audifon
hearing systems

# Hearing Systems – Part 2 of 3

https://hearingsystems.github.io/

TU Ilmenau – Audio Signal Processing & Audio Systems

January 24, 2023

Dr.-Ing. Tamas Harczos

# 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 240 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. in Information Technology (Veszprém, Hungary)
    Ph.D. in Biomedical Technology (Ilmenau)

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# Introduction

- Reminder:
  - Three lectures and one seminar.
  - Useful links:
    - https://hearingsystems.github.io/ (presentation slides and recordings),
    - https://moodle2.tu-ilmenau.de/course/view.php?id=1373.
- Topics we will cover today:
  - *Recap of the basics:* **units**, human hearing, **tonotopy**.
  - A few more words on **inner and outer hair cells** and **equal loudness contours**.
  - Properties and characterization of hearing impairment: **pure tone audiogram** and **speech in noise test**s.
  - ***Hearing aids:*** early history, modern day form factors, features and requirements.

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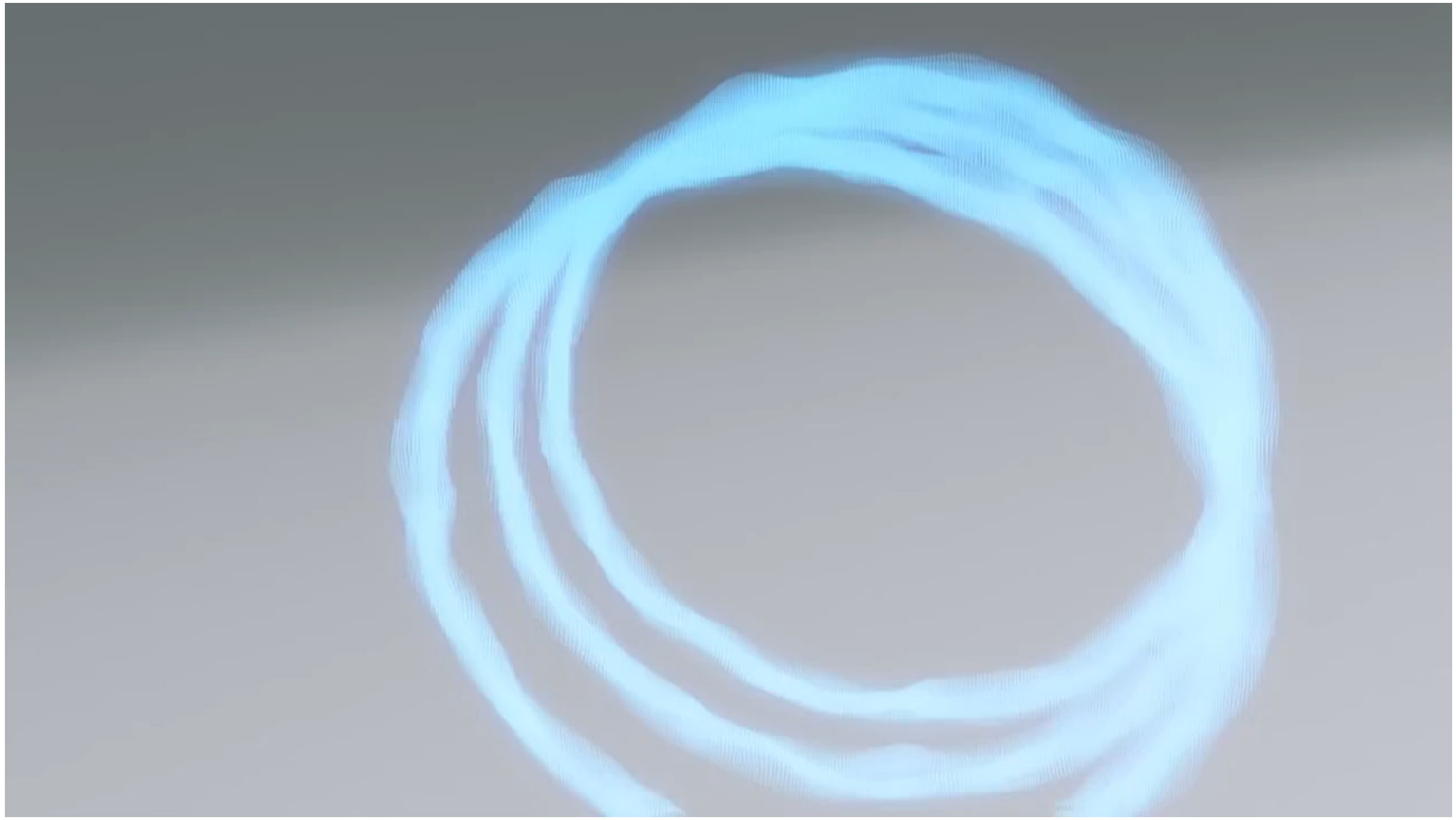
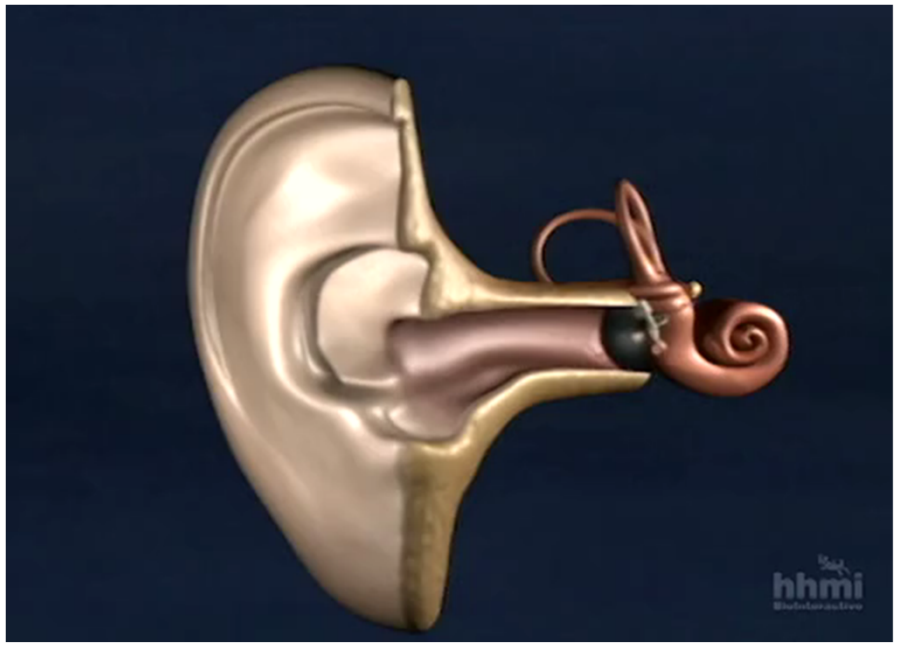
# Recap of the basics: scales and units

