audifon hearing systems

Hearing Systems – Part 1

https://hearingsystems.github.io/

TU Ilmenau – Audio Systems Technology

(Online) | Januar 19, 2022

Dr.-Ing. Tamas Harczos

audifon hearing systems

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”.

audifon
hearing systems

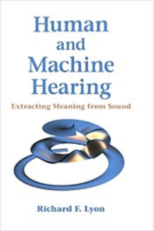
•• Introduction

- 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)

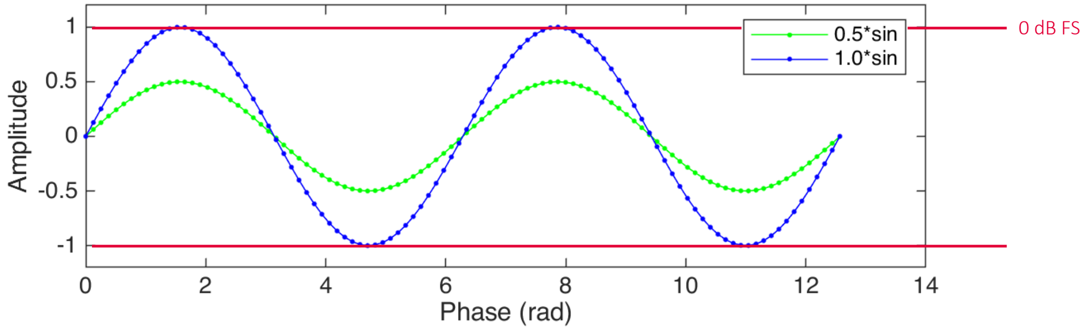
•• Ready?

- Face-off

Source: ec.europa.eu, 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: $A_{dB} = 20 \log_{10} (AmplitudeRatio)$, meaning:
  - if AmplitudeRatio = A1/A2 = **1/100** → $20 \log_{10}(1/100) =$ **-40 dB**,
  - if AmplitudeRatio = A1/A2 = **1/10** → $20 \log_{10}(1/10) =$ **-20 dB**,
  - if AmplitudeRatio = A1/A2 = **1/2** → $20 \log_{10}(1/2) =$ -6.02 dB ≈ **-6 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) → 0 dB FS means |signal| values approach 1.



Further increase in amplitude
→ clipping.

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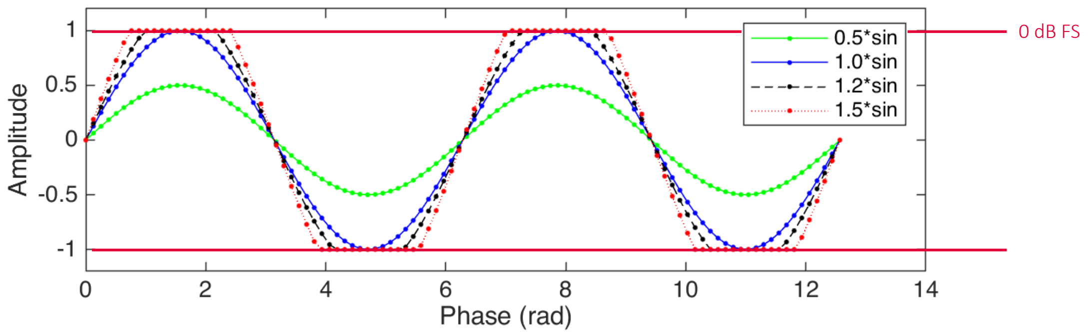

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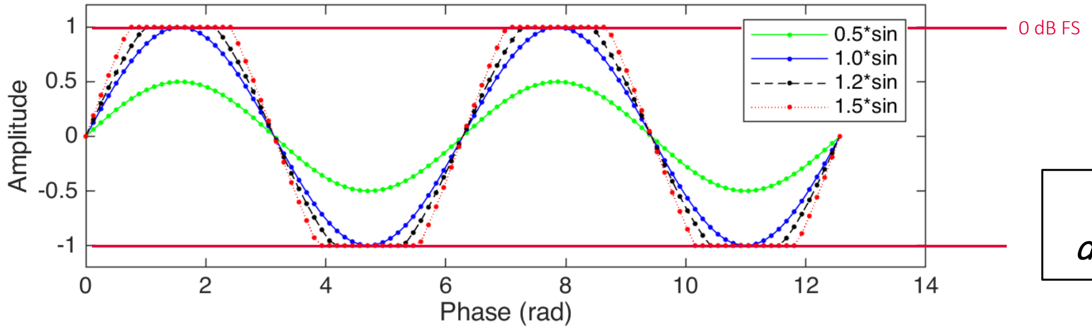


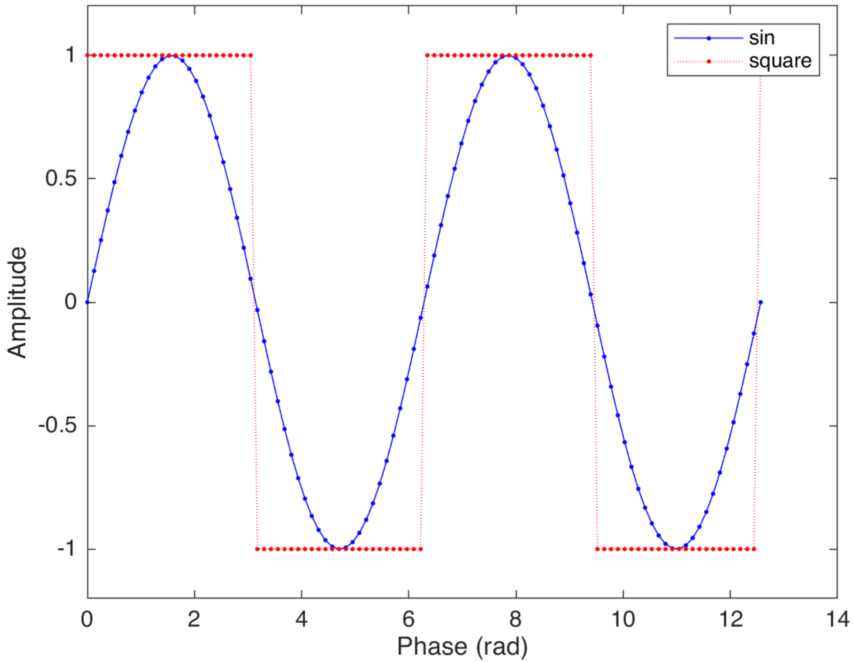
Further increase in amplitude
→ clipping.

Conversion:

$$dB = 20 \log_{10}(mag) \leftrightarrow mag = 10^{(dB/20)}$$

•• 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
```

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

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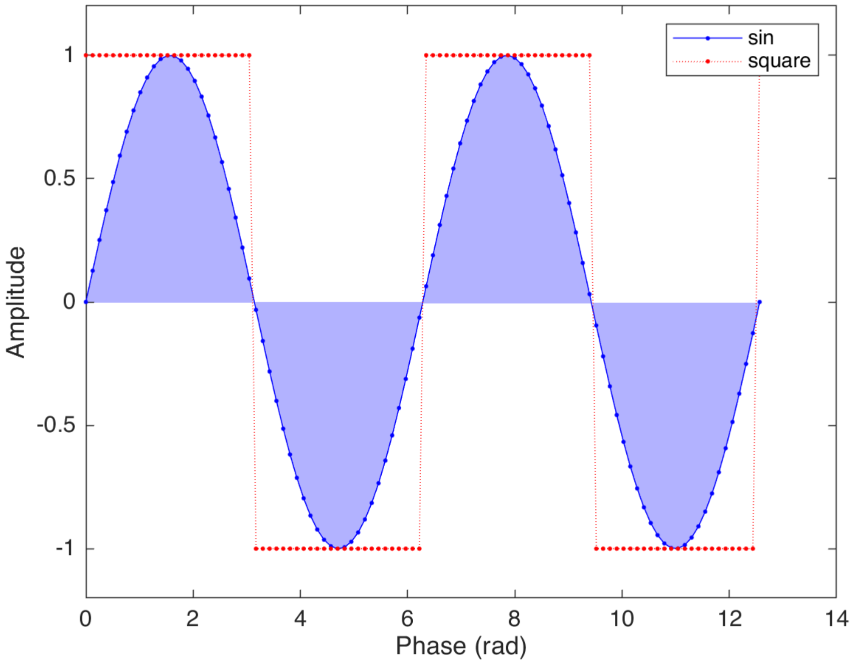

$$RMS = \sqrt{\frac{1}{N}\sum_{n=1}^{N} x_n^2}$$

