



# Hearing Systems – Part 1

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

TU Ilmenau – Audio Systems Technology

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(Online) | January 19, 2022

Dr.-Ing. Tamas Harczos

## •• Introduction

- Two lectures, one seminar, one shared lecture about current topics (possible thesis projects).
- Useful links:
  - <https://hearingsystems.github.io/> (presentation slides and recordings),
  - <https://moodle2.tu-ilmenau.de/course/view.php?id=1373>.
- 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 in the field of “human hearing”.

## •• Introduction

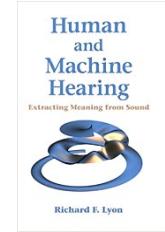
- audifon:
  - audifon GmbH & Co. KG develops, produces and sells hearing systems
  - Headquarter located in Kölleda, Thüringen (also place of production)
  - R&D offices in Köln and Ilmenau (System / Embedded SW Engineering)
  - About 200 employees
- myself:
  - First home computer generation (1980s)
  - 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
- *Human and Machine Hearing* (Richard F. Lyon), ISBN: 978-1-1070-0753-6, see [draft online](#)
- *Auditory Prostheses: New Horizons* (Zeng, Popper, Fay, eds.), ISBN: 978-1-4419-9434-9



- 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?

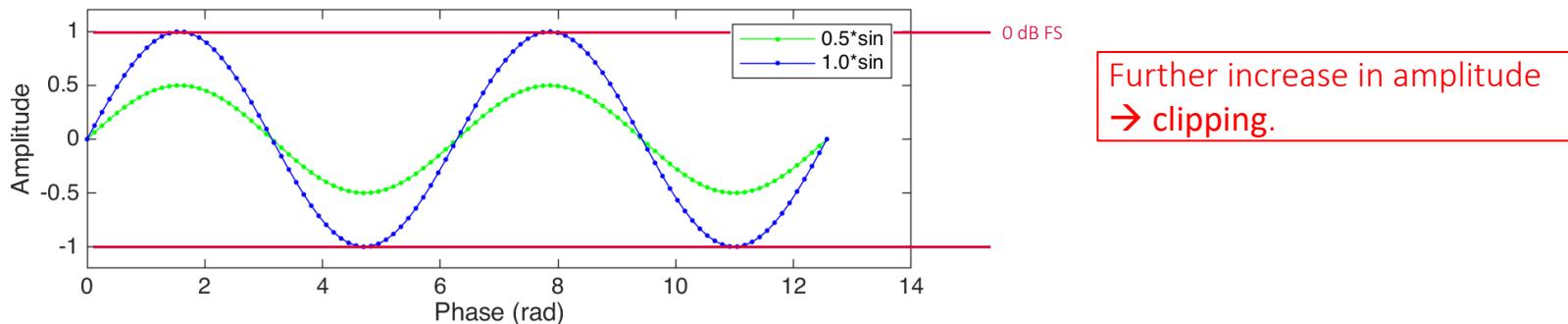
- Face-off



Source: [ec.europa.eu](https://ec.europa.eu), 2022.

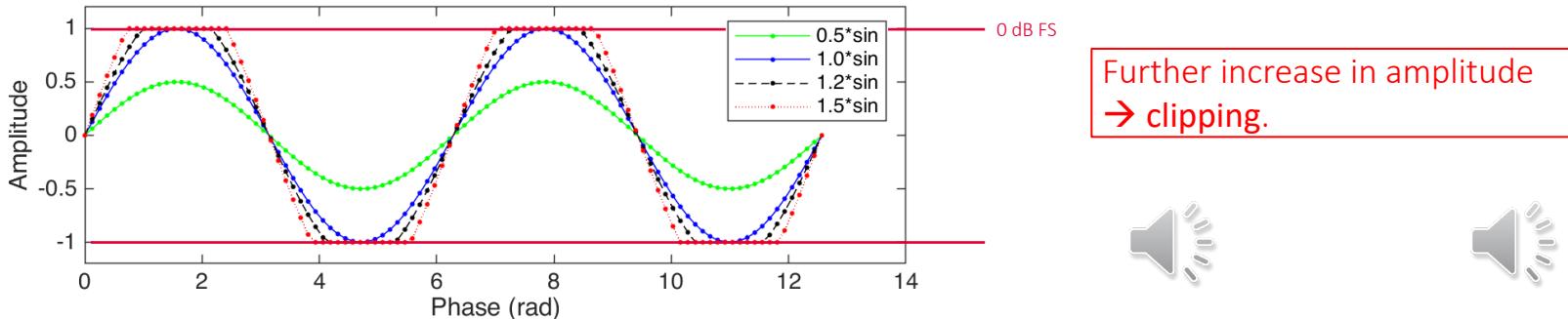
## •• Scales and units in audio signal processing

- First of all: Decibel (dB) alone is not a unit, it's a non-linear scale. It describes a relationship between two levels.
- Definition for (sound) amplitudes:  $A_{\text{dB}} = 20 \log_{10} (\text{AmplitudeRatio})$ , meaning:
  - if  $\text{AmplitudeRatio} = A_1/A_2 = 1/100 \rightarrow 20 \log_{10}(1/100) = -40 \text{ dB}$ ,
  - if  $\text{AmplitudeRatio} = A_1/A_2 = 1/10 \rightarrow 20 \log_{10}(1/10) = -20 \text{ dB}$ ,
  - 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.



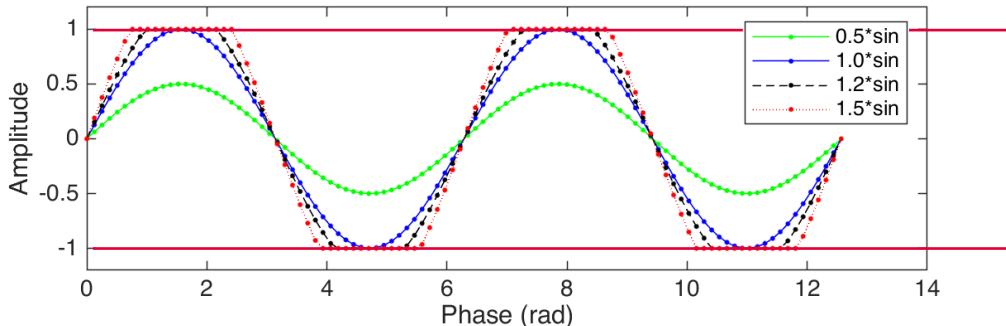
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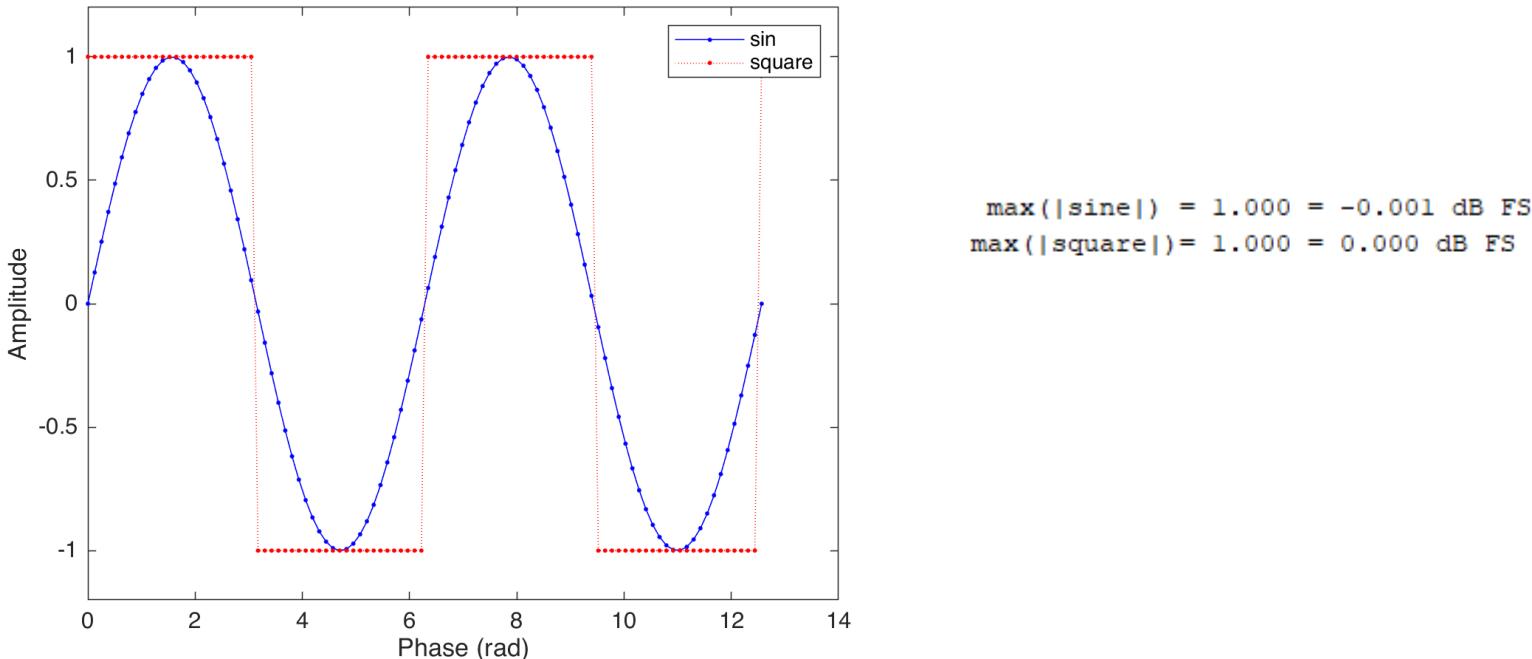


Further increase in amplitude  
→ clipping.

