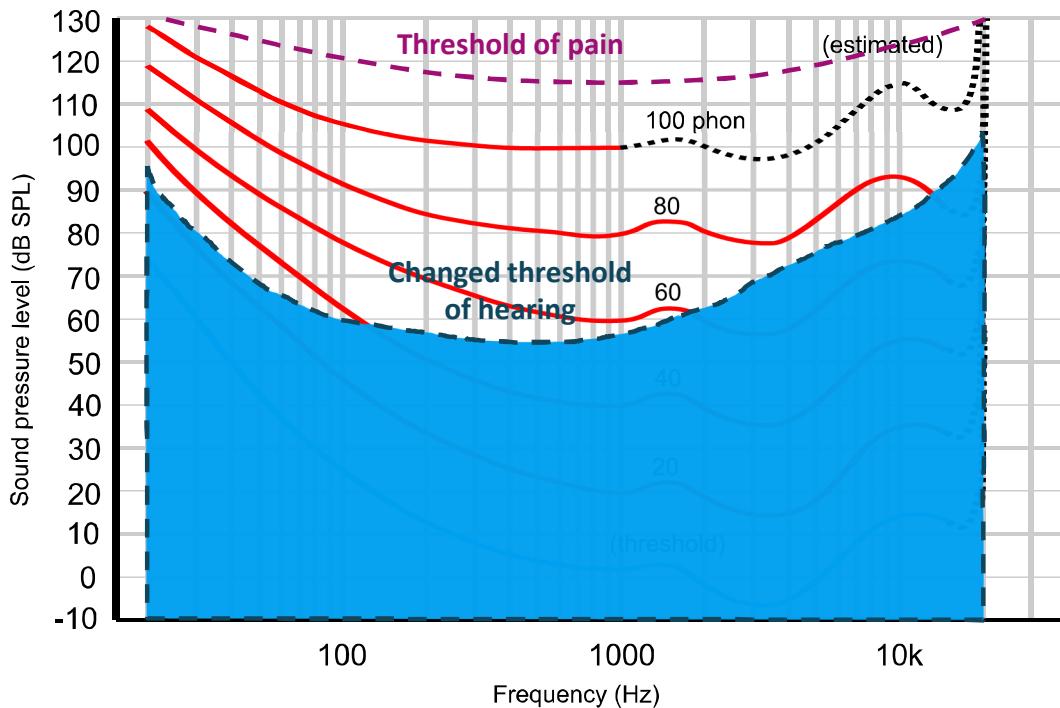
•• Consequences of hearing impairment

- Communication is difficult to follow, uncertainties become frequent in everyday life.
- Environmental sounds missing (bird song, water dripping, water boiling over when cooking,).
- Withdrawal, due to
 - missing what others are talking about → frustration;
 - unwilling to ask repeatedly → shame, embarrassment;
 - everyday situations become challenging;
 - listening to speech becomes very effortful.
- Most of the time no sudden decline but a creeping process → unconscious adaptation.
- Often leads to "pro-active strategy": responses to what was meant to be said.
- May lead to loneliness, isolation, depression (false sense of others often being angry with them).
- **Unavoidable cognitive decline if untreated.**
- Danger: confusion with dementia.