```
 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
max(|square/2|)= 0.500 = -6.021 dB FS
```

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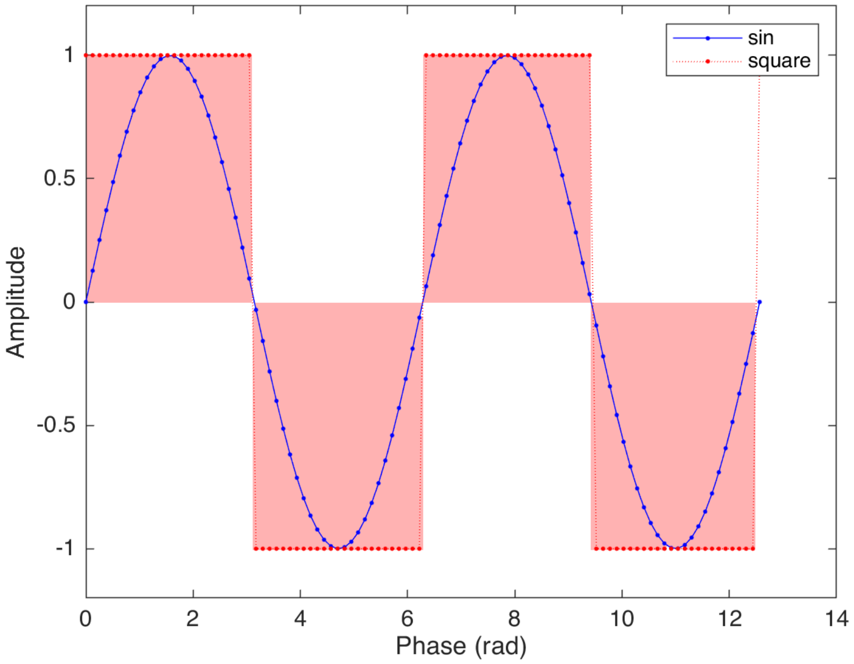

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 max(|sine/2|)  = 0.500 = -6.022 dB FS
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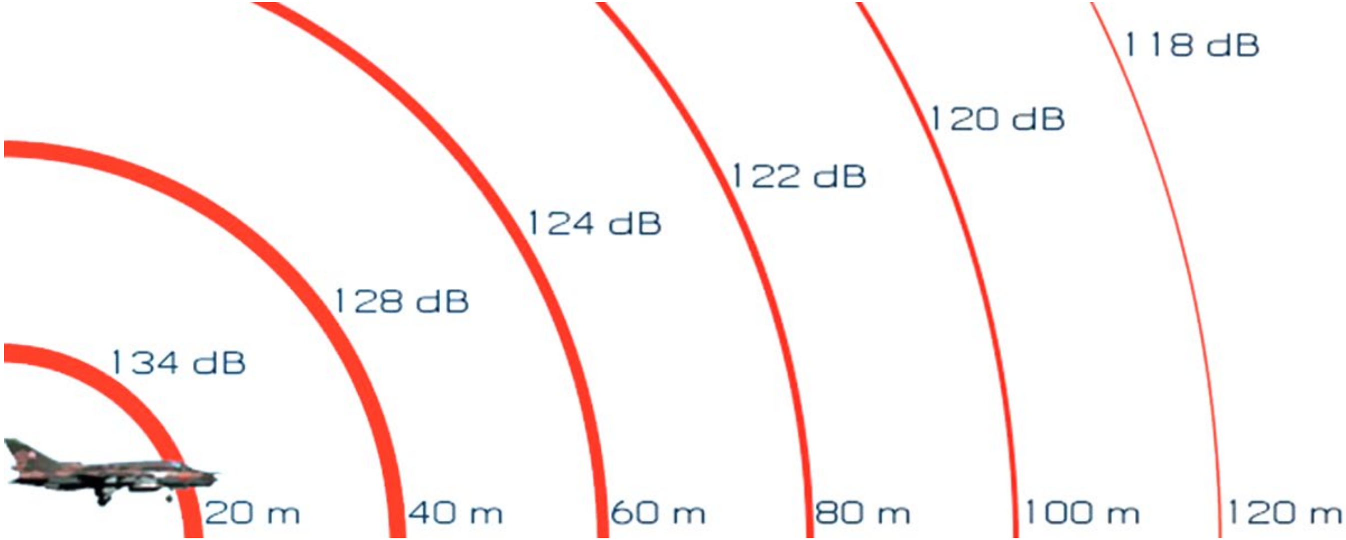
 RMS(sine)  = 0.704 = -3.054 dB FS (RMS)
RMS(square)= 1.000 = 0.000 dB FS (RMS)
```

•• 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, 1 m 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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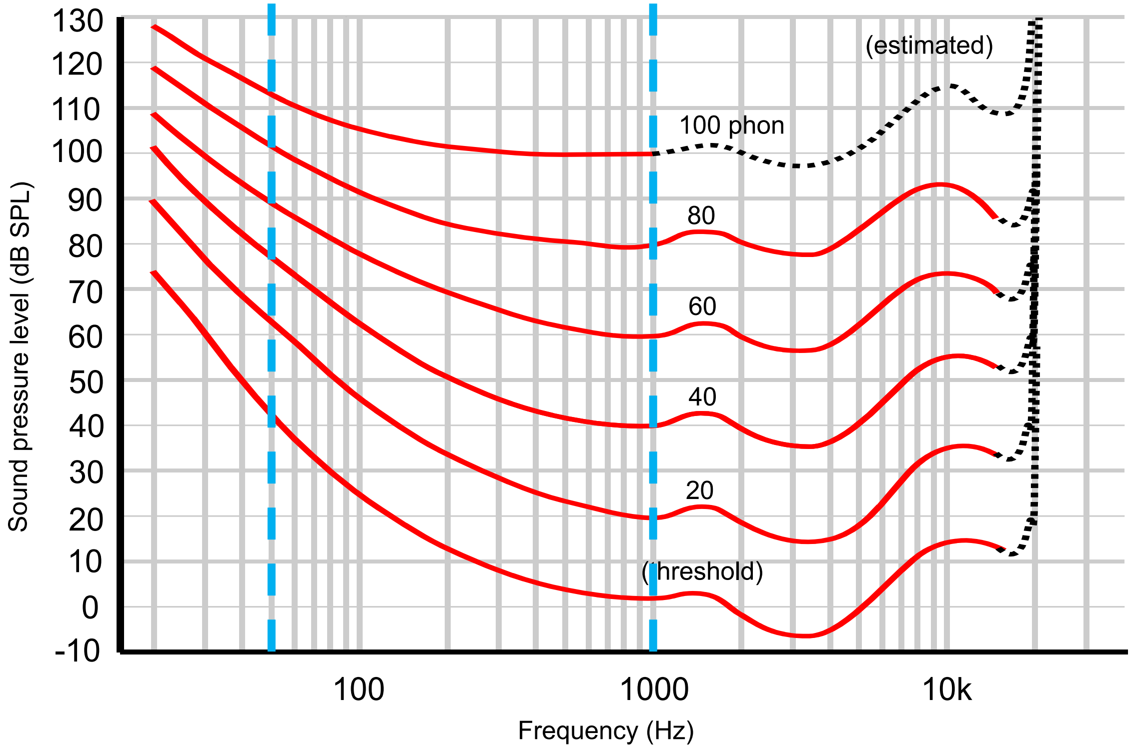
  - Distance (source to receiver) is important, 1 m is frequently used as standard distance.
  - Doubling the distance halves the SPL (in free field).
  - Typical ranges:
    - **20-30 dB SPL**: very calm room,
    - **40-60 dB SPL** (1 m): normal conversation,
    - **70-90 dB SPL** (10 m): nearby heavy 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

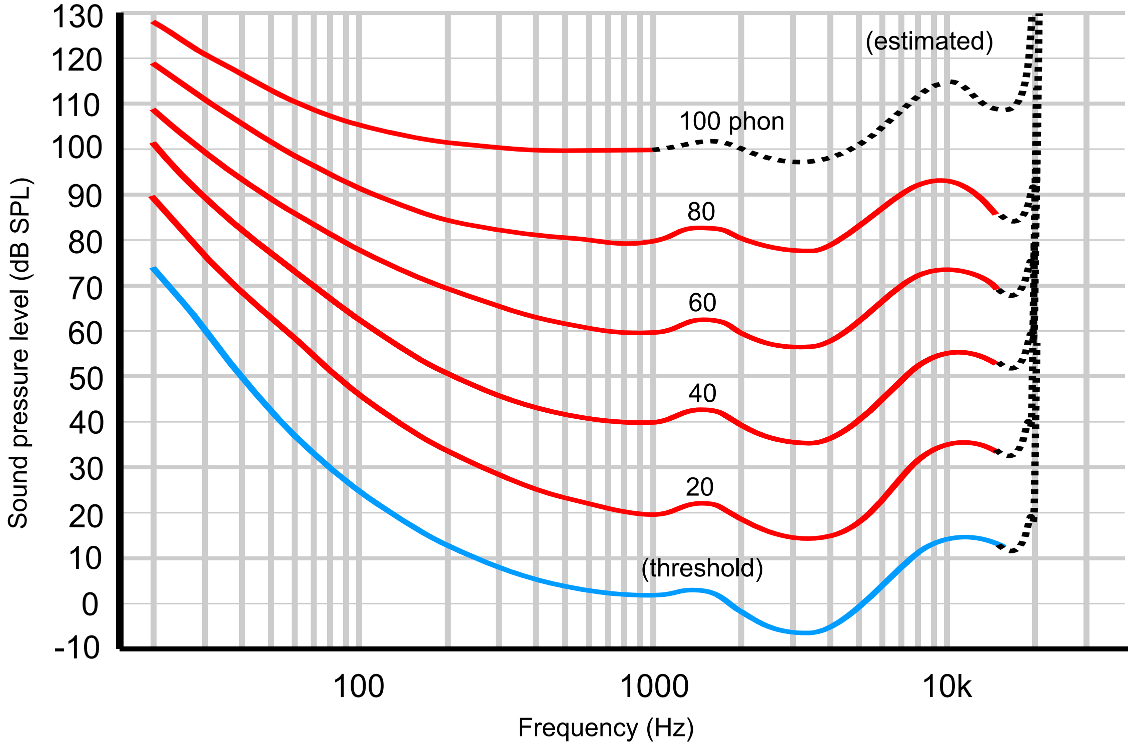


- 1933: Fletcher & Munson (*JASA*)
- 1956: Robinson & Dadson (*BJAP*)
- 2003: Multisite study, averaged over many normal hearing (NH) listeners → **ISO 226:2003**
- At 1000 Hz: dB SPL ≈ loudness.
- At other frequencies, e.g. at 50 Hz (mainly at higher levels) not.