**Conversion:**  
 $dB = 20 \log_{10} (\text{mag}) \leftrightarrow \text{mag} = 10^{(dB/20)}$

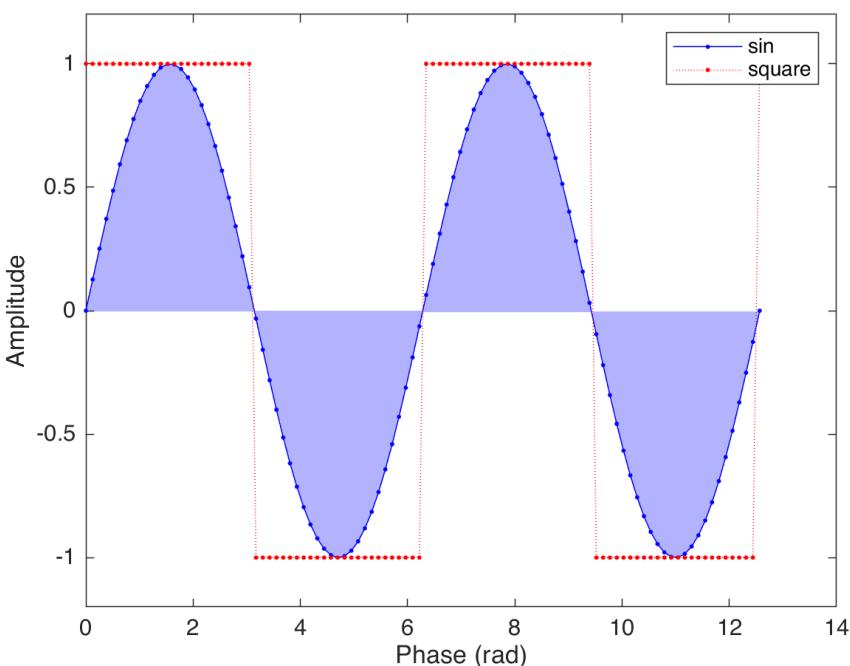
## •• Scales and units in audio signal processing: dB FS

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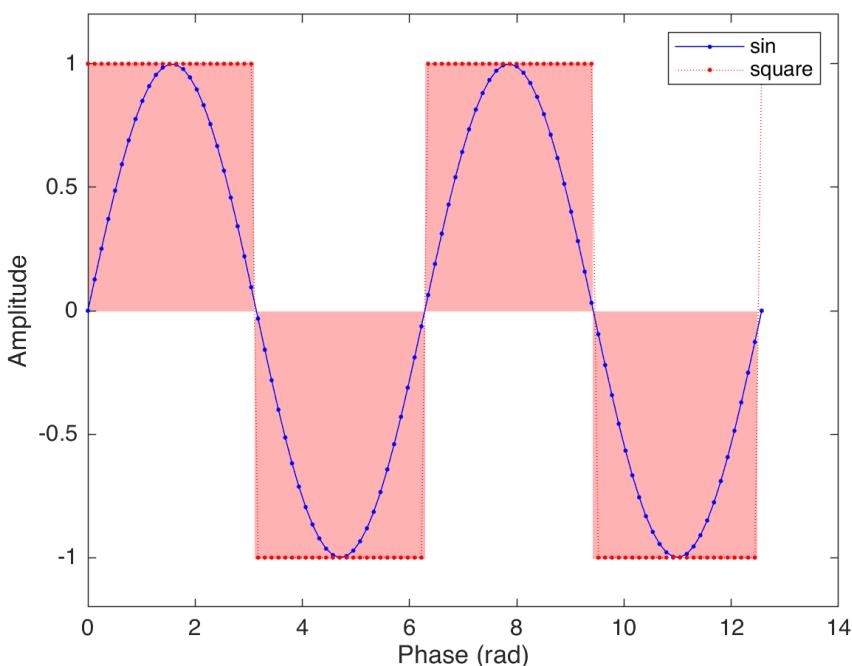
$$RMS = \sqrt{\frac{1}{N} \sum_{n=1}^N x_n^2}$$

`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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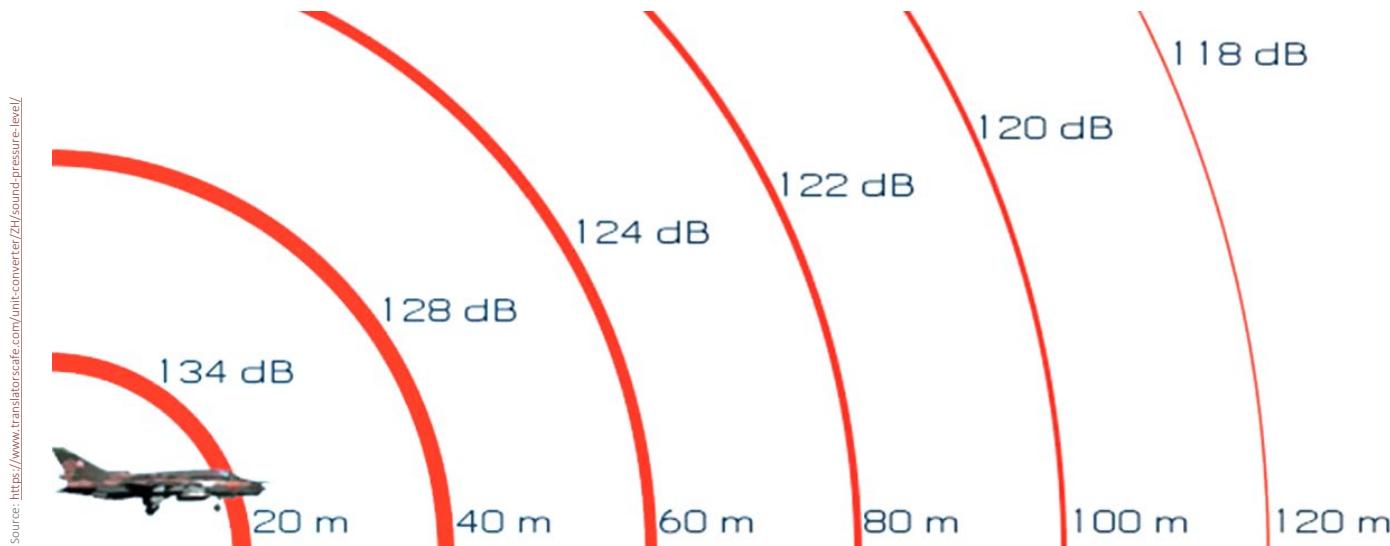
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`RMS (sine) = 0.704 = -3.054 dB FS (RMS)`  
`RMS (square) = 1.000 = 0.000 dB FS (RMS)`

## •• Scales and units in audio signal processing

- 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).

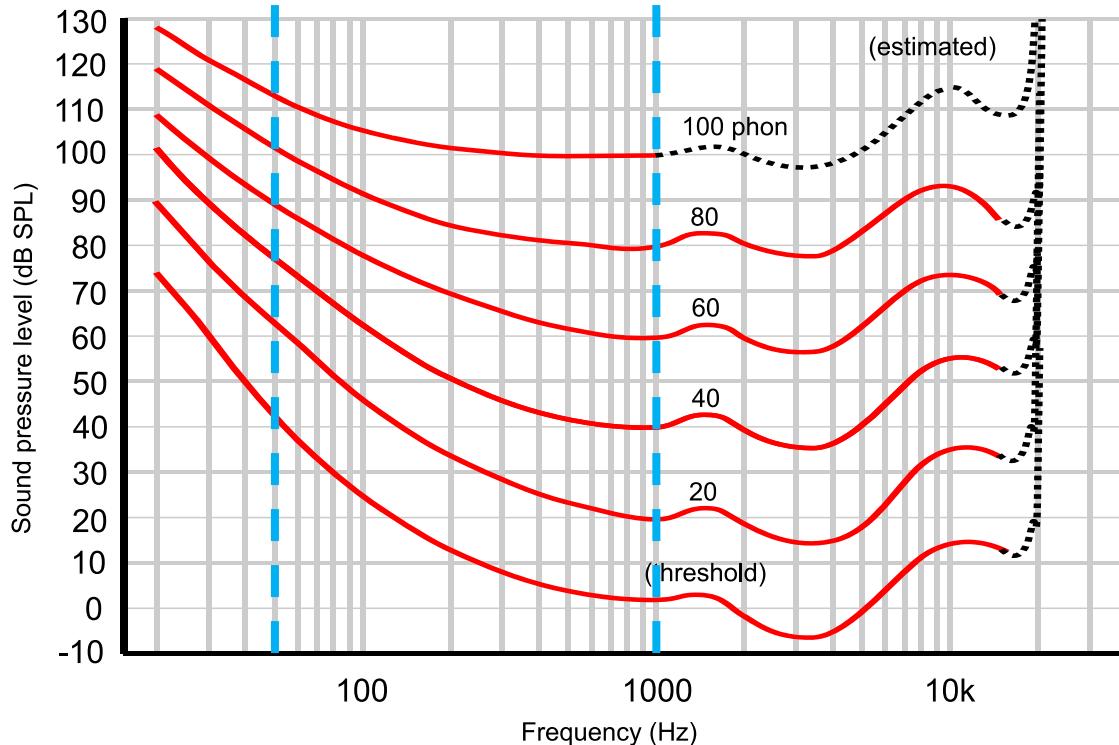


Source: <https://www.translatorscafe.com/unit-converter/ZH/sound-pressure-level/>

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  - Distance (source to receiver) is important, 1 m is frequently used as standard distance.
  - Doubling the distance halves the SPL (in free field).
  - 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, >85 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 variation an undistorted sound wave can have in Earth's atmosphere.