- Decibel (**dB**) alone is not a unit, it's a scale. It describes a relationship between two levels.
- The unit **dB FS** (Decibel full scale) relates to the maximum output of the given system.
  - 0 dB FS means maximum signal amplitude for a given system.
  - 1/100, 1/10, 1/2 of maximum amplitude: -40 dB FS, -20 dB FS, ca. -6 dB FS, respectively.
  - Conversion: $dB = 20 \log_{10}(mag) \leftrightarrow mag = 10^{(dB/20)}$.
  - A dB FS value does not necessarily relate to the loudness of a signal.
- The root mean square (RMS) of a signal is related to the energy residing in it.
  - The RMS of a recorded audio signal correlates to its sound pressure level.
- The unit **dB SPL** relates to the reference sound pressure $p_0 = 20\,\mu Pa$ in air.
  - 20 µPa is often considered as the threshold of human hearing.
  - Distance (source to receiver) is important, 1 m is frequently used as standard distance for dB SPL measurements.
  - Doubling the distance reduces the SPL by about 6 dB (in free field).

# •• Recap of the basics: human hearing

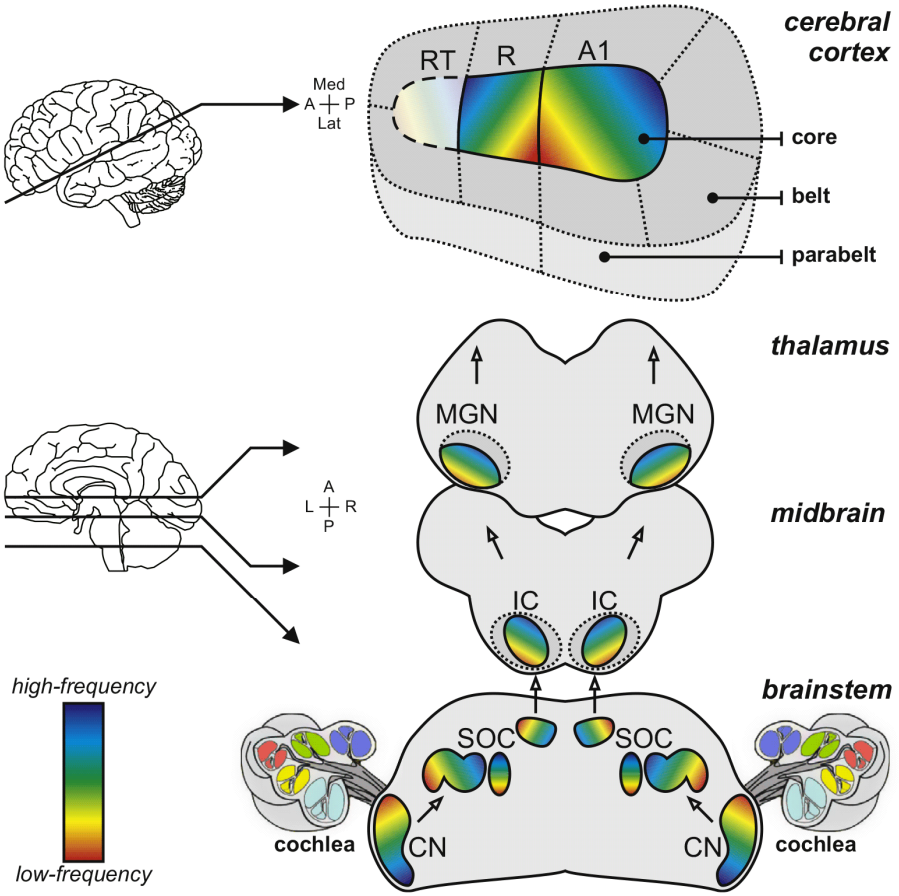


# Recap of the basics: tonotopy



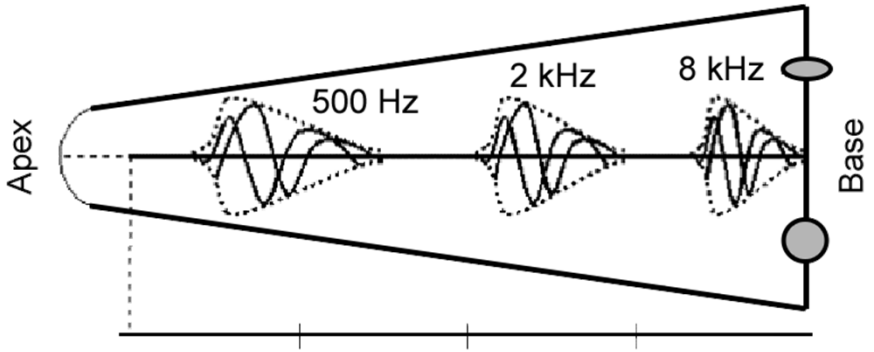

Source: HHMI, 2000.

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

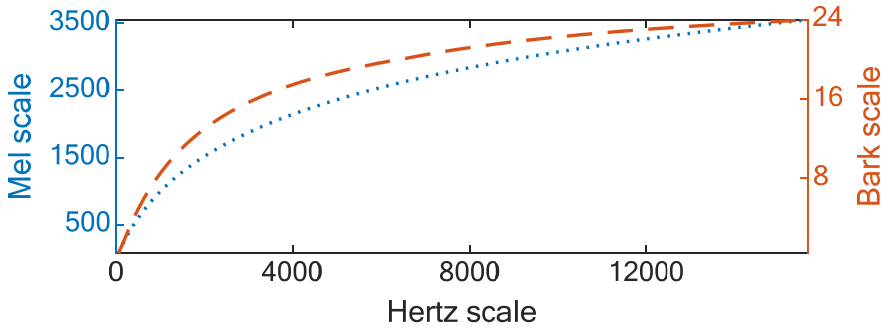



Source: Saenz & Langers, 2014.