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

Source: https://upload.wikimedia.org/wikipedia/commons/4/49/Lindos4.svg

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



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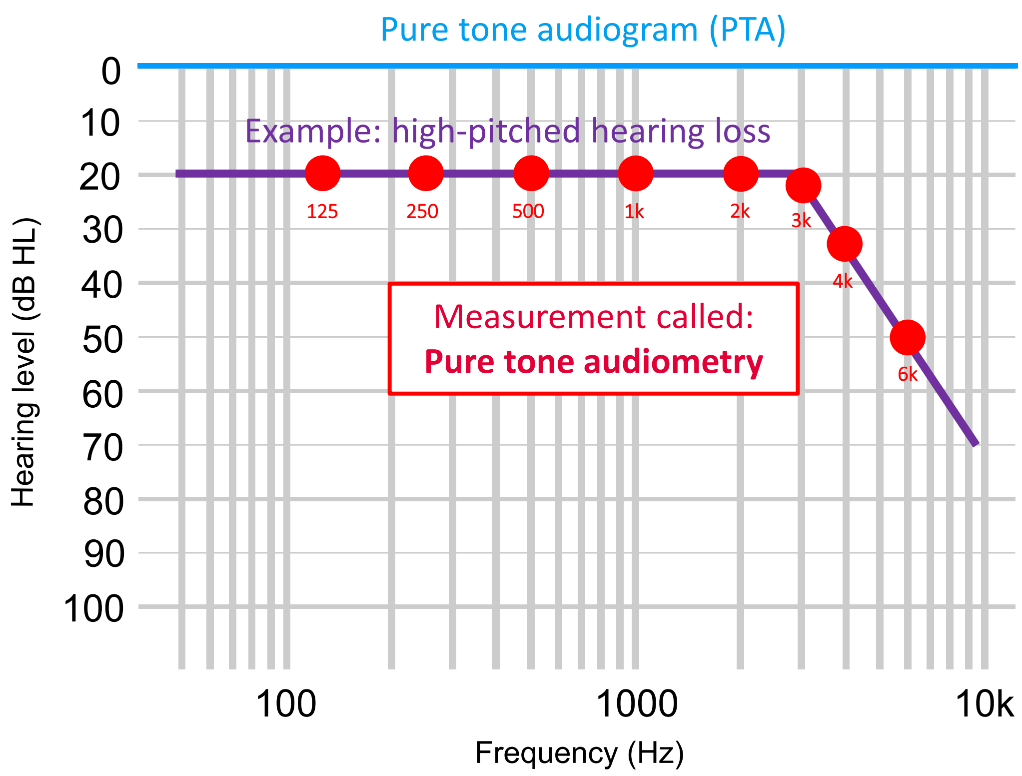
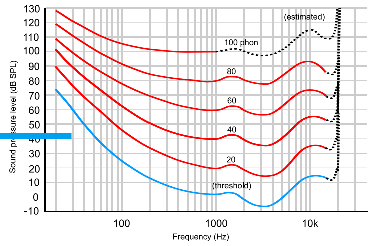


Equal loudness contours



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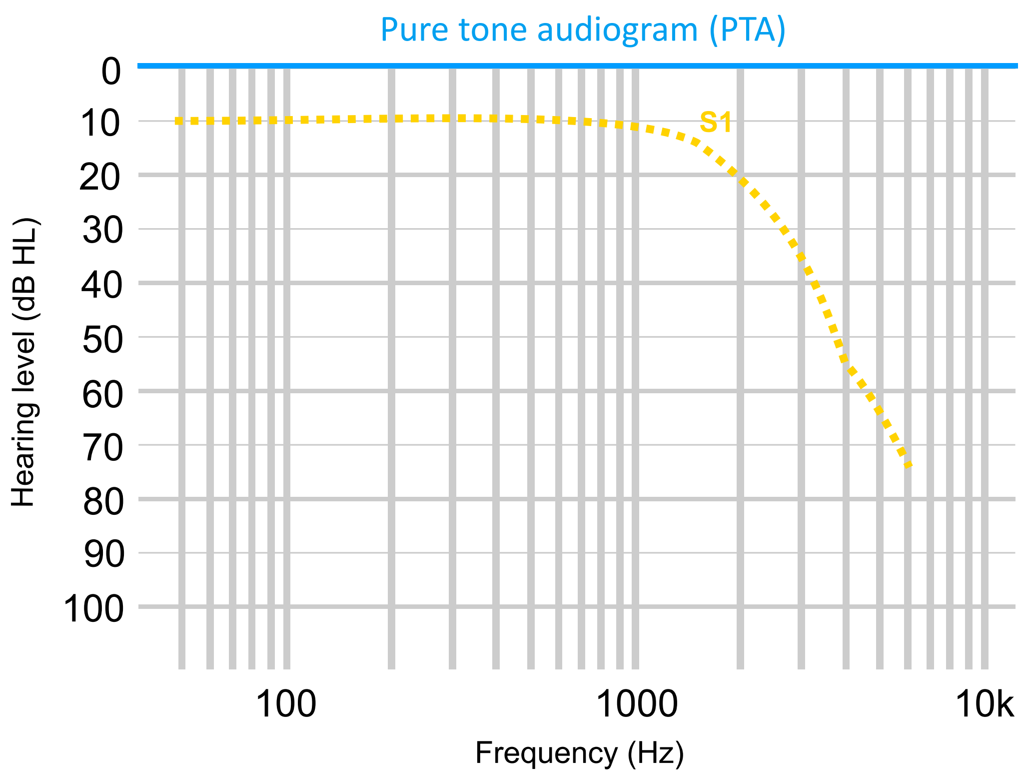
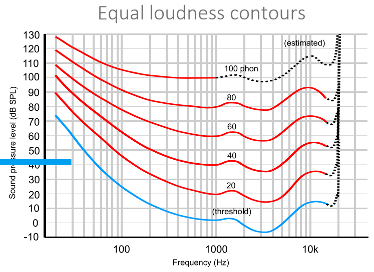
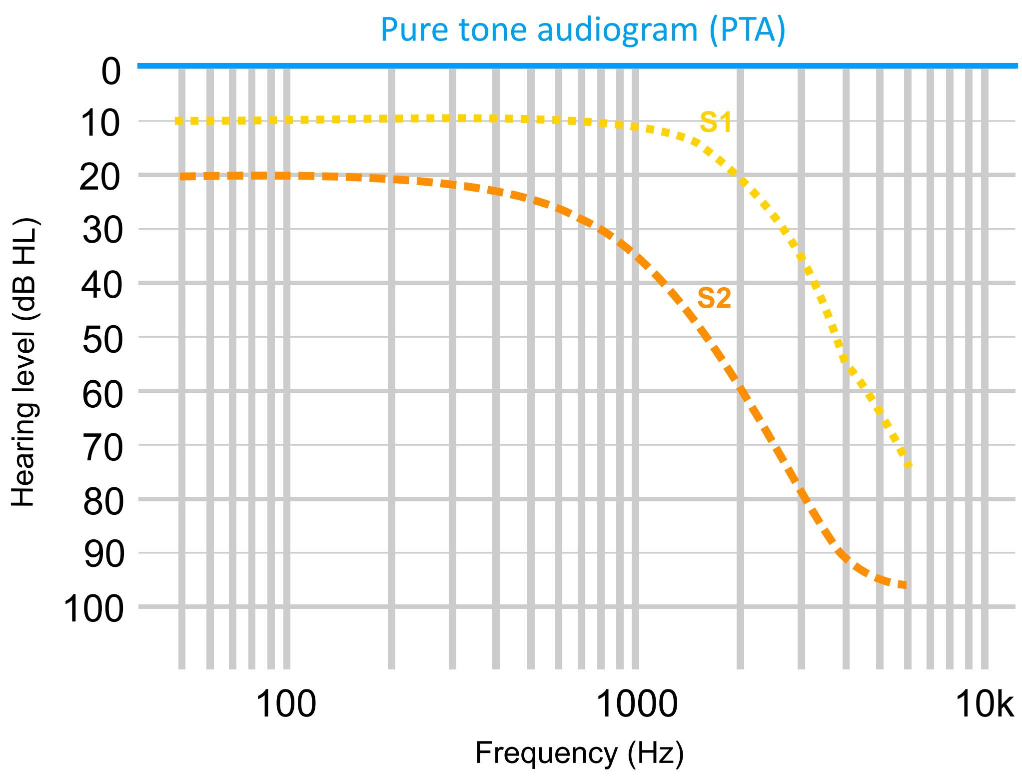