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

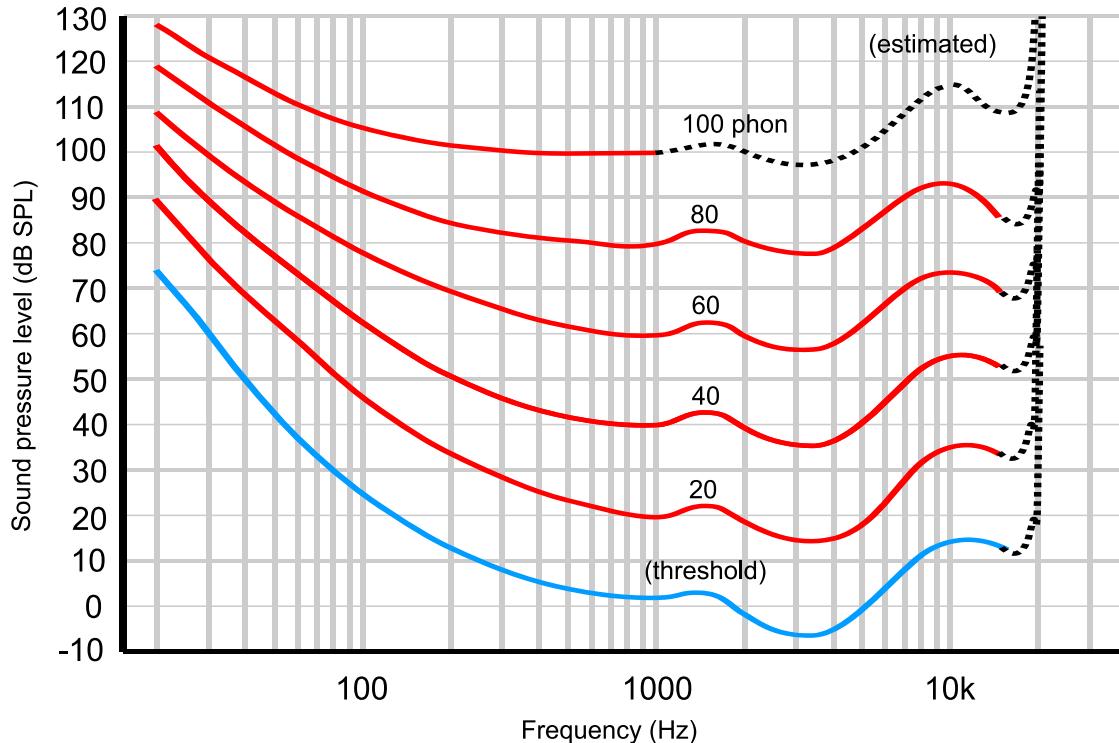


- 1933: Fletcher & Munson (*JASA*)
- 1956: Robinson & Dadson (*BJAP*)
- 2003: Multisite study, averaged over many normal hearing (NH) listeners → ISO 226:2003
- At 1000 Hz: dB SPL ≈ loudness.
- At other frequencies, e.g. at 50 Hz (mainly at higher levels) not.

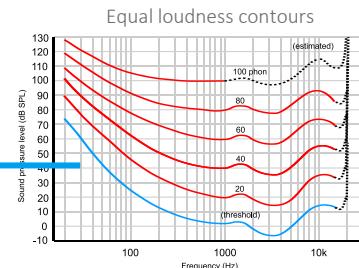
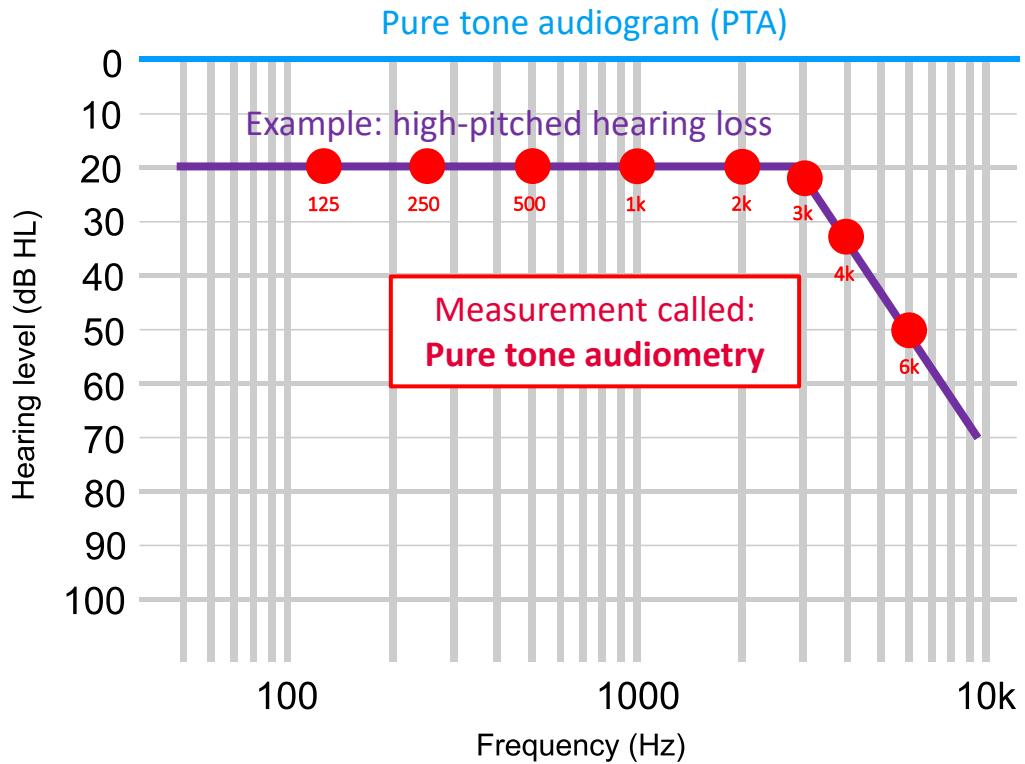
Loudness perception is  
**frequency dependent**  
and **non-linear**.

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

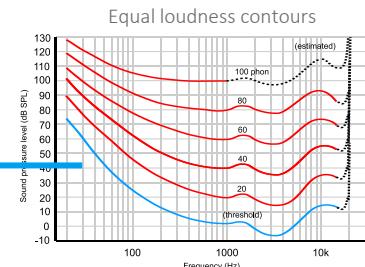
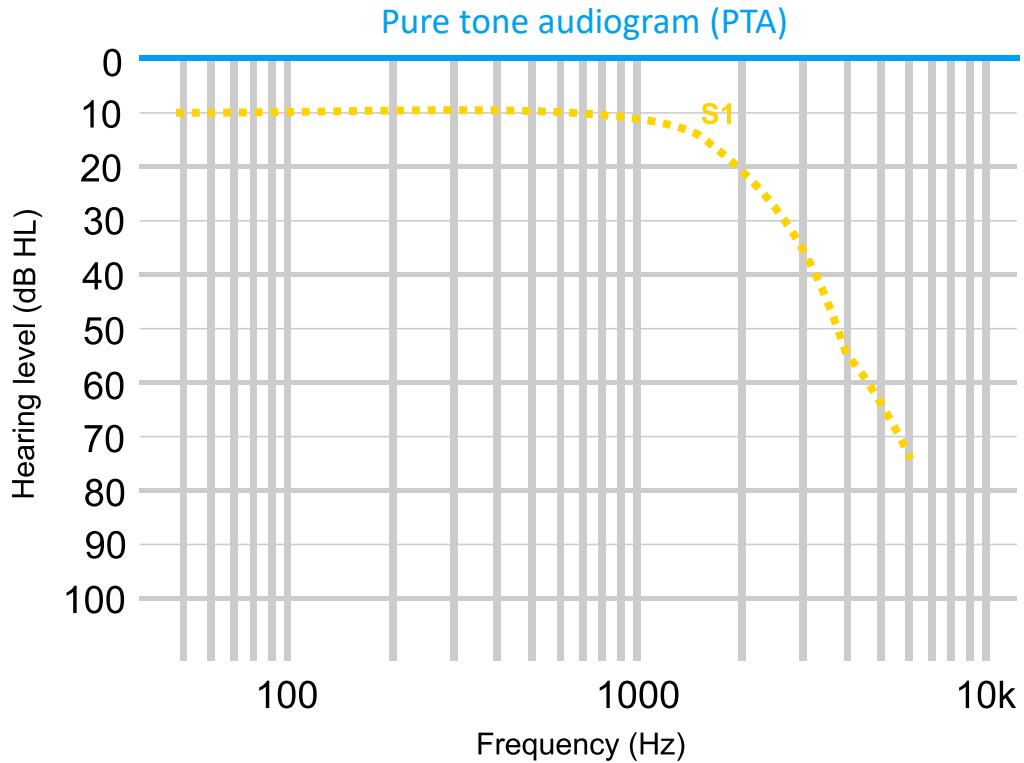
Equal loudness contours