•• First signs of a hearing impairment #1

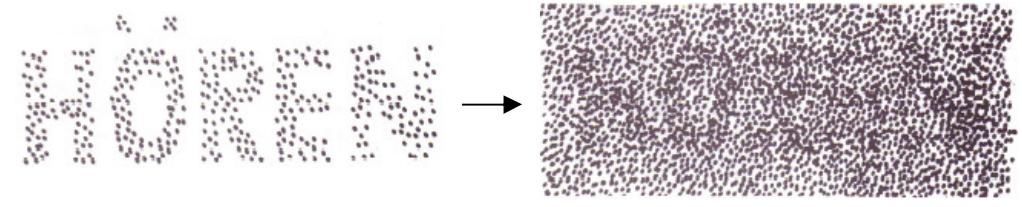
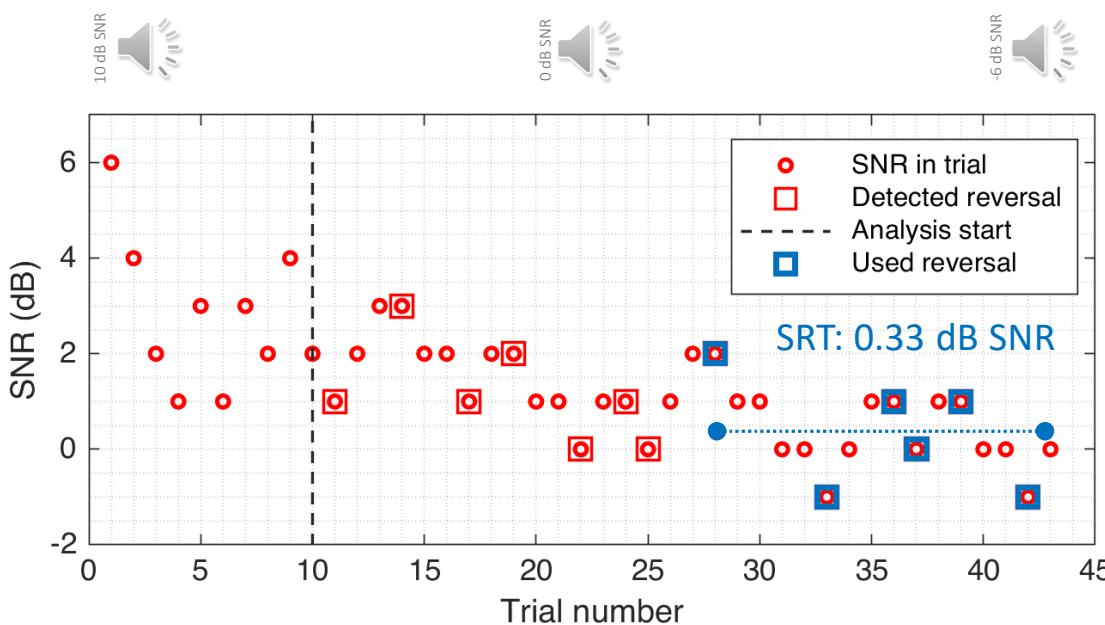
- Speech at moderate level not always understood, but **loud speech becomes disturbing** and misinterpreted as offensive.



- In most cases, the amount of energy arriving at the IHCs is comparable to that of the NH (normal hearing) case.
- Threshold of pain is unchanged (and also the range of uncomfortably loud signals).
- But the dynamic range is narrower.
- In hearing assistive technology:
 - need to know the thresholds (**pure tone audiology**),
 - need to apply dynamic compression.

•• First signs of a hearing impairment #2

- Understanding **speech in noise** (other talkers, traveling, background music) becomes increasingly **difficult**.
- If pure tone audiogram looks OK → hidden hearing loss.
- Speech in noise test can clarify the issue.
In German-speaking regions: [OLSA \(Oldenburger Satztest\)](#).



- Problems with understanding speech in noise often arise before a pure tone audiogram indicates hearing impairment.
Speech reception threshold, SRT, increases.
- Threshold and equal loudness curves may remain largely unchanged.
- Frequency and amplitude resolution declines, which makes it the auditory system harder to distinguish signal from noise.
- Hearing assistive technologies may help with signal reduction algorithms.

•• Hearing aids – Early history

Source: hearingaidmuseum.com, 2021

Ear trumpets



17th century

Vactuphone
(1st vacuum-tube HA)



1902

Behind-the-ear
hearing aids



1952

Widex Senso
full digital BTE HA



1956-57



Hutchison's Acousticon
(1st electrical HA)



Sonotone Model 1010
(1st transistor HA)



Nicolet Phoenix
(programmable digital HA)

•• Hearing aids – Modern form factors



Behind the ear (BTE)



Receiver in canal (RIC)



In the canal (ITC)



Completely in canal (CIC)