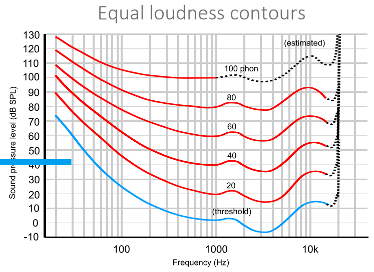


Bisgaard standard audiograms:

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

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





Bisgaard standard audiograms:

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- **S2**: mild

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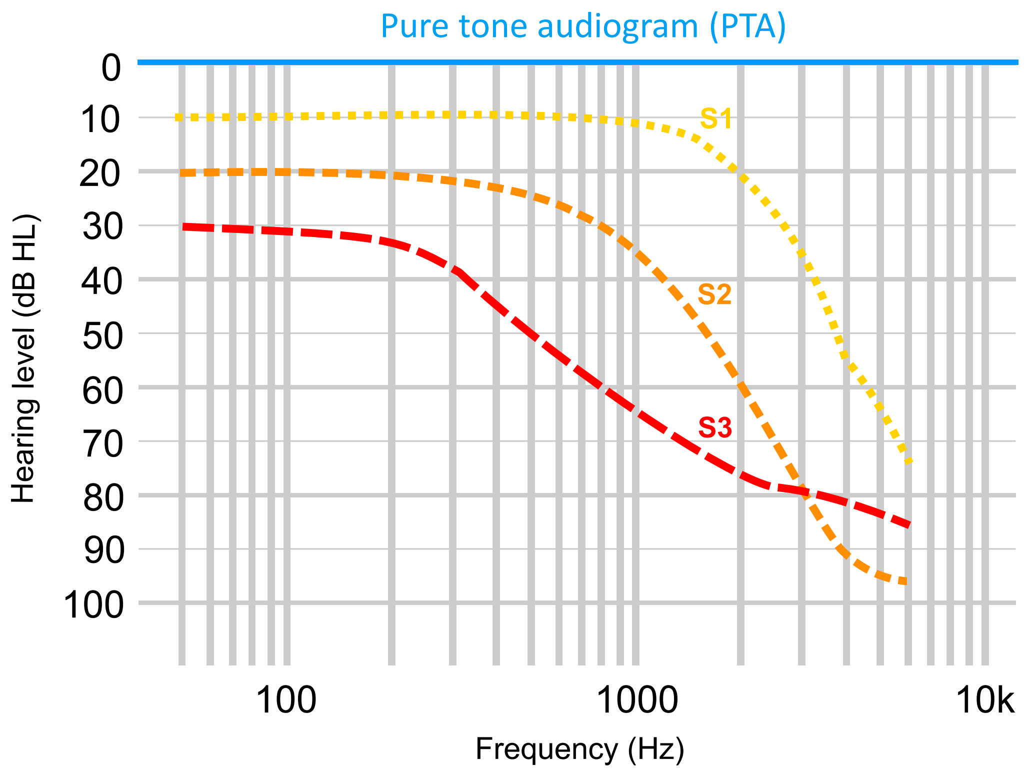
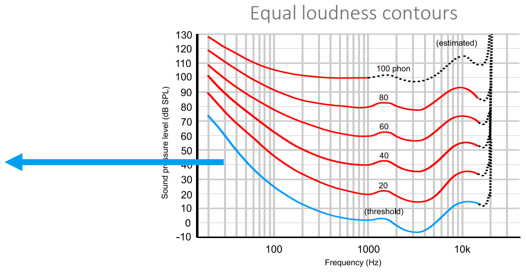




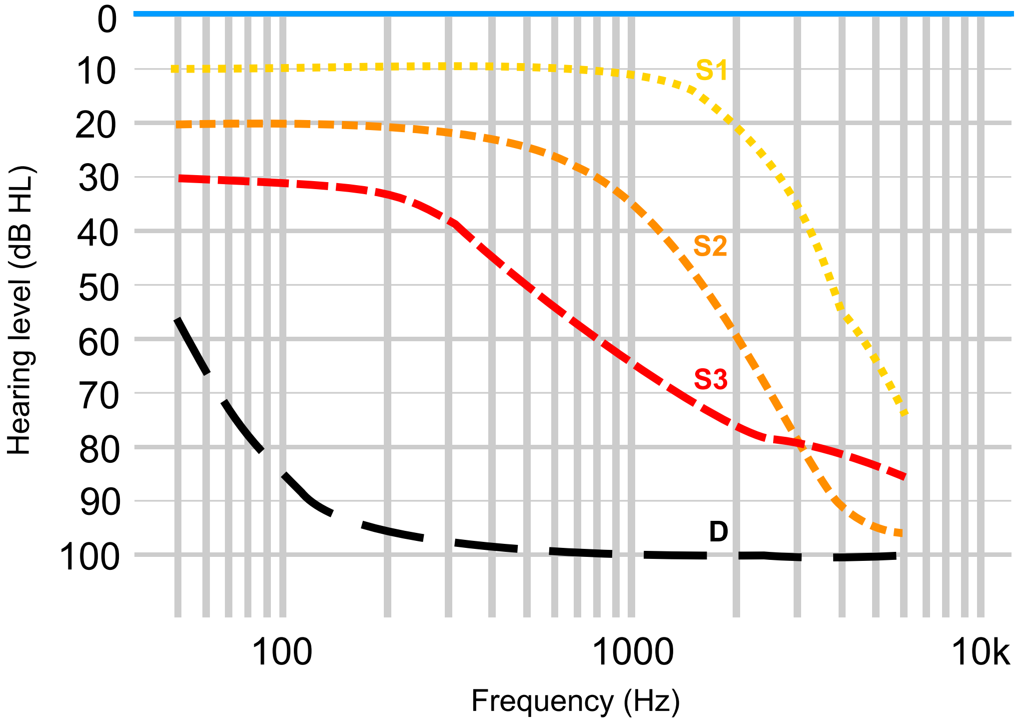
Bisgaard standard audiograms:

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

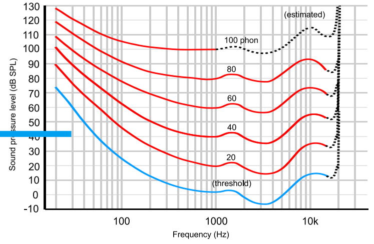
Source: Bisgaard et al. (2010)

Scales and units in audio signal processing: dB HL

Pure tone audiogram (PTA)



Equal loudness contours



Bisgaard standard audiograms:

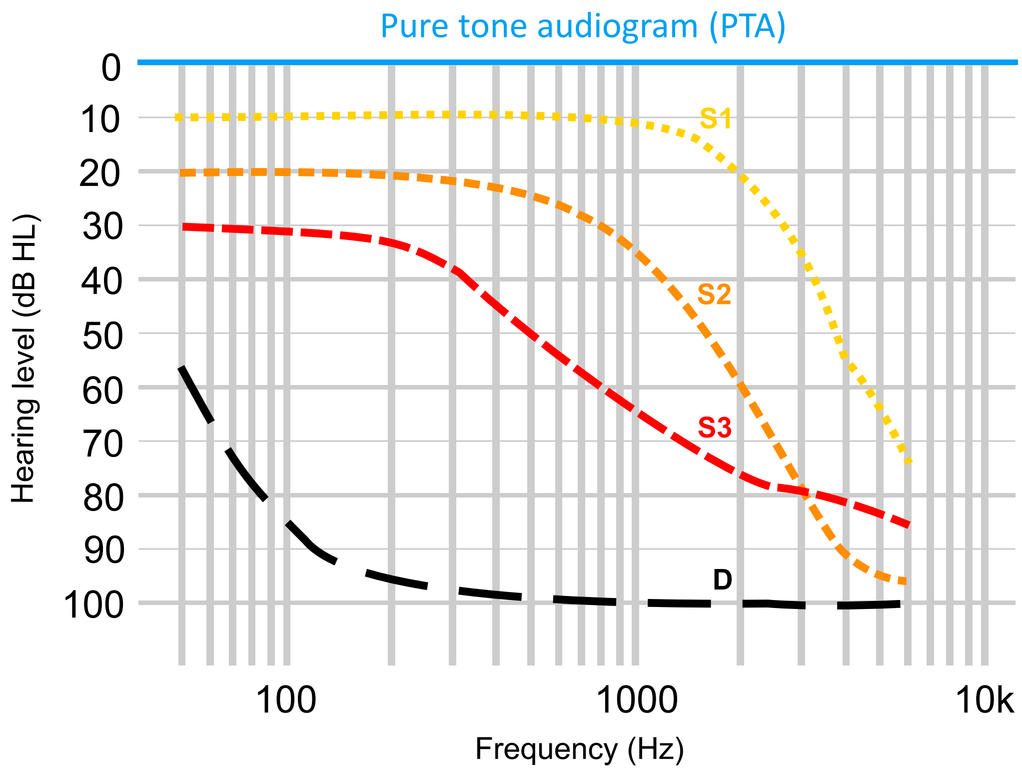
- **S1**: very mild *(degree of hearing loss)*
- **S2**: mild
- **S3**: severe

Source: Bisgaard et al. (2010)

- D: hearing loss bordering on deafness

audifon hearing systems

•• Hearing and hearing impairments



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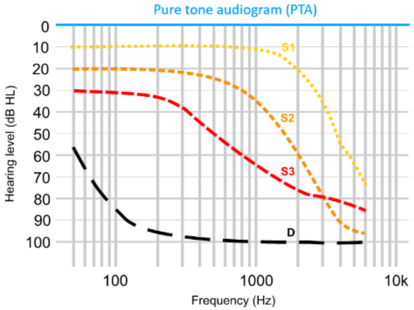