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



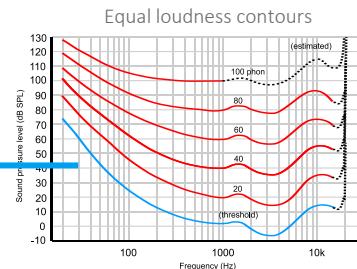
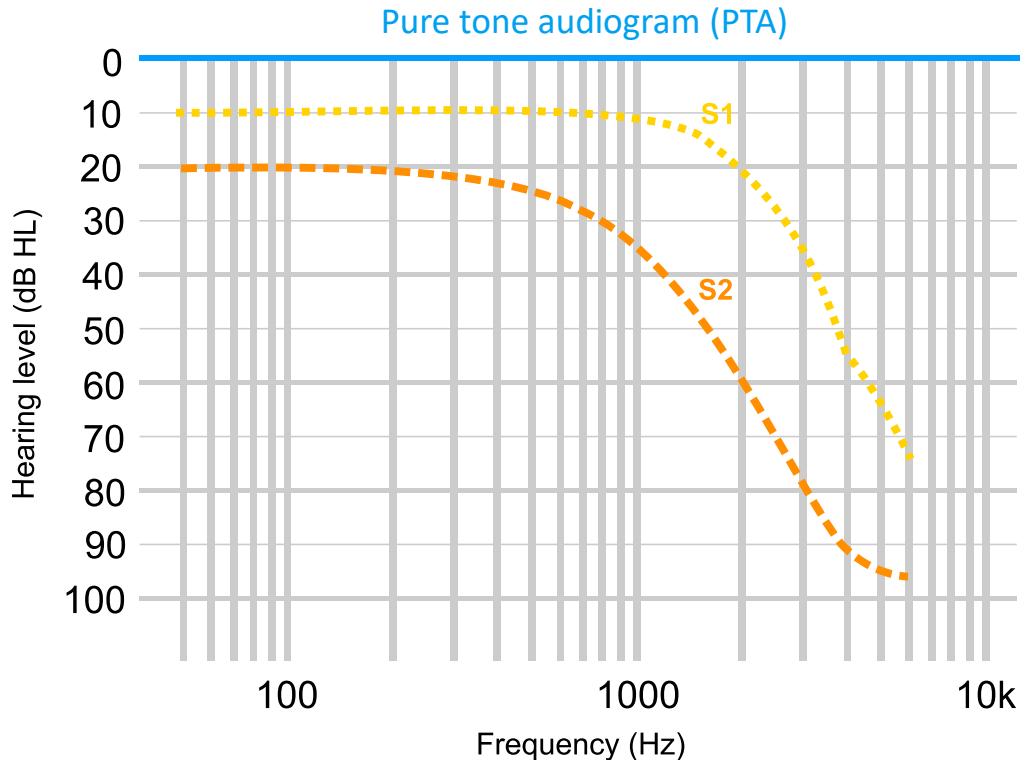
## •• Scales and units in audio signal processing: dB HL



Bisgaard standard audiograms:

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

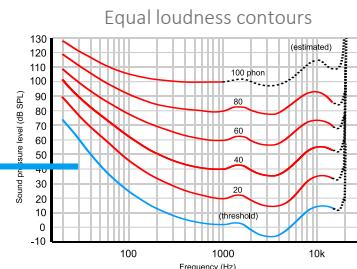
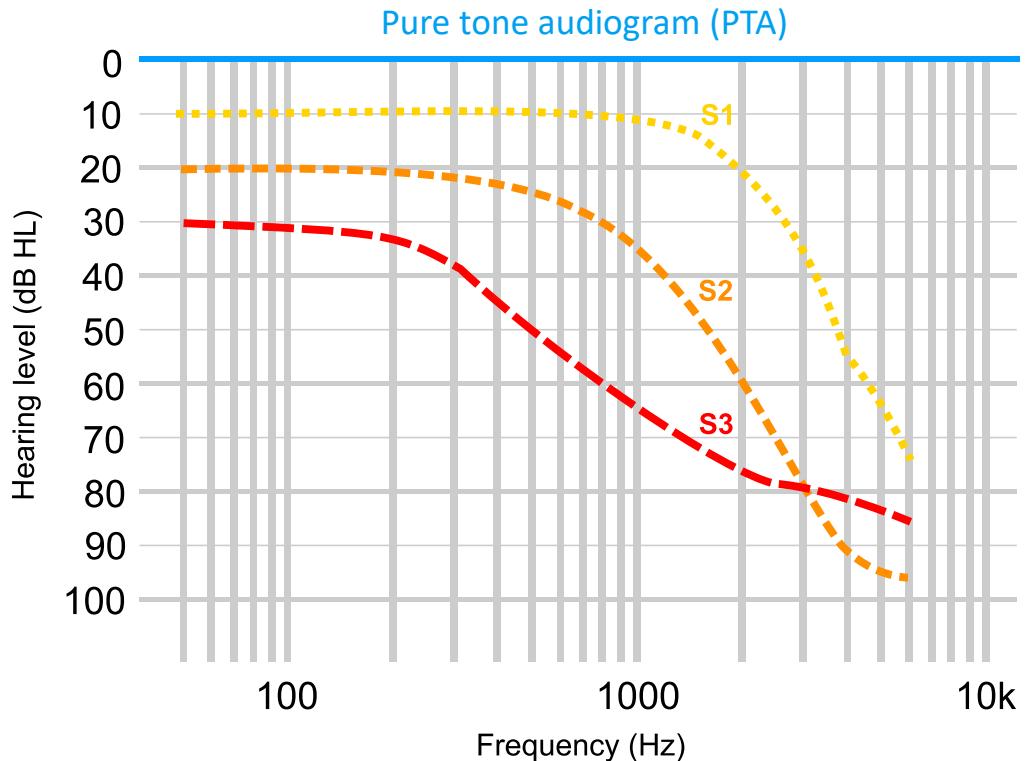
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Bisgaard standard audiograms:

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

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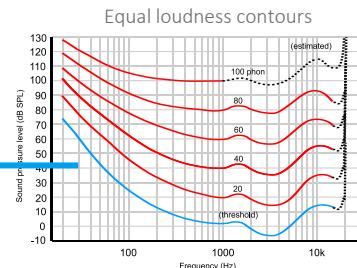
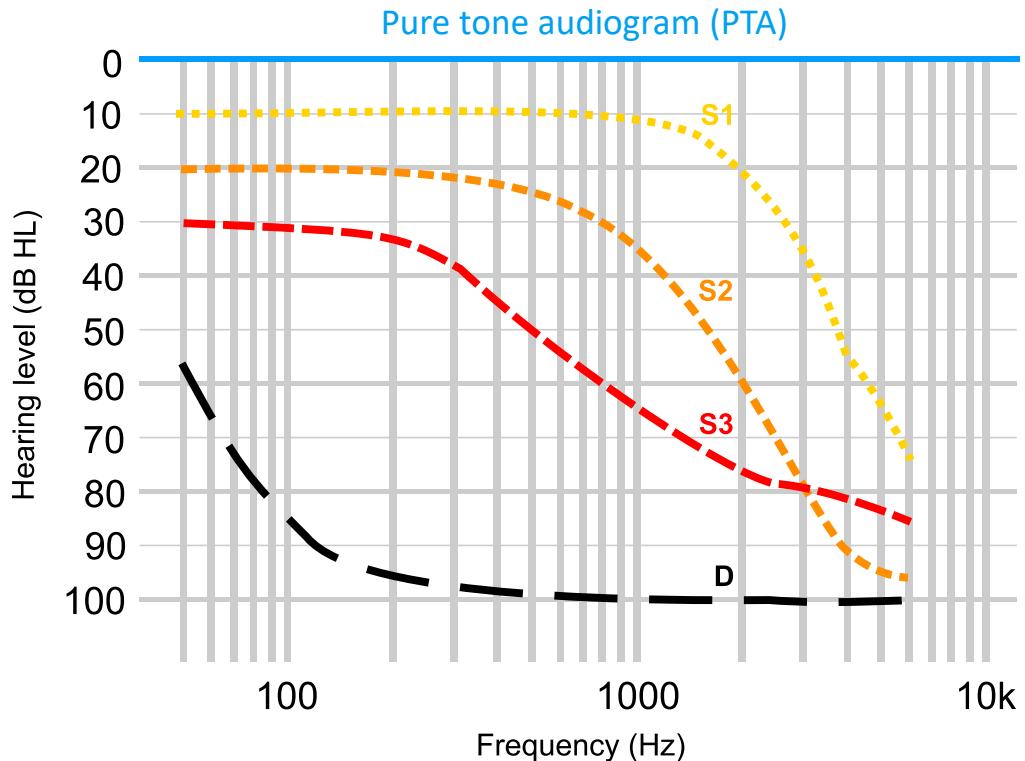


Bisgaard standard audiograms:

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

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

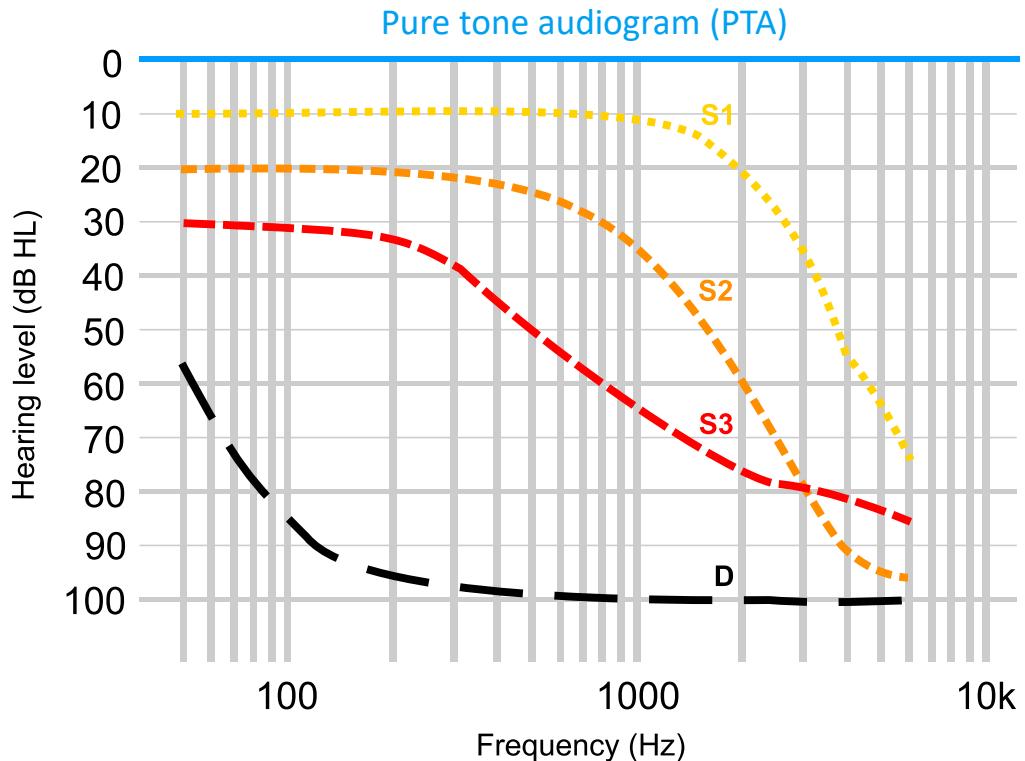
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Bisgaard standard audiograms:

- S1: very mild (*degree of hearing loss*)
  - S2: mild
  - S3: severe
- Source: [Bisgaard et al. \(2010\)](#)
- D: hearing loss bordering on deafness

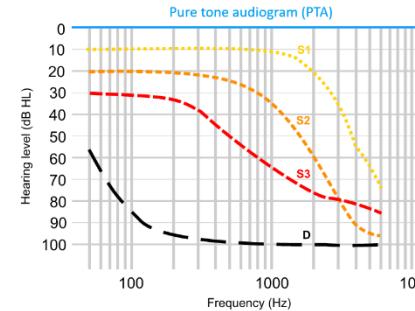
## •• Hearing and hearing impairments



## •• Hearing and hearing impairments

Questions:

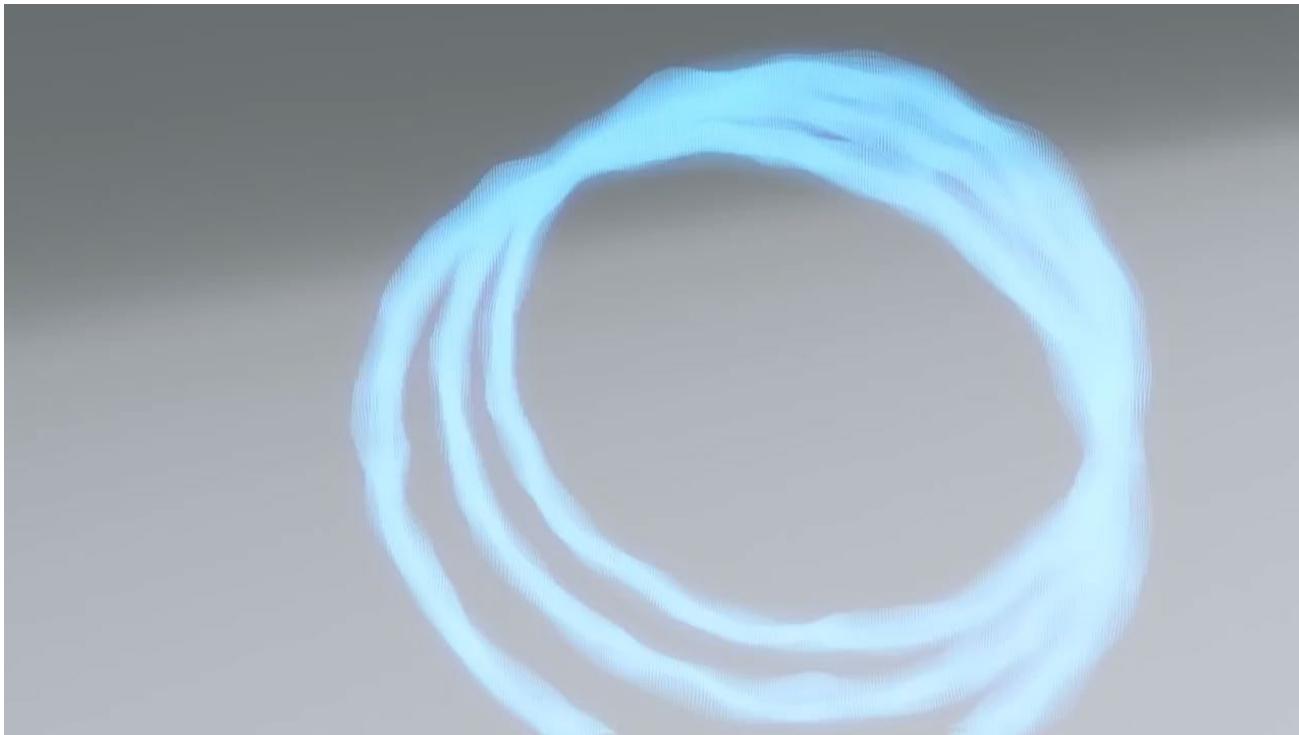
- How many are affected?
  - [WHO 2021](#): worldwide ca. 466M people with disabling hearing loss.
- How bad is impaired hearing?
  - It is bad, especially in background noise. Try for yourself → see **slide 4**: hearing loss simulators.
- What are the causes of the impairments?
  - Genetic causes, complications 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 2021](#): currently only 17% of those who could benefit from use of a hearing aid actually use one);
  - sign language and social support.



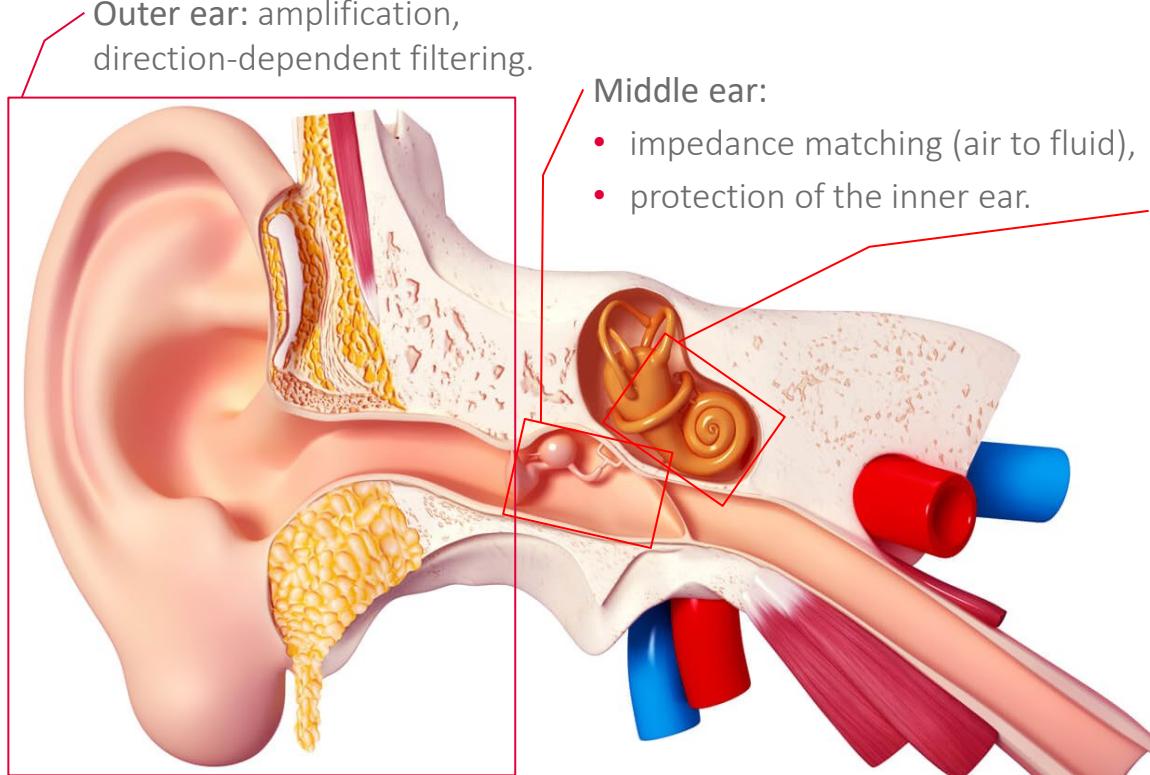
## •• Short recap

- 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



## •• Overview



Outer ear: amplification,  
direction-dependent filtering.

Middle ear:

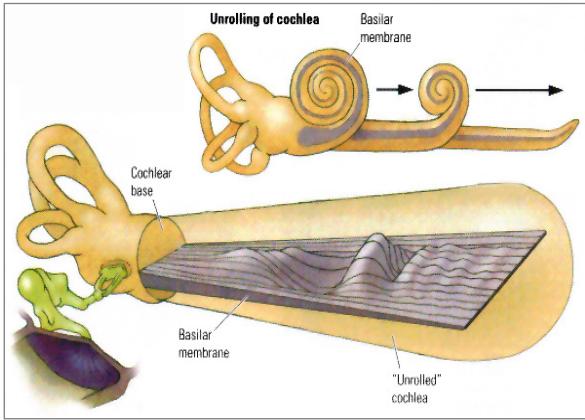
- impedance matching (air to fluid),
- protection of the inner ear.