# A few more words on 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 |

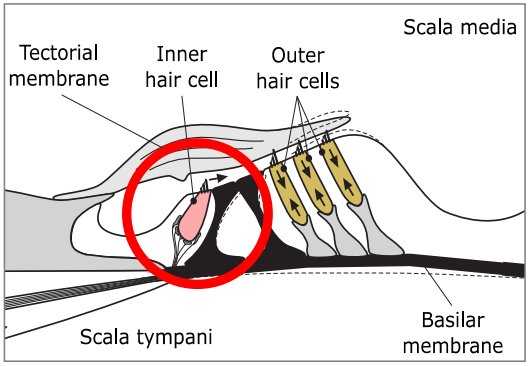



**Frequency scale of the ear** :

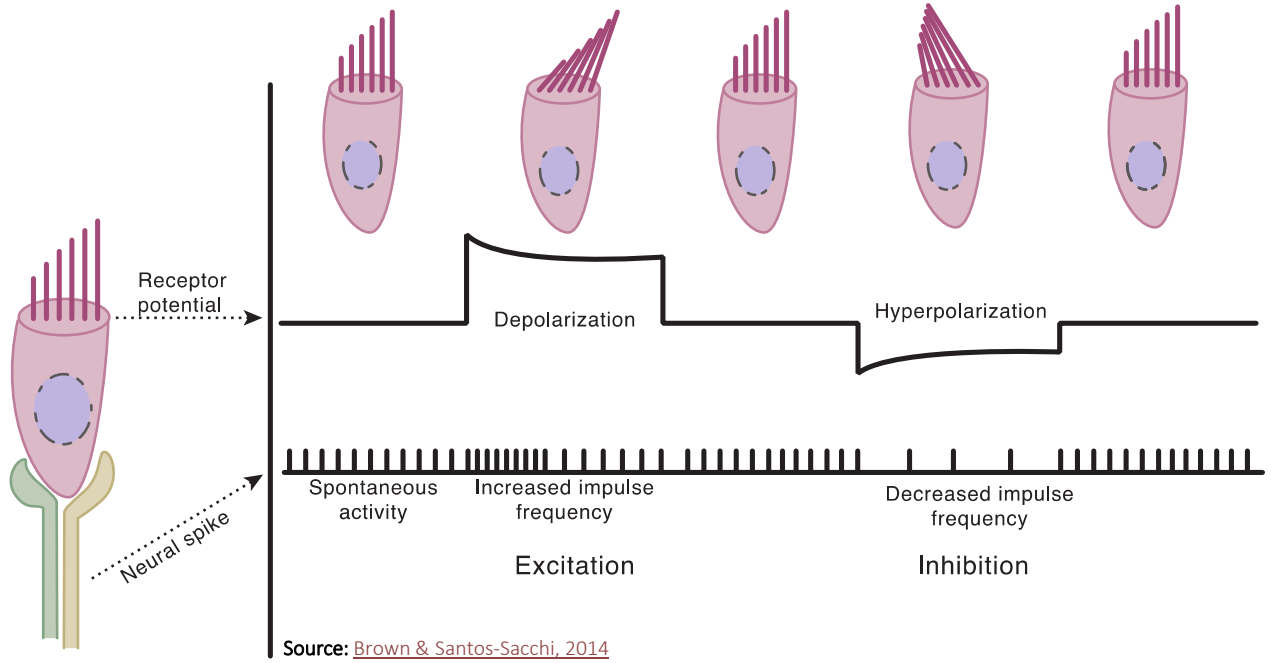
- The human basilar membrane (BM) is approx. 32-35 mm long. Along the BM ca. 3500 IHCs and 12000 OHCs are distributed.
- Regardless of whether we take Bark or Mel scale, it is important to remember that place pitch is not distributed linearly along the cochlea;
  - 210±10 Hz (Δ=0.2 Bark): good discrimination, but
  - 4410±10 Hz (Δ=0.03 Bark): bad discrimination.
- Pitch difference of 1 Bark roughly equals to 1.3 mm on the BM; you only have around 150 IHCs along that cochlear section.

# How hearing works: Inner hair cells

Organ of Corti




Adapted from: Baumgarte, 2000



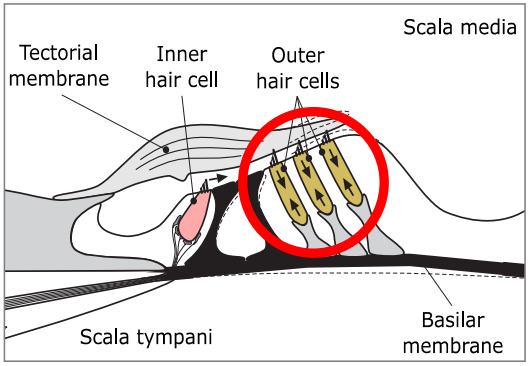

Source: Brown & Santos-Sacchi, 2014

Inner hair cells:

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

# How hearing works: Outer hair cells

Organ of Corti

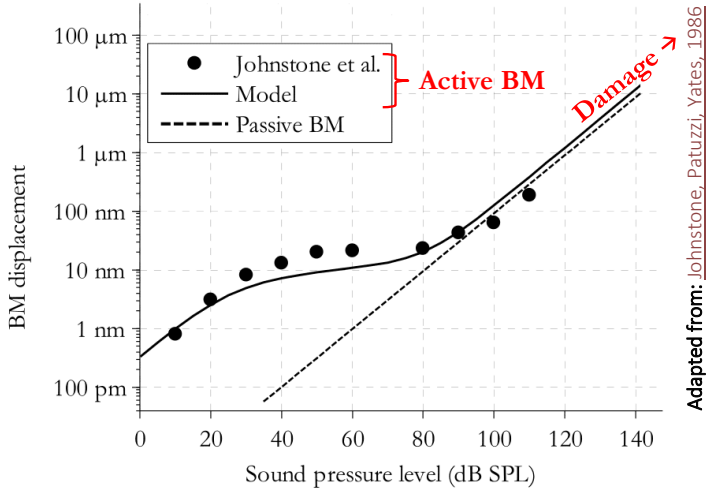



**Adapted from:** Baumgarte, 2000

OHC motility

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

BM nonlinearity



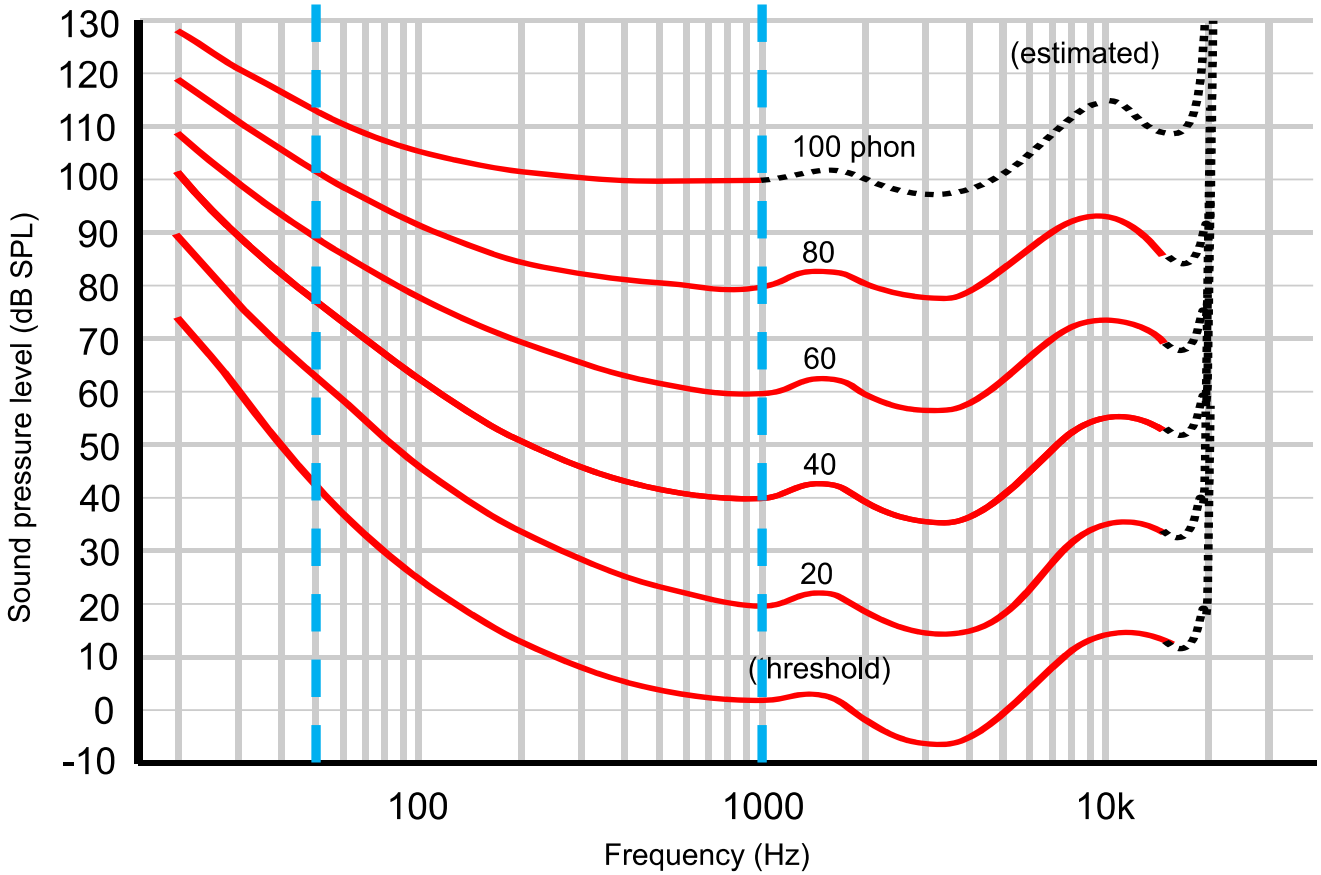

**Adapted from:** Johnstone, Patuzzi, Yates, 1986

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

# Equal-loudness contours

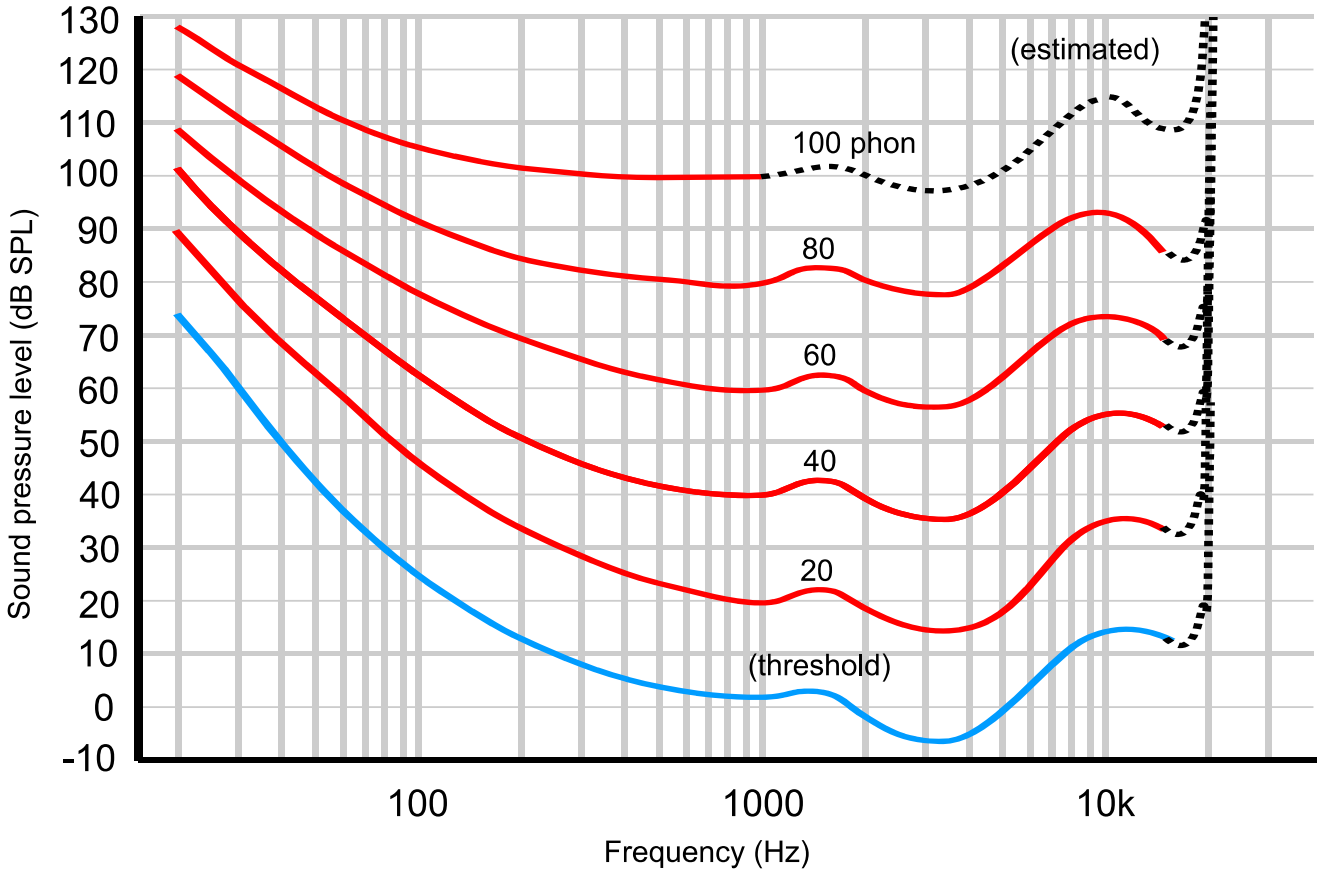