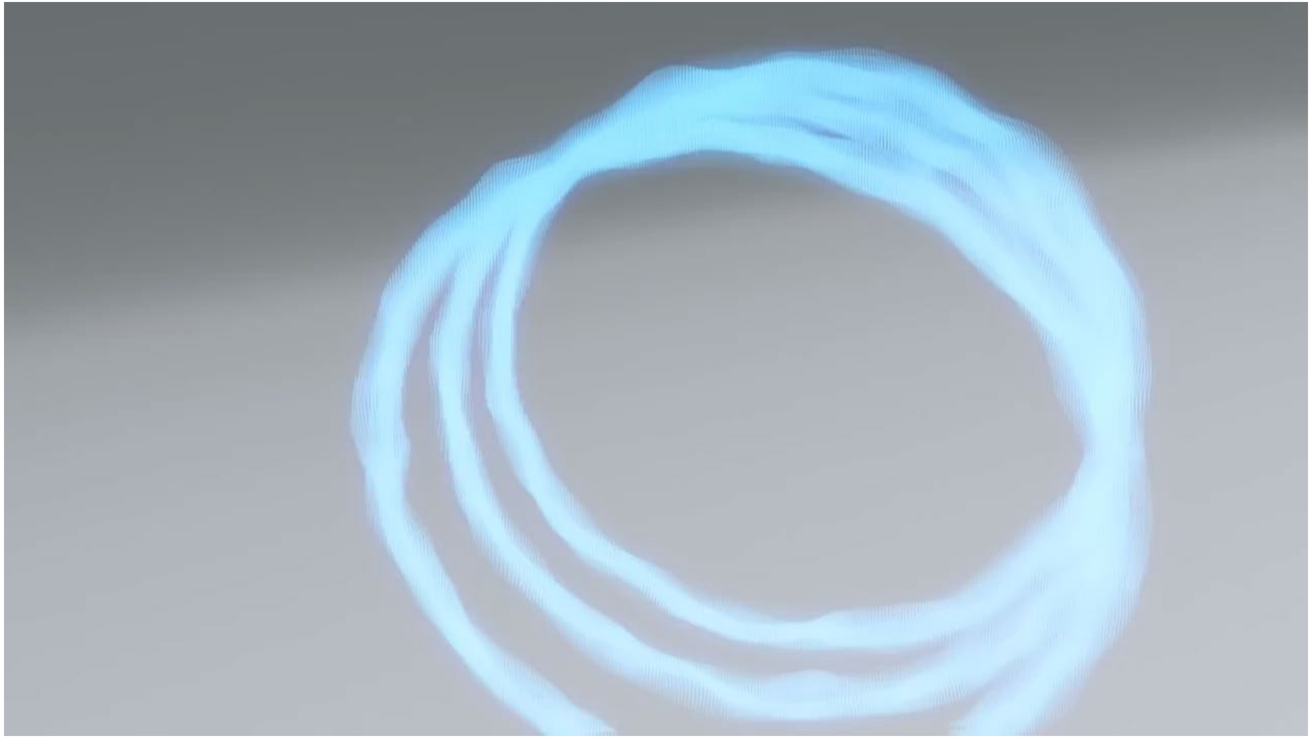
Questions:

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

•• How hearing works

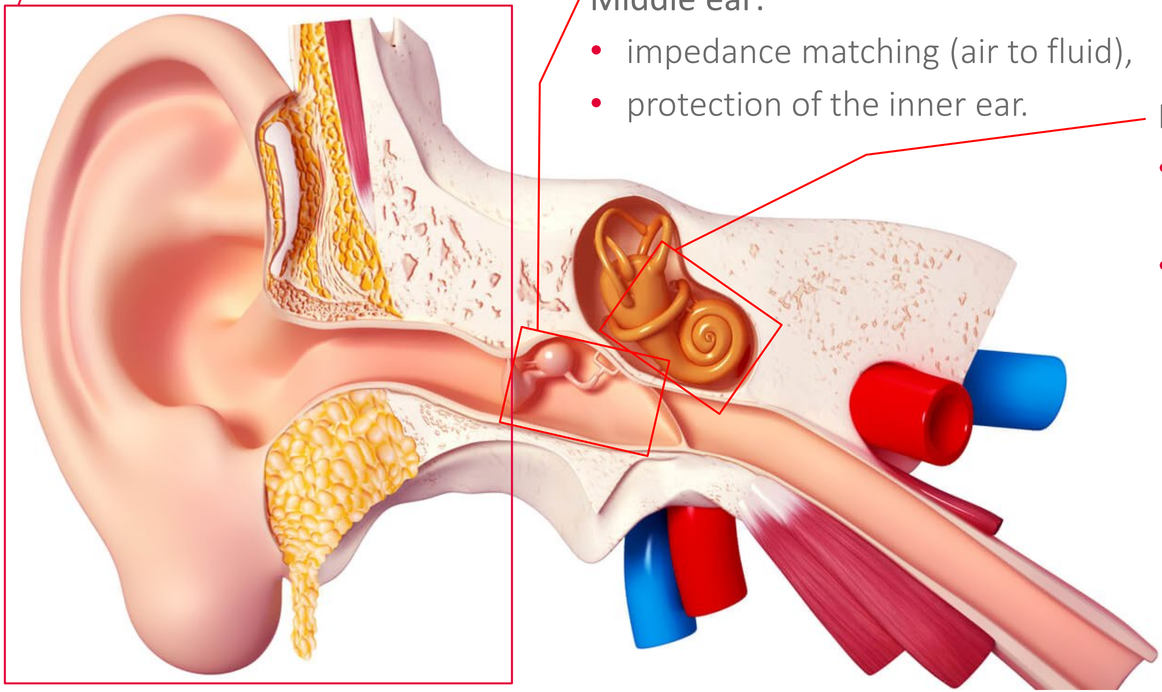


•• Overview

Outer ear: amplification, direction-dependent filtering.

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

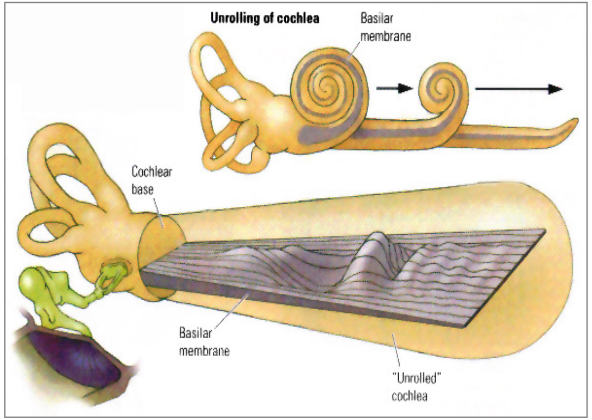
Inner ear:
- spectral decomposition of signal (~filter bank),
- transformation into electrical signals (neural spikes).



Source: www.lobe.ca, 2021.