Inner ear:

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

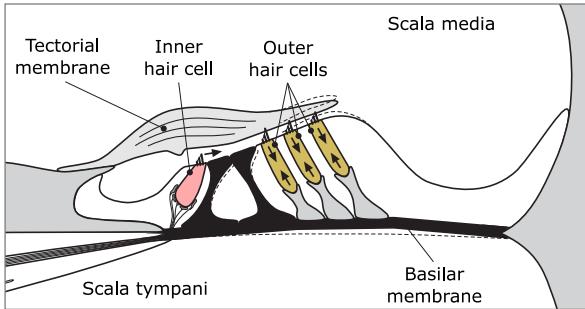
## •• How hearing works

Unrolled cochlea



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

Organ of Corti



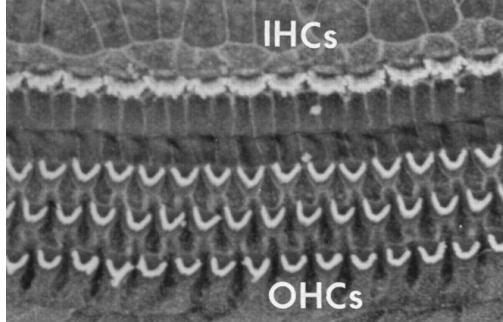
Adapted from: Baumgartner, 2000

Cochlear cross-section



Source: [www.meniett.com](http://www.meniett.com)

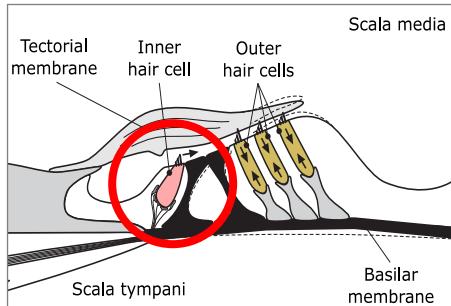
Hair cell rows



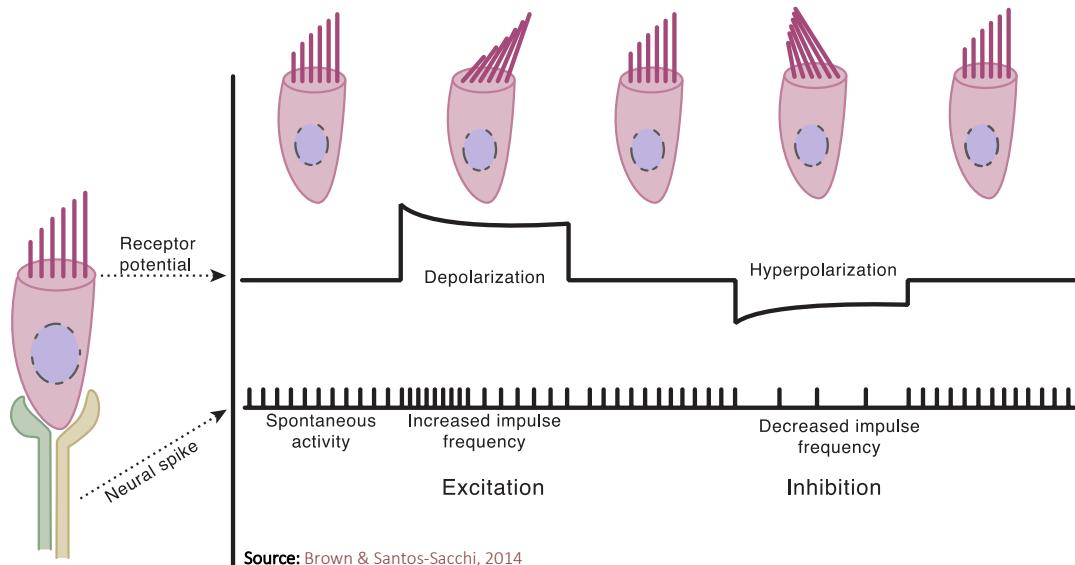
Source: Ryan, 2000

## •• How hearing works: Inner hair cells

Organ of Corti



Adapted from: [Baumgarte, 2000](#)

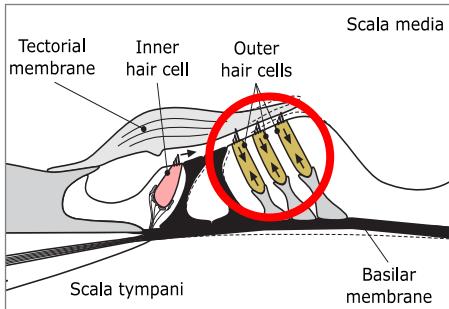


### Inner hair cells:

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

## •• How hearing works: Outer hair cells

Organ of Corti



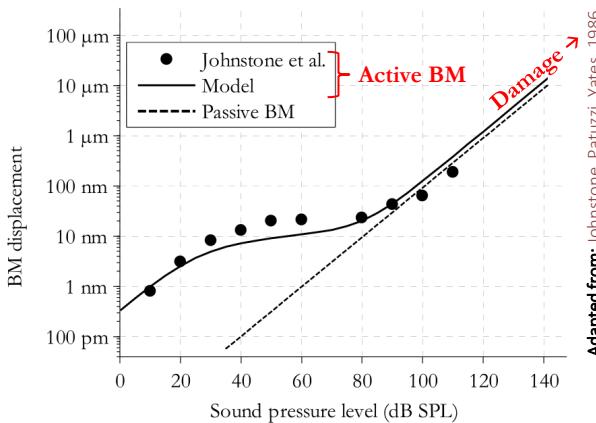
Adapted from: Baumgarte, 2000

OHC motility



Source: J. Ashmore for BBC 'Ear we go', 1987

BM nonlinearity



Adapted from: Johnstone, Patuzzi, Yates, 1986

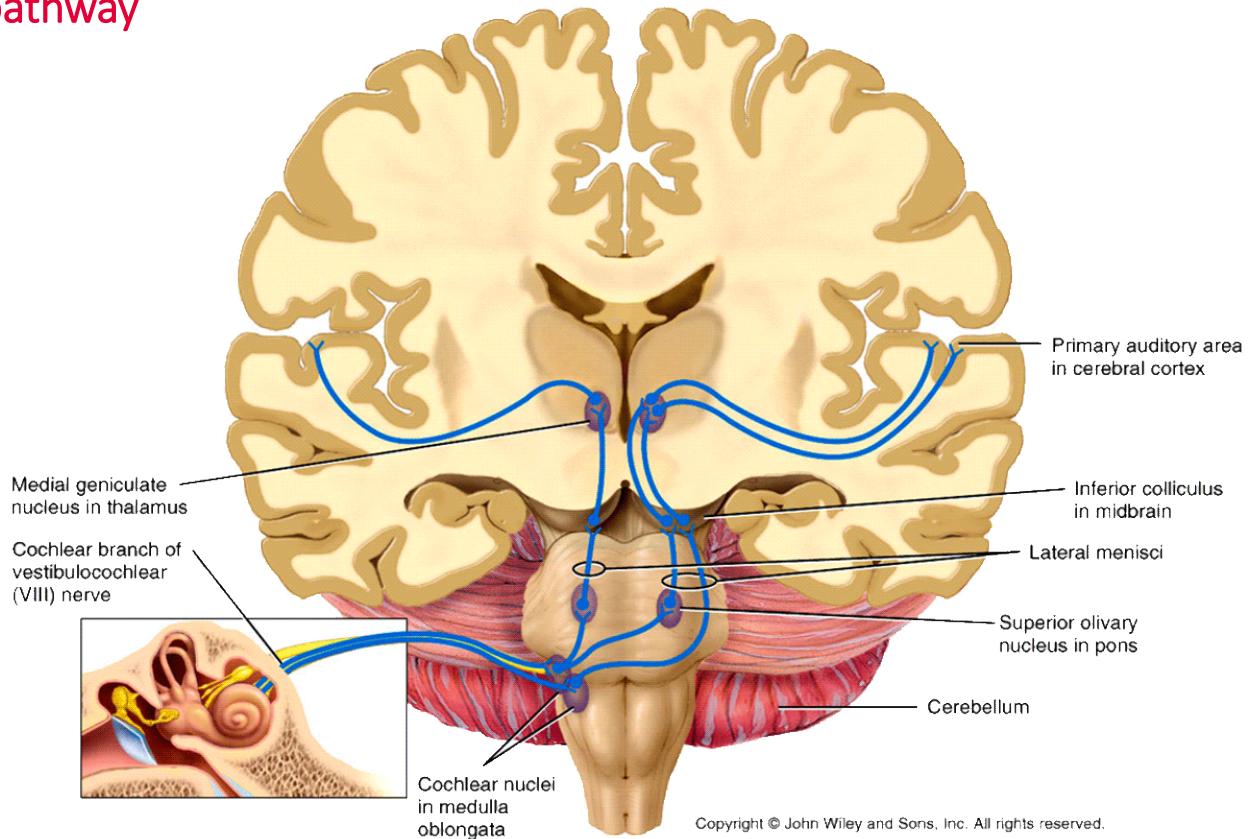
### Outer hair cells (OHCs):

- 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



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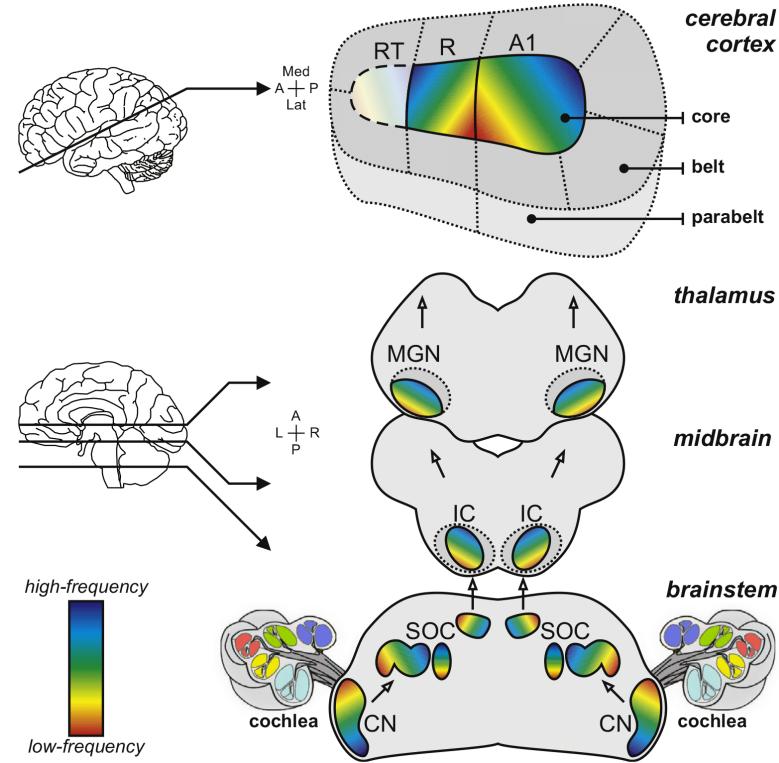
Source: [Tortora & Derrickson: Principles of Anatomy and Physiology, 2016](#)