- 1933: Fletcher & Munson (*JASA*)
- 1956: Robinson & Dadson (*BJAP*)
- 2003: Multisite study, averaged over many normal hearing (NH) listeners → ISO 226:2003
- At 1000 Hz: dB SPL ≈ loudness.
- At other frequencies, e.g. at 50 Hz (mainly at higher levels) not.

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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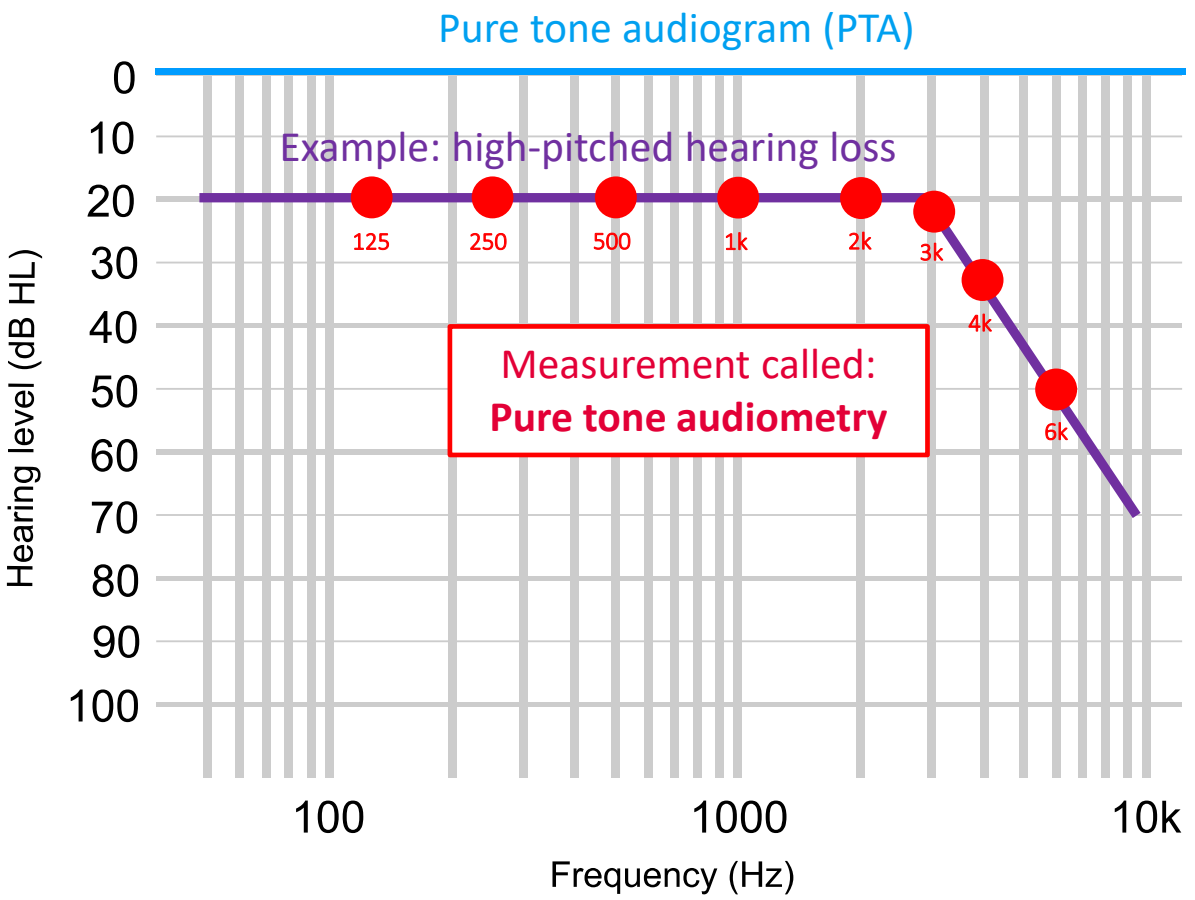
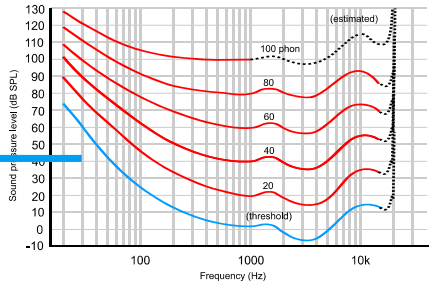