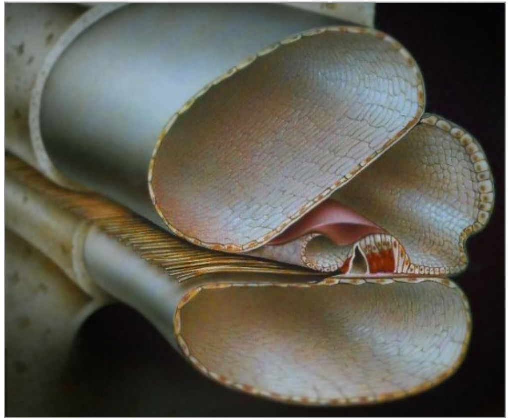
How hearing works

Unrolled cochlea



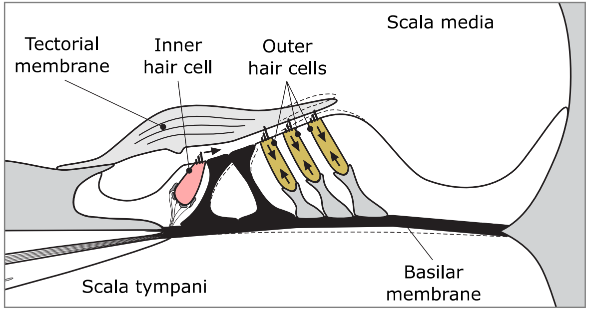
Source: http://www.pc.rhul.ac.uk

Cochlear cross-section



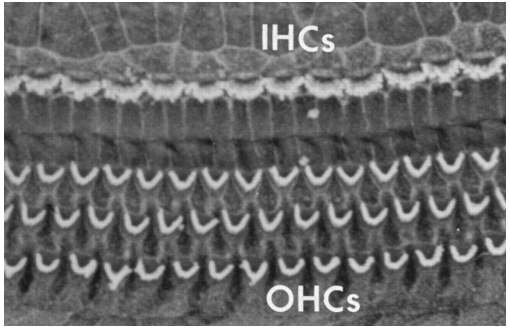
Source: www.meniett.com

Organ of Corti



Adapted from: Baumgarte, 2000

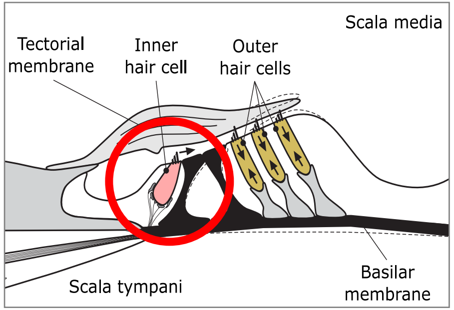
Hair cell rows



Source: Ryan, 2000

How hearing works: Inner hair cells

Organ of Corti



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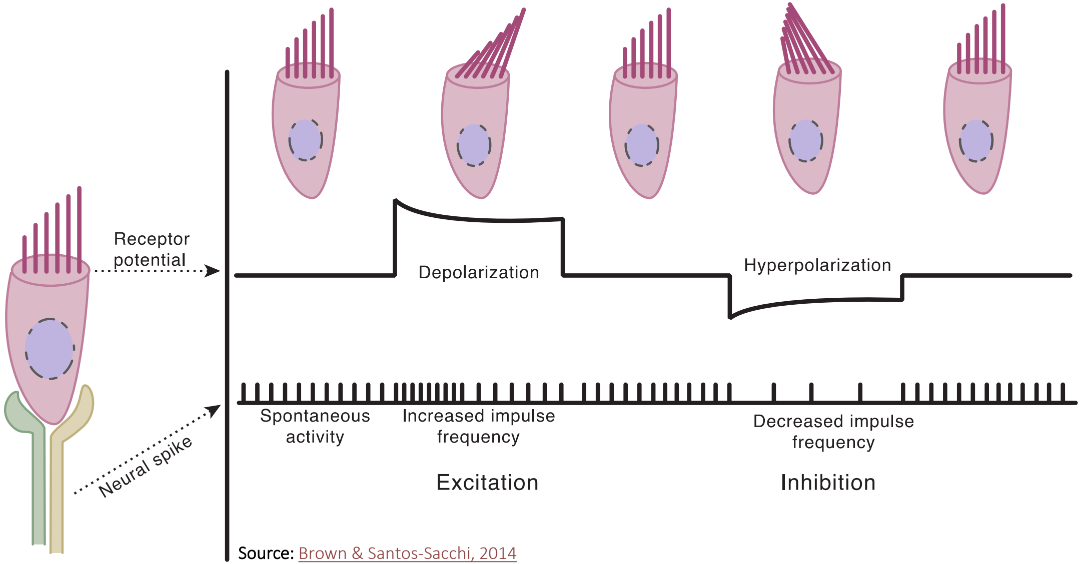


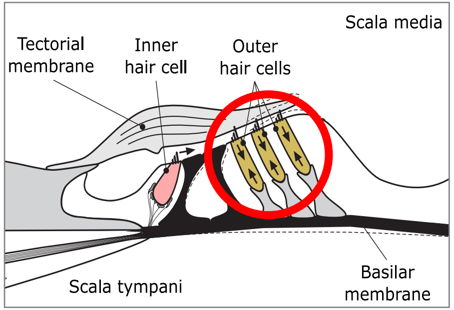
Source: Brown & Santos-Sacchi, 2014

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

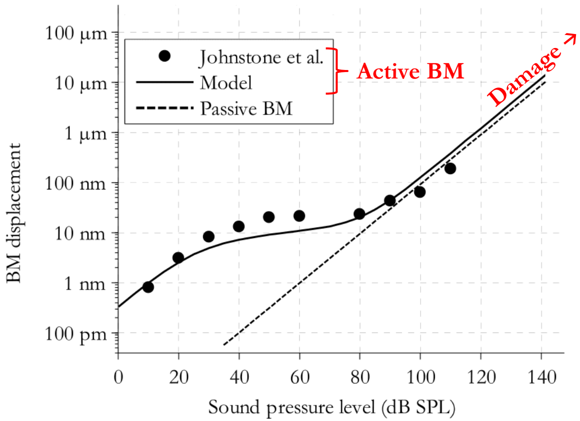


Adapted from: Baumgarte, 2000

OHC motility

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

BM nonlinearity



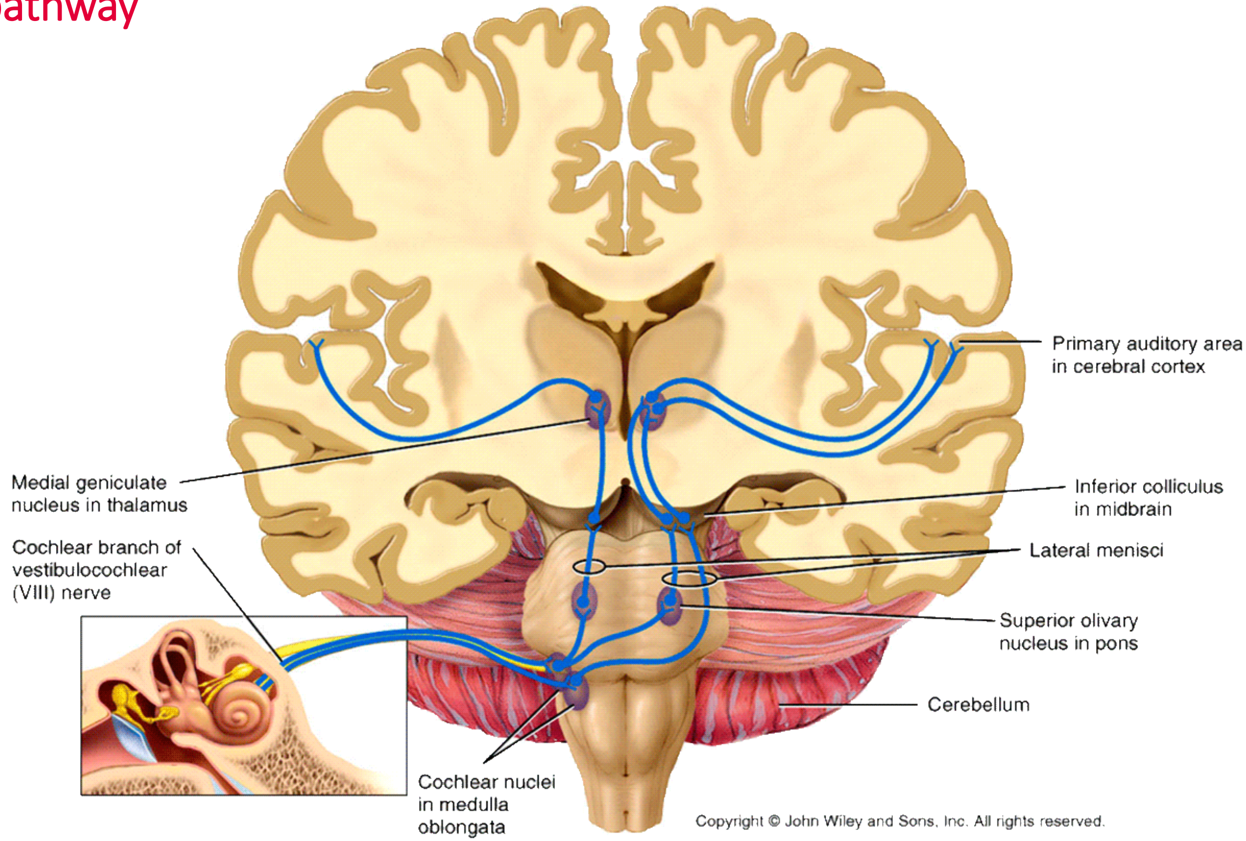
Adapted from: Johnstone, Patuzzi, Yates, 1986

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

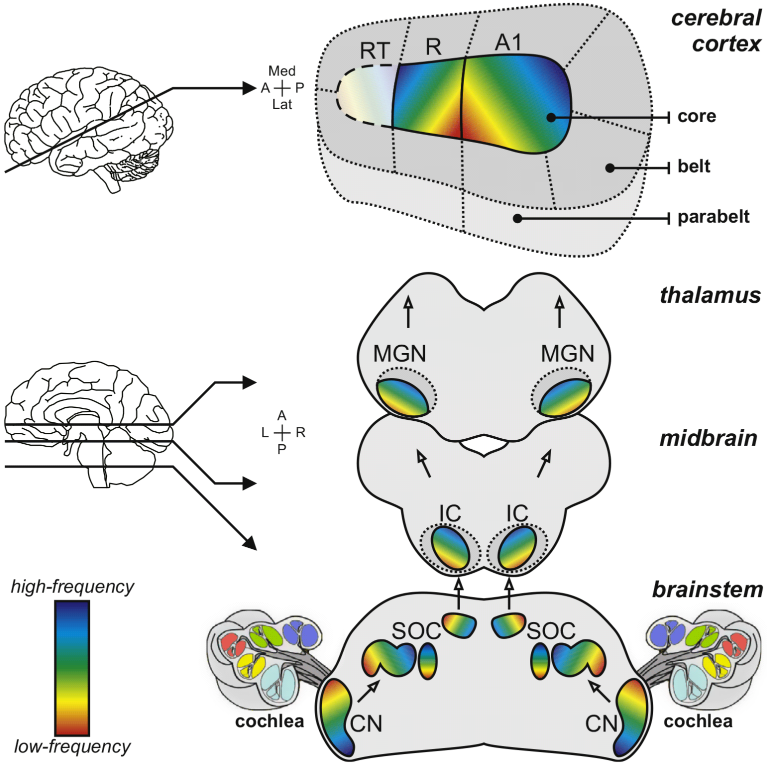


Source: Tortora & Derrickson: Principles of Anatomy and Physiology, 2016

•• Tonotopy

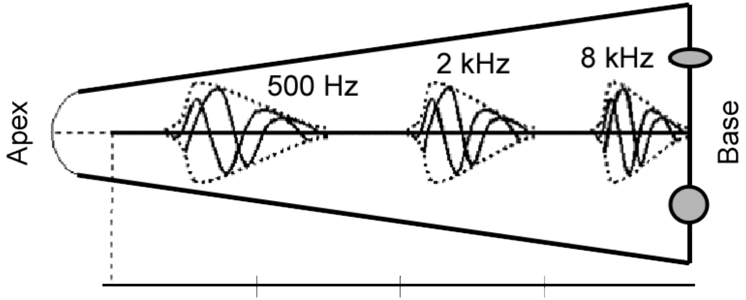
Source: HHMI, 2000.