## •• Tonotopy



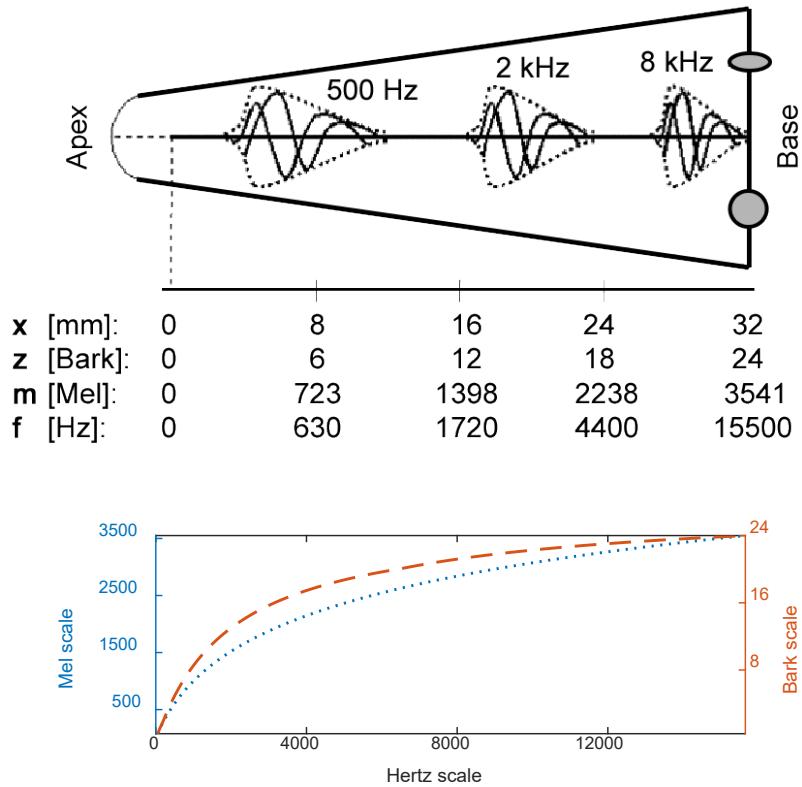
Source: [HHMI, 2000](#).

**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 :

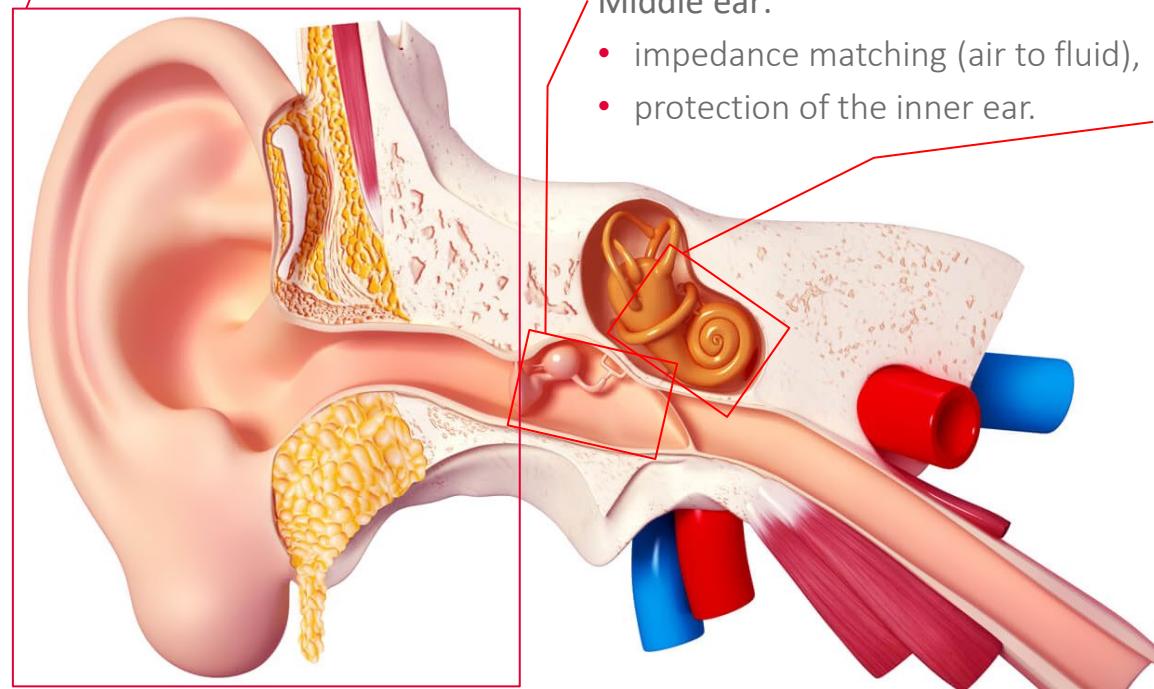
- The human basilar membrane (BM) is approx. 32-35 mm long. Along the BM ca. 3500 IHCs and 12000 OHCs are distributed.
- Regardless of whether we take Bark or Mel scale, it is important to remember that place pitch is not distributed linearly along the cochlea;
  - $210 \pm 10$  Hz we can discriminate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

## •• Short recap

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).

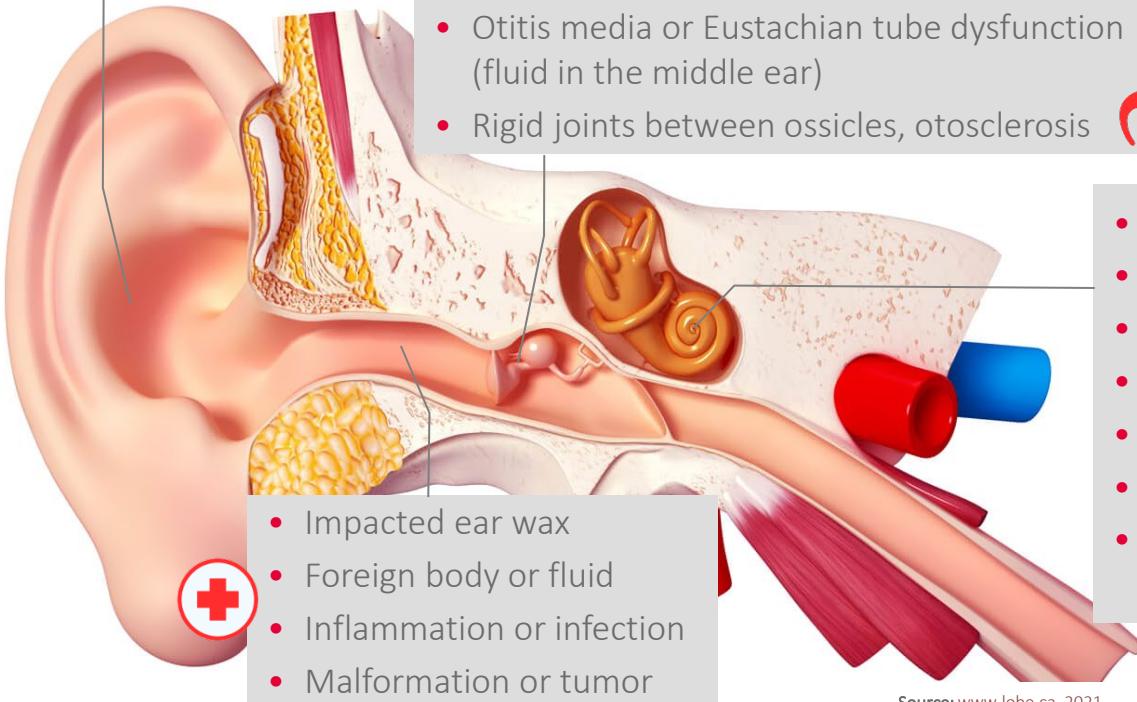
Properties:

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

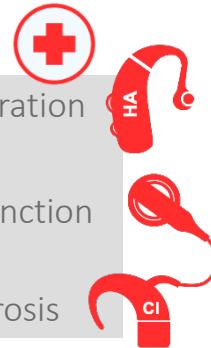
## •• Causes of hearing impairment



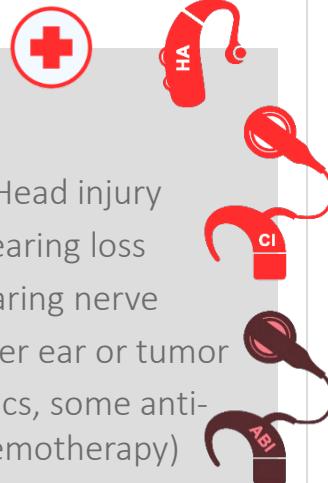
- Malformation
- Foreign body



- Eardrum scars / malformation / perforation
- Barotrauma (can be temporary)
- Otitis media or Eustachian tube dysfunction (fluid in the middle ear)
- Rigid joints between ossicles, otosclerosis



- Aging (presbycusis)
- Exposure to loud noise
- Trauma / Barotrauma / Head injury
- Genetic or hereditary hearing loss
- Viral infection of the hearing nerve
- Malformation of the inner ear or tumor
- Ototoxic drugs (antibiotics, some anti-inflammatory drugs, chemotherapy)