Equal loudness contours



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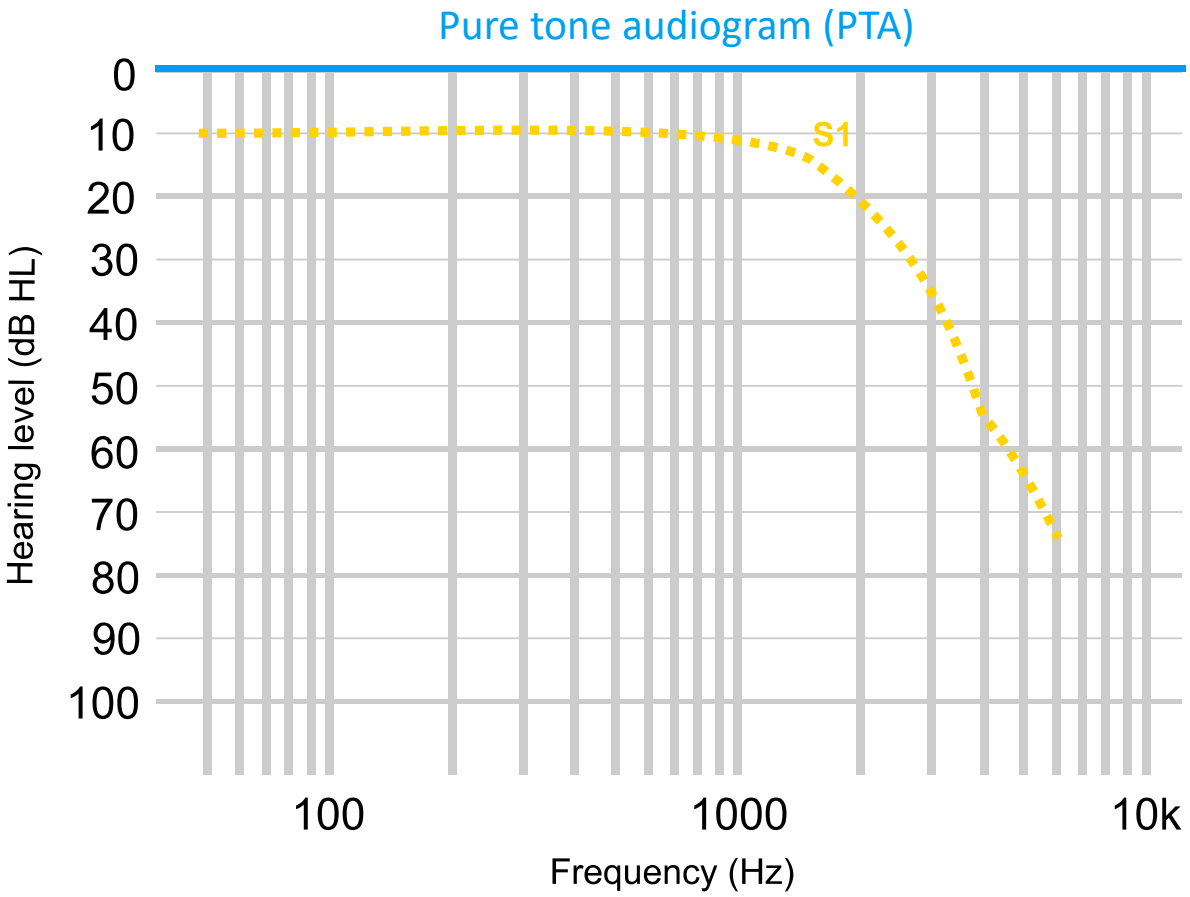
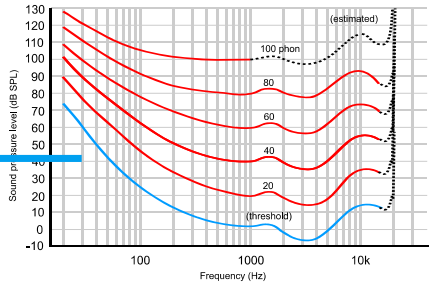



Equal loudness contours




Bisgaard standard audiograms:

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

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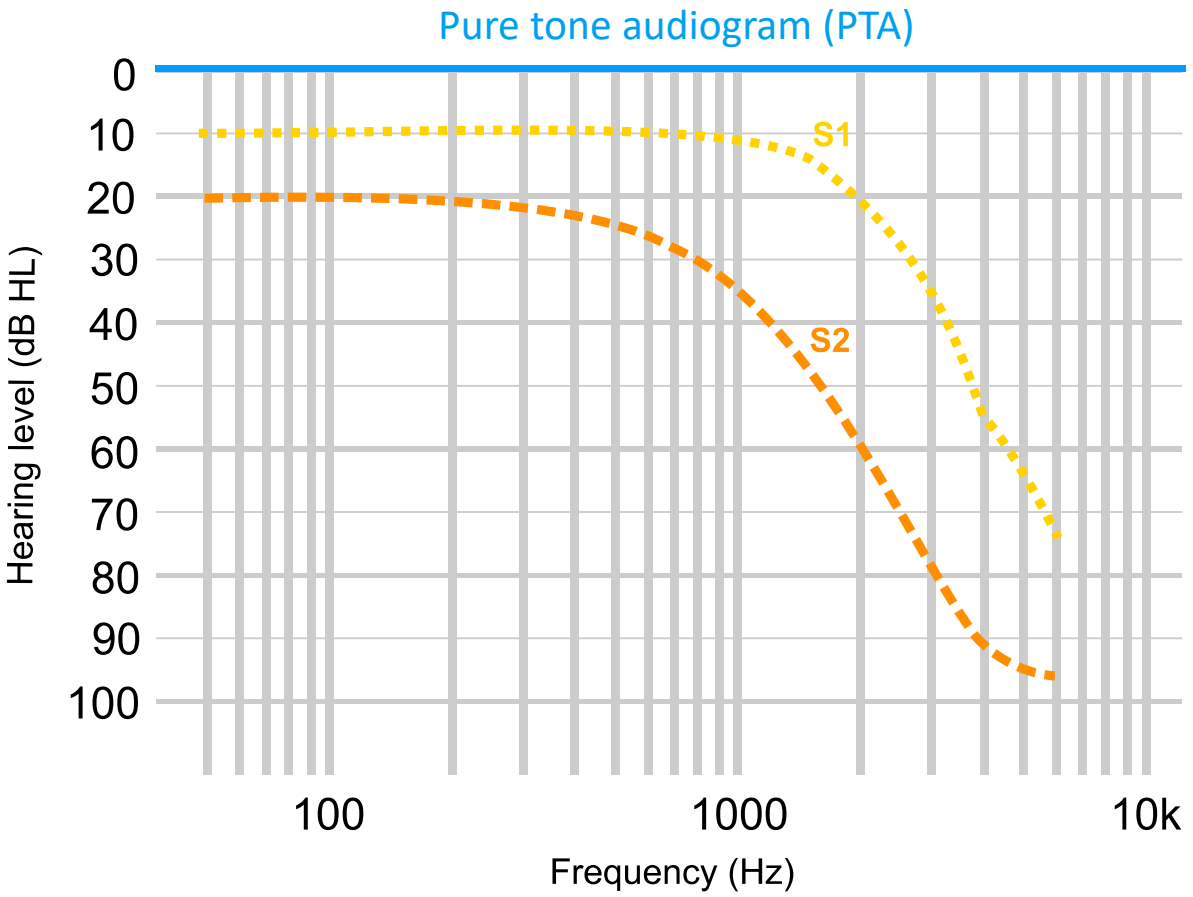
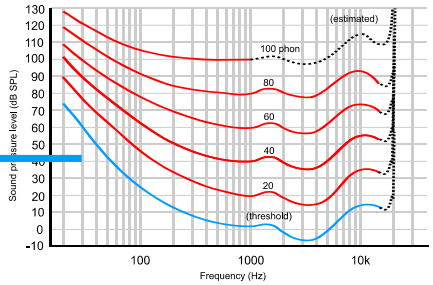