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

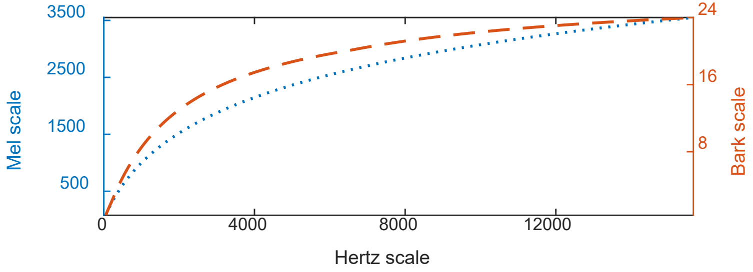


Source: Saenz & Langers, 2014.

•• Tonotopy



x [mm]:	0	8	16	24	32
z [Bark]:	0	6	12	18	24
m [Mel]:	0	723	1398	2238	3541
f [Hz]:	0	630	1720	4400	15500



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.

•• Short recap

Outer ear: amplification, direction-dependent filtering.

Middle ear:

- impedance matching (air to fluid),
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Inner ear:

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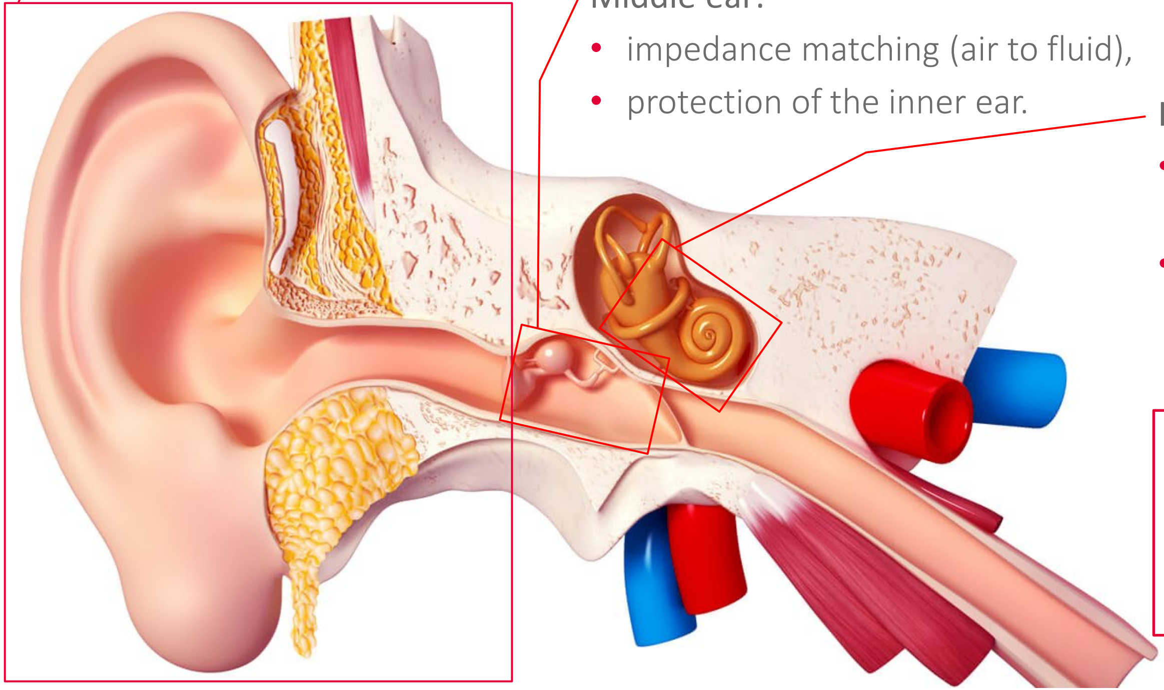


Properties:

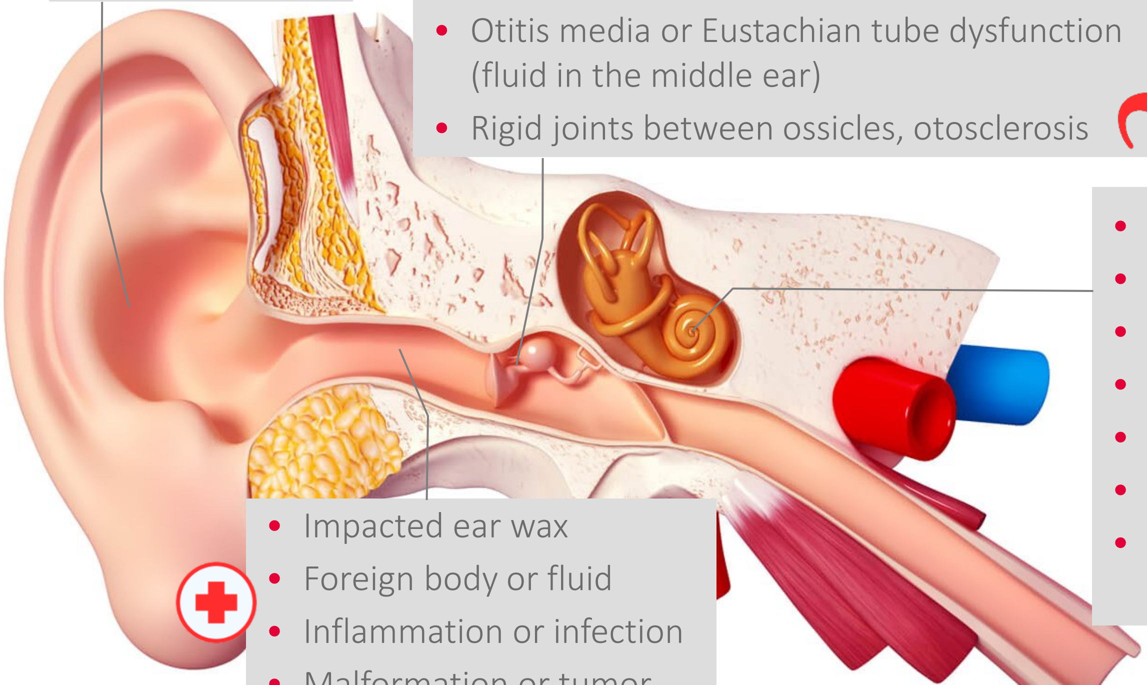
- Amplitude: compressive nonlinearity.
- Frequency: non-linear (log-like) map.
- Frequency: tonotopy.

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 (fluid in the middle ear)
- Rigid joints between ossicles, otosclerosis



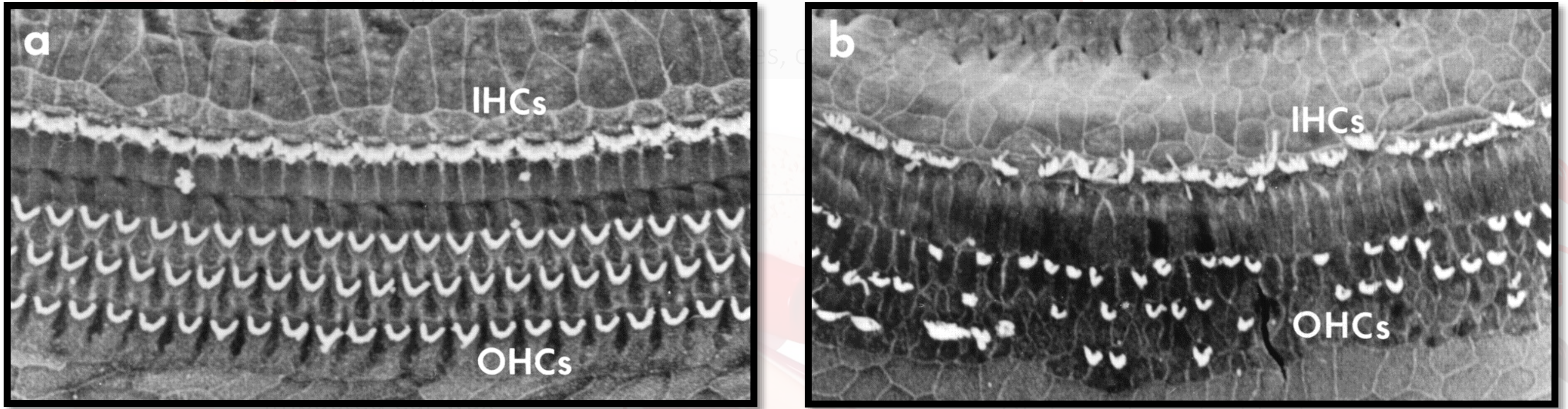
- Aging (presbyacusis)
- Exposure to loud noise
- Trauma / Barotrauma / Head injury
- Genetic or hereditary hearing loss
- Viral infection of the hearing nerve
- Malformation of the inner ear or tumor
- Ototoxic drugs (antibiotics, some anti-inflammatory drugs, chemotherapy)

- Impacted ear wax
- Foreign body or fluid
- Inflammation or infection
- Malformation or tumor

Source: www.lobe.ca, 2021.