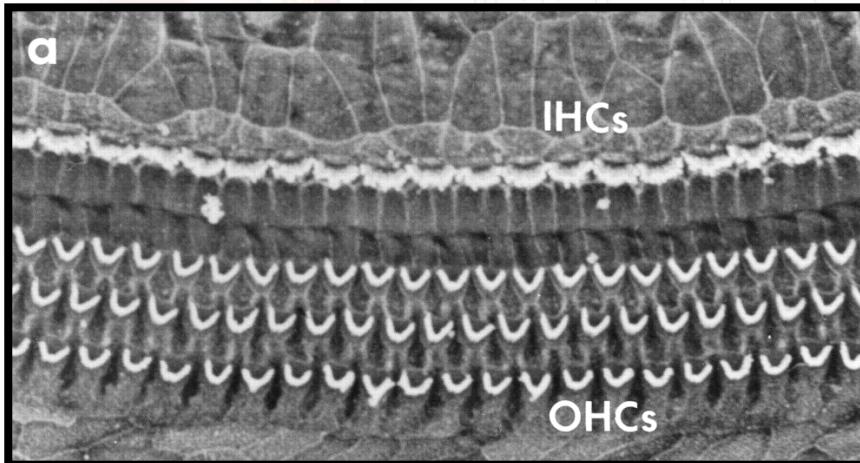


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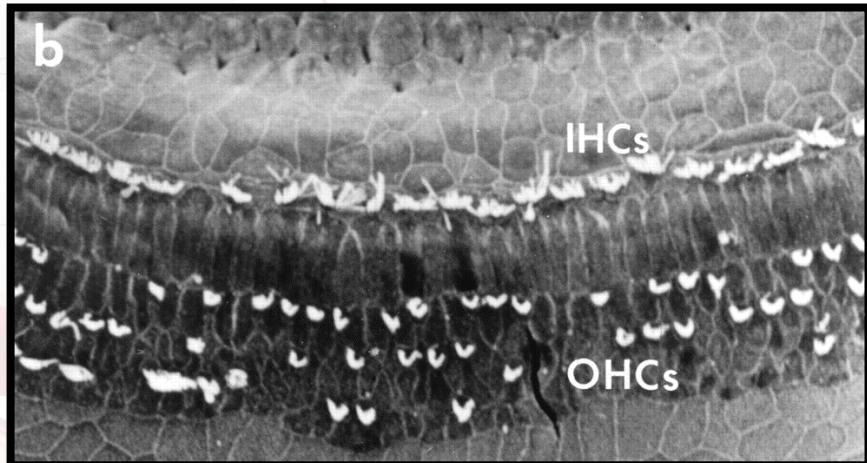
- Malformation
- Foreign body

- Eardrum scars / malformation / perforation
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- 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](http://www.lobe.ca), 2021

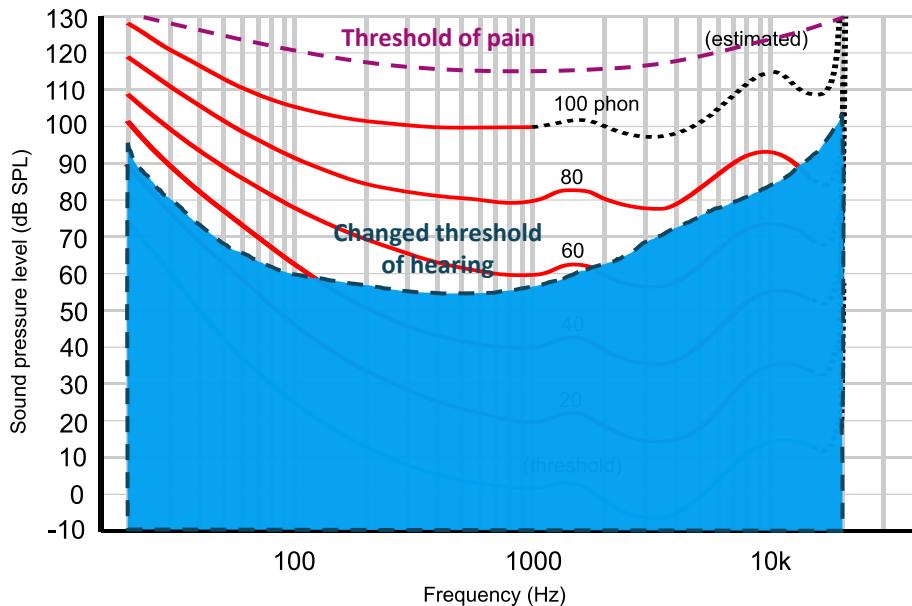
## •• Consequences of hearing impairment

- 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.

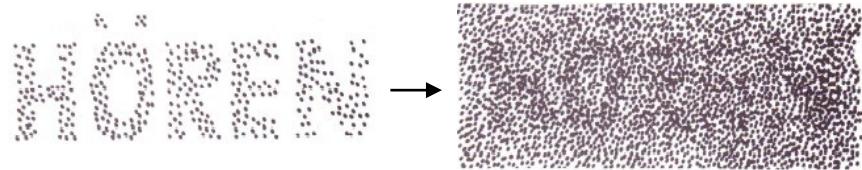
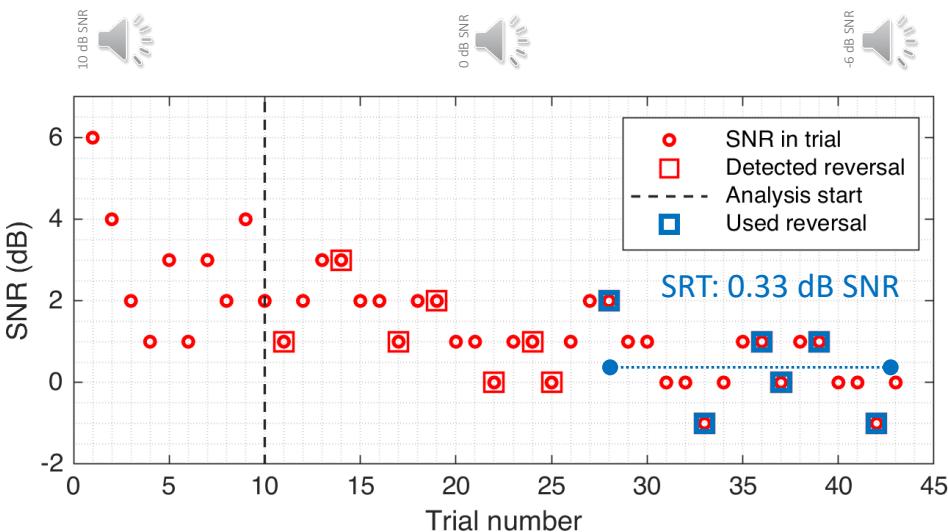


- In most cases, the amount of energy arriving at the IHCs is comparable to that of the NH (normal hearing) case.
- Threshold of pain is unchanged (and also the range of uncomfortably loud signals).
- But the dynamic range is narrower.
- In hearing assistive technology:
  - need to know the thresholds (**pure tone audiometry**),
  - 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 harder for the auditory system to distinguish signal from noise.
- Hearing assistive technologies may help with signal reduction algorithms.

## •• Hearing aids – Early history

Source: hearingaidmuseum.com, 2021

Ear trumpets



Vactuphone  
(1<sup>st</sup> vacuum-tube HA)



Behind-the-ear  
hearing aids



Widex Senso  
full digital BTE HA



17<sup>th</sup> century

1902

1921

1952

1956-57

1980s

1995



Hutchison's Acousticon  
(1<sup>st</sup> electrical HA)



Sonotone Model 1010  
(1<sup>st</sup> transistor HA)



Nicolet Phoenix  
(programmable digital HA)

## •• Hearing aids – Modern form factors



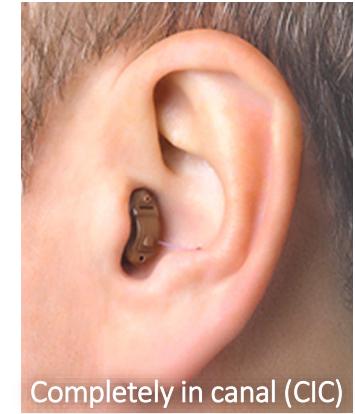
Behind the ear (BTE)



Receiver in canal (RIC)



In the canal (ITC)



Completely in canal (CIC)



- + 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.

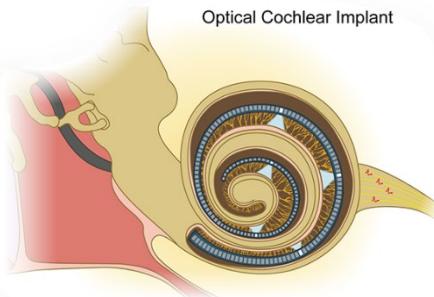
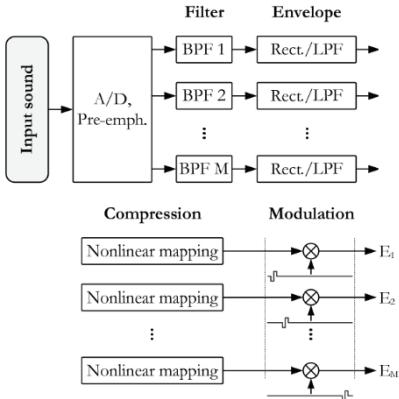
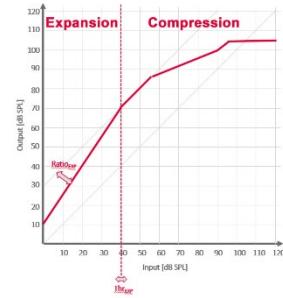
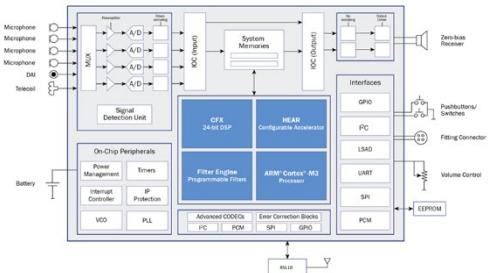
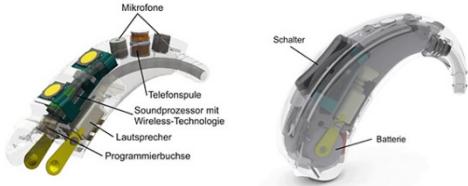


Audiological features:

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



## •• Next week





Thank you very much!  
Questions?

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