Equal loudness contours




Bisgaard standard audiograms:

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

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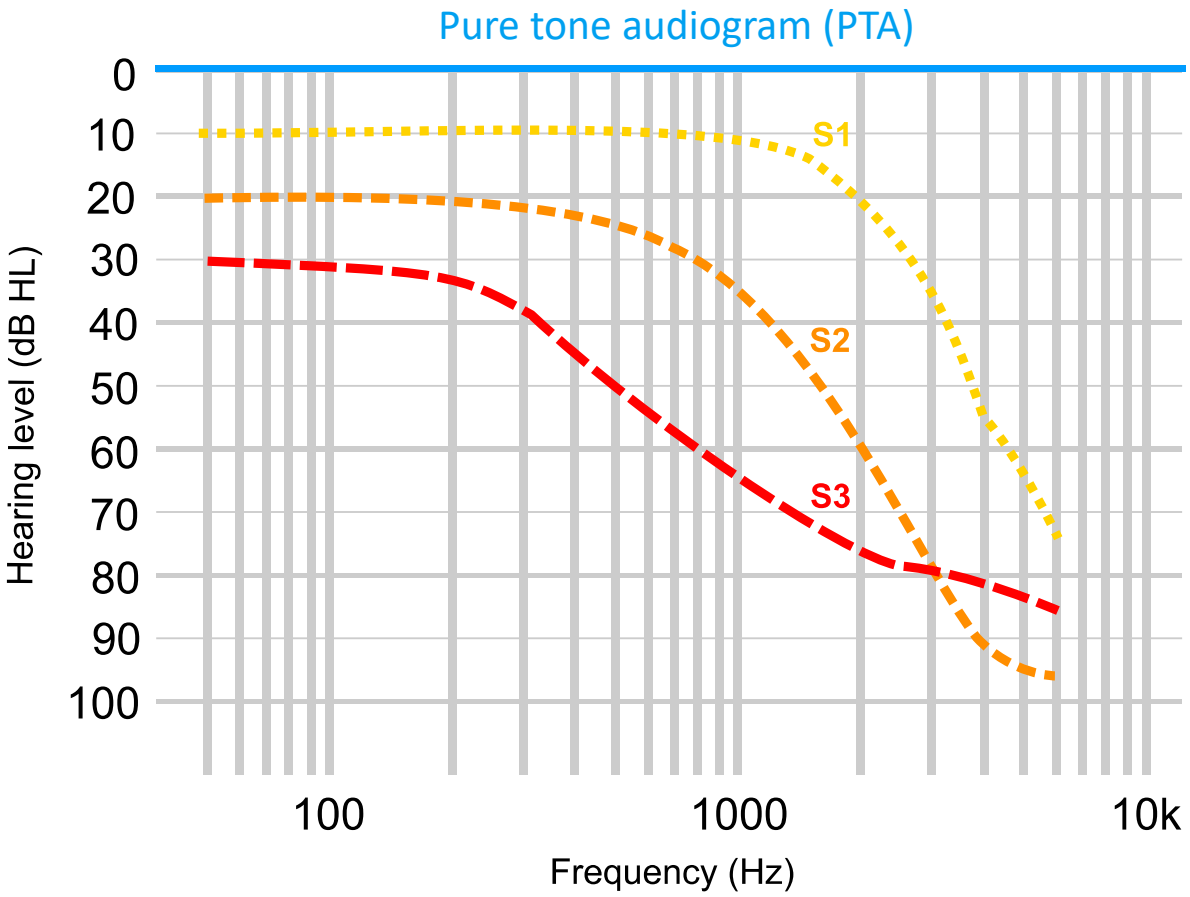


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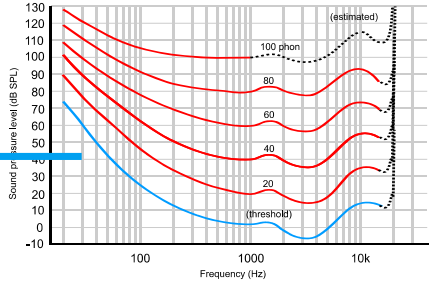


Bisgaard standard audiograms:

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

Source: Bisgaard et al. (2010)

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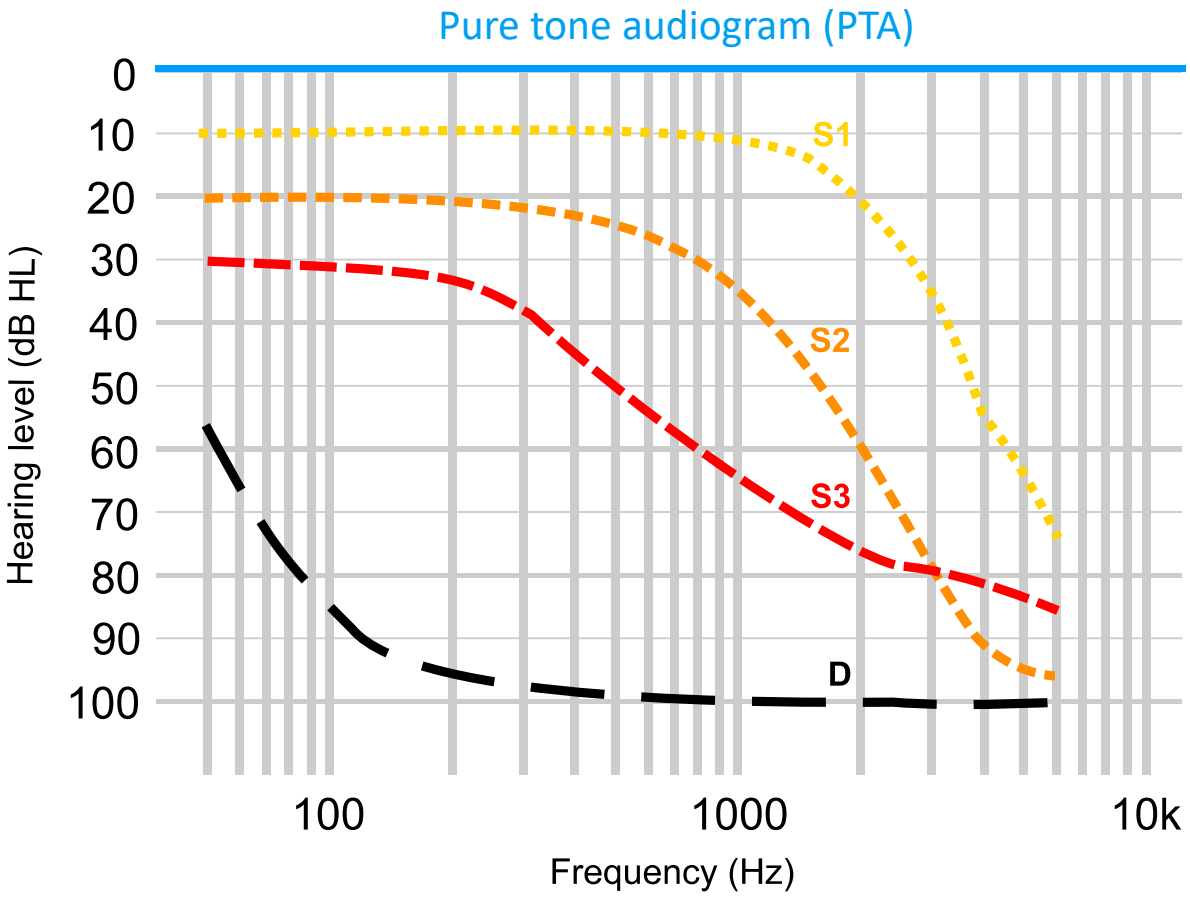
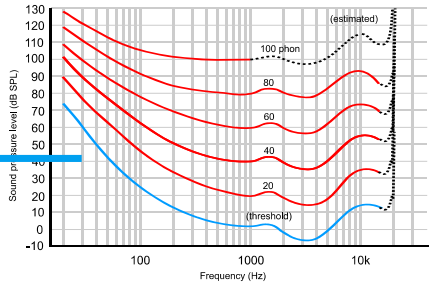



Equal loudness contours



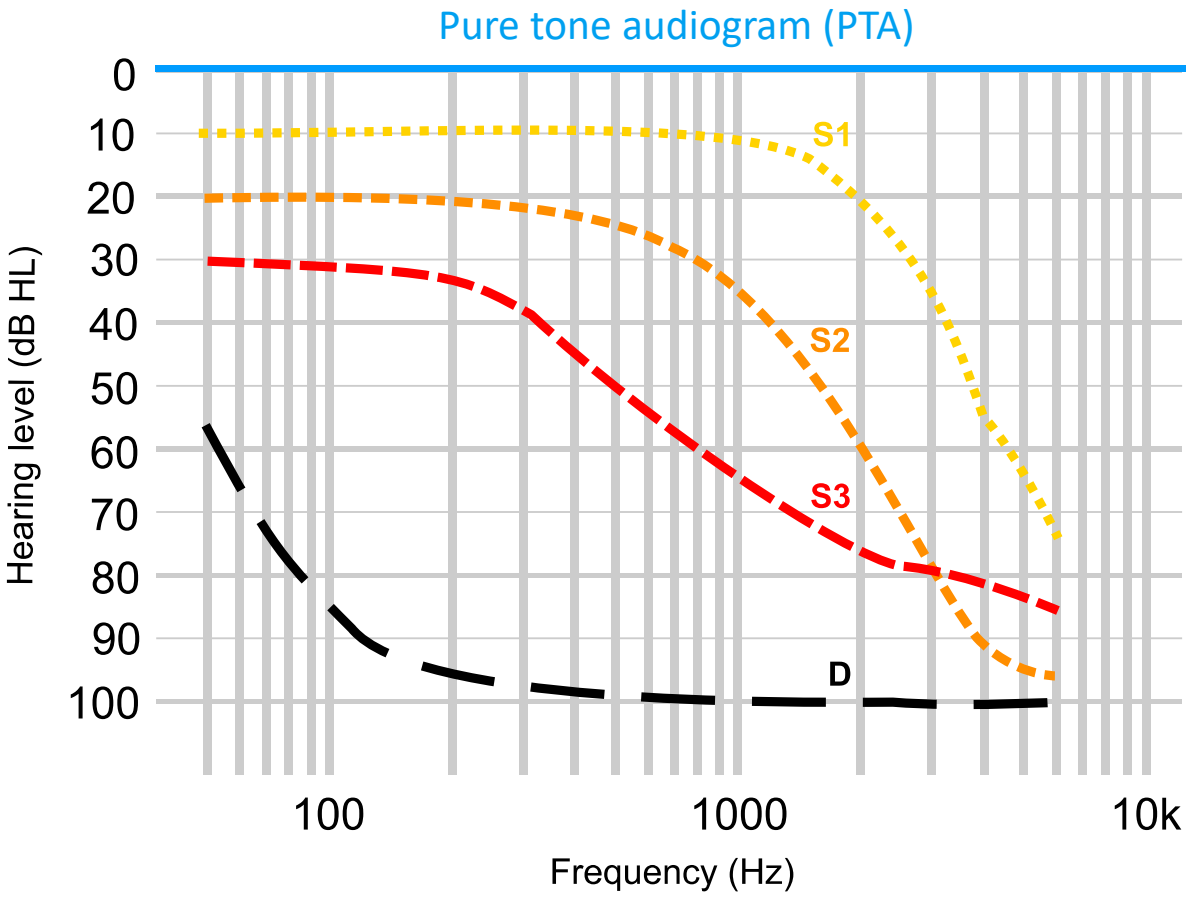

Bisgaard standard audiograms:

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

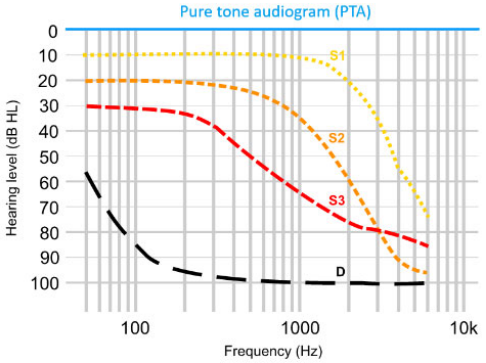
Source: Bisgaard et al. (2010)

- D: hearing loss bordering on deafness

# Hearing and hearing impairments



# Hearing and hearing impairments