•• Causes of hearing impairment

Hair cell damage



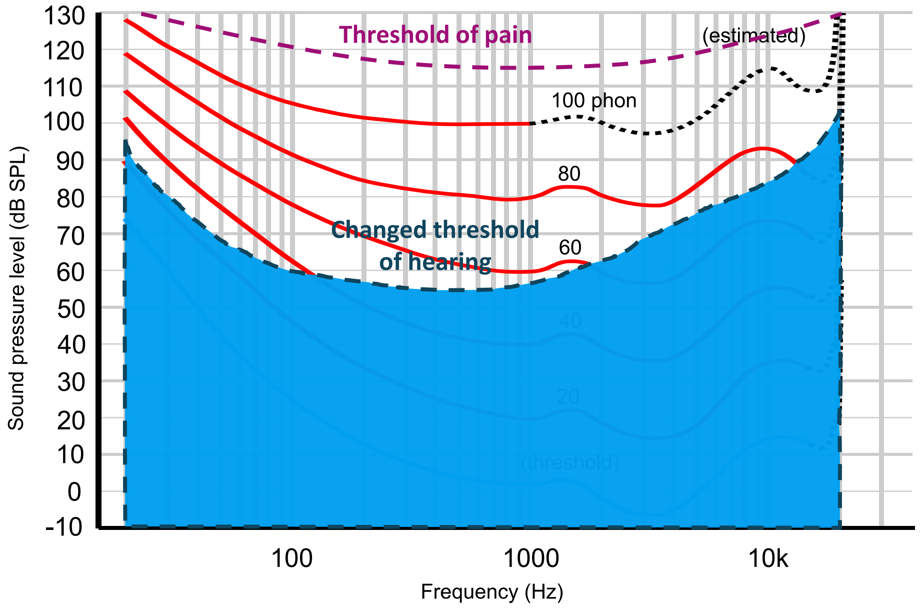
Source: Ryan, 2000

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

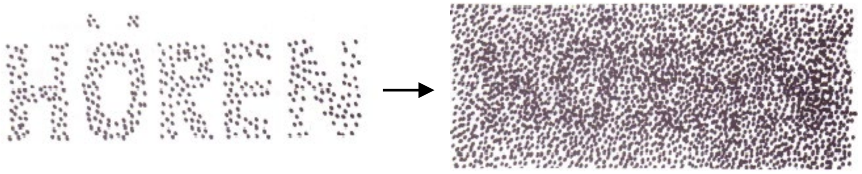
- Speech at moderate level not always understood, but **loud speech becomes disturbing** and misinterpreted as offensive.

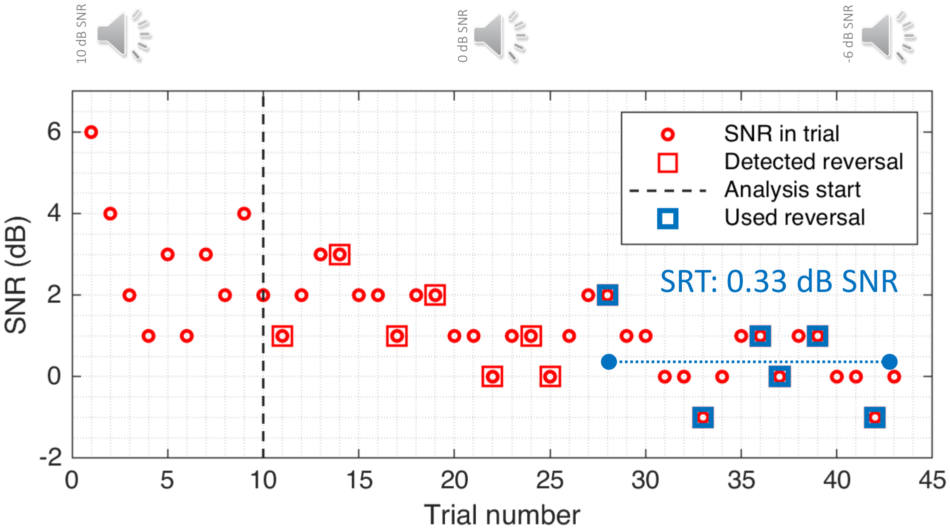


- **In most cases**, the amount of energy arriving at the IHCs is comparable to that of the NH (normal hearing) case.
- **Threshold of pain** is **unchanged** (and also the range of uncomfortably loud signals).
- But the **dynamic range** is **narrower**.
- In hearing assistive technology:
  - need to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

Hearing aids – Early history

Ear trumpets

Vactuphone
(1st vacuum-tube HA)

Behind-the-ear
hearing aids

Widex Senso
full digital BTE HA

17th century | 1902 | 1921 | 1952 | 1956-57 | 1980s | 1995

Hutchison's Acousticon
(1st electrical HA)

Sonotone Model 1010
(1st transistor HA)

Nicolet Phoenix
(programmable digital HA)

Source: hearingaidmuseum.com, 2021

•• Hearing aids – Modern form factors

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

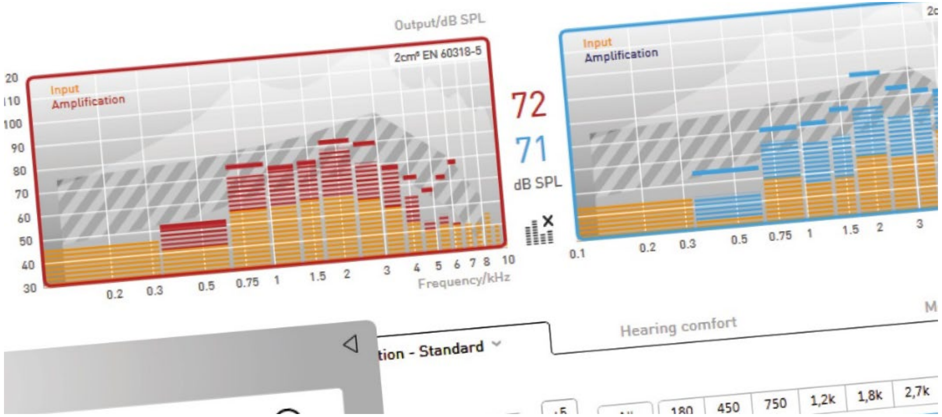
General:

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

Audiological features:

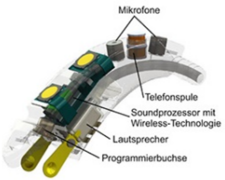
- Low noise, high bandwidth (10 kHz+).
- 16+ frequency channels for DRC.
- Adaptive microphone directionality.
- Noise reduction: ambient, wind, impulse.
- Environmental classification.
- Advanced feedback cancelation.
- Frequency shifting.
- Low latency (<< 10 ms), binaural algorithms.

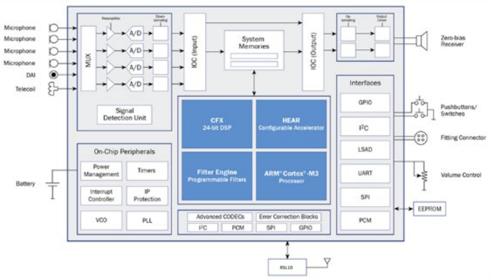
vs

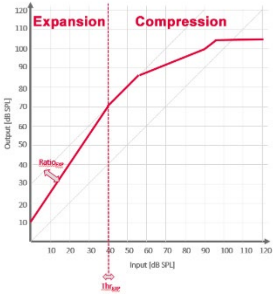


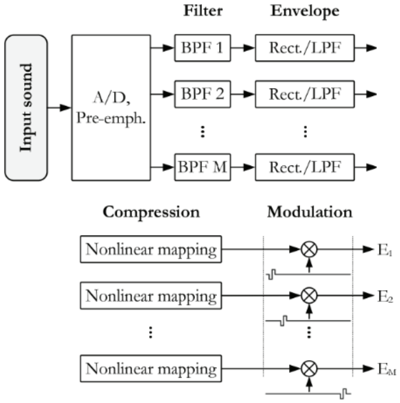
audifon hearing systems

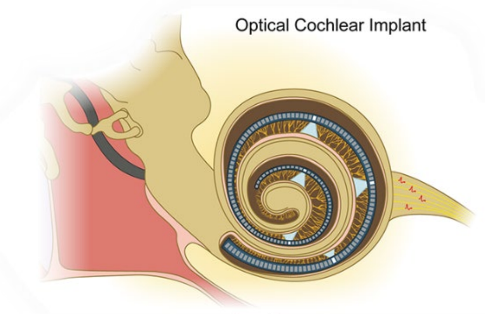
•• Next week











Thank you very much!
Questions?

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