Source: betterhearing.org, 2021



- + least earwax impact
- definitely visible



- + least feedback



- + glasses-friendly
- ear occlusion



- + glasses-friendly
- ear occlusion
- usability

•• Hearing aids – Modern requirements

- Attested hearing impairment is a **disability**.
- Health insurance (in Germany) pays for an adequate hearing aid system. Requirements:
 - digital technology;
 - a minimum of 4 frequency channels with compression;
 - a minimum of 3 selectable, individualized programs (=*settings*);
 - availability of noise reduction algorithm;
 - availability of feedback cancellation algorithm.
- Plus, requirements of the Medical Device Regulation (MDR) of the European Union:
 - manufacturer must implement quality and risk management systems;
 - performance, user benefit, and user safety must be proven in clinical trials.

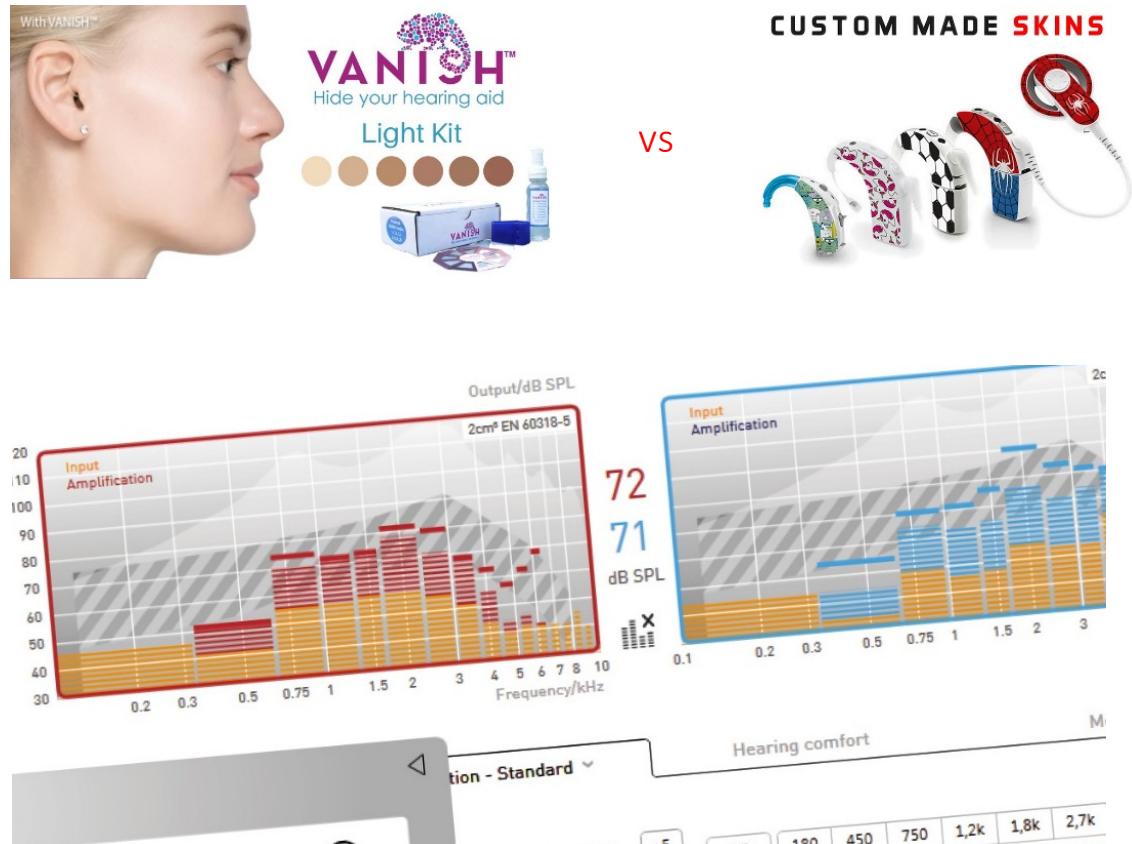
•• Hearing aids – Expected features

General:

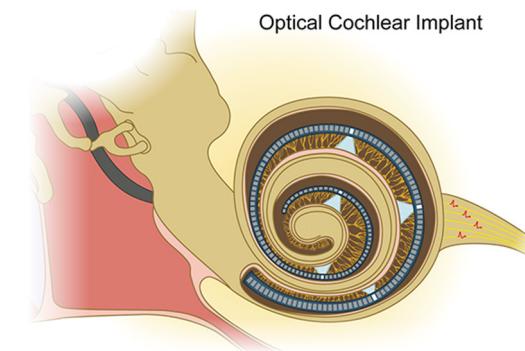
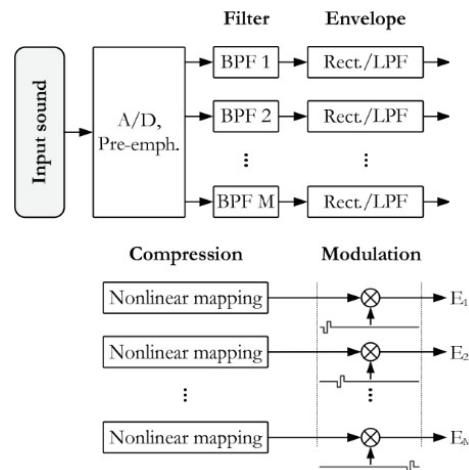
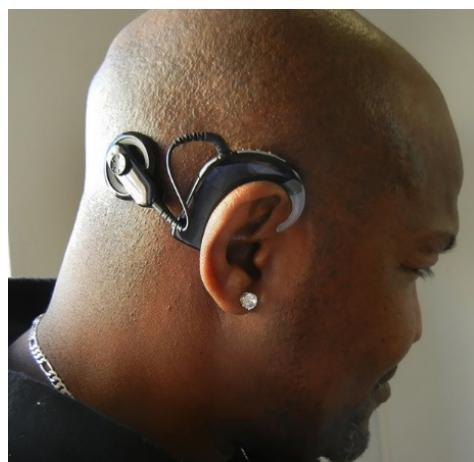
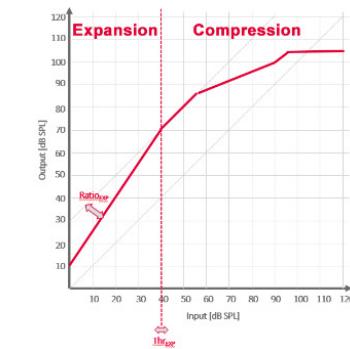
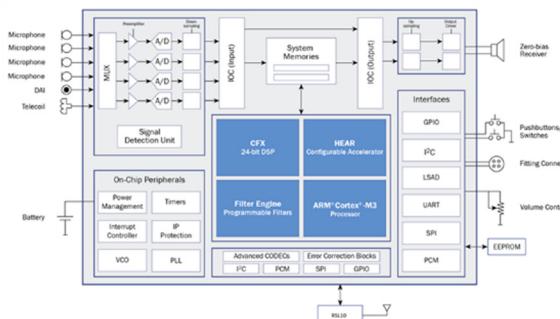
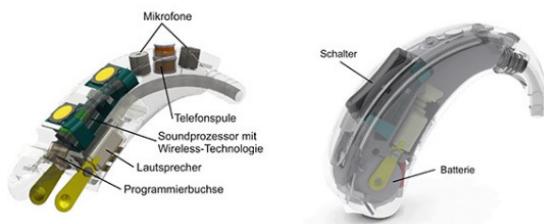
- Small, lightweight, intuitive, discrete*.
- Remote control, smartphone app.
- Wireless streaming (TV, remote microphone).
- Quickly rechargeable, long lasting battery.

Audiological features:

- Low noise, high bandwidth (10 kHz+).
- 16+ frequency channels for DRC.
- Adaptive microphone directionality.
- Noise reduction: ambient, wind, impulse.
- Environmental classification.
- Advanced feedback cancellation.
- Frequency shifting.
- Low latency (<< 10 ms), binaural algorithms.



•• Next week





Thank you very much!
Questions?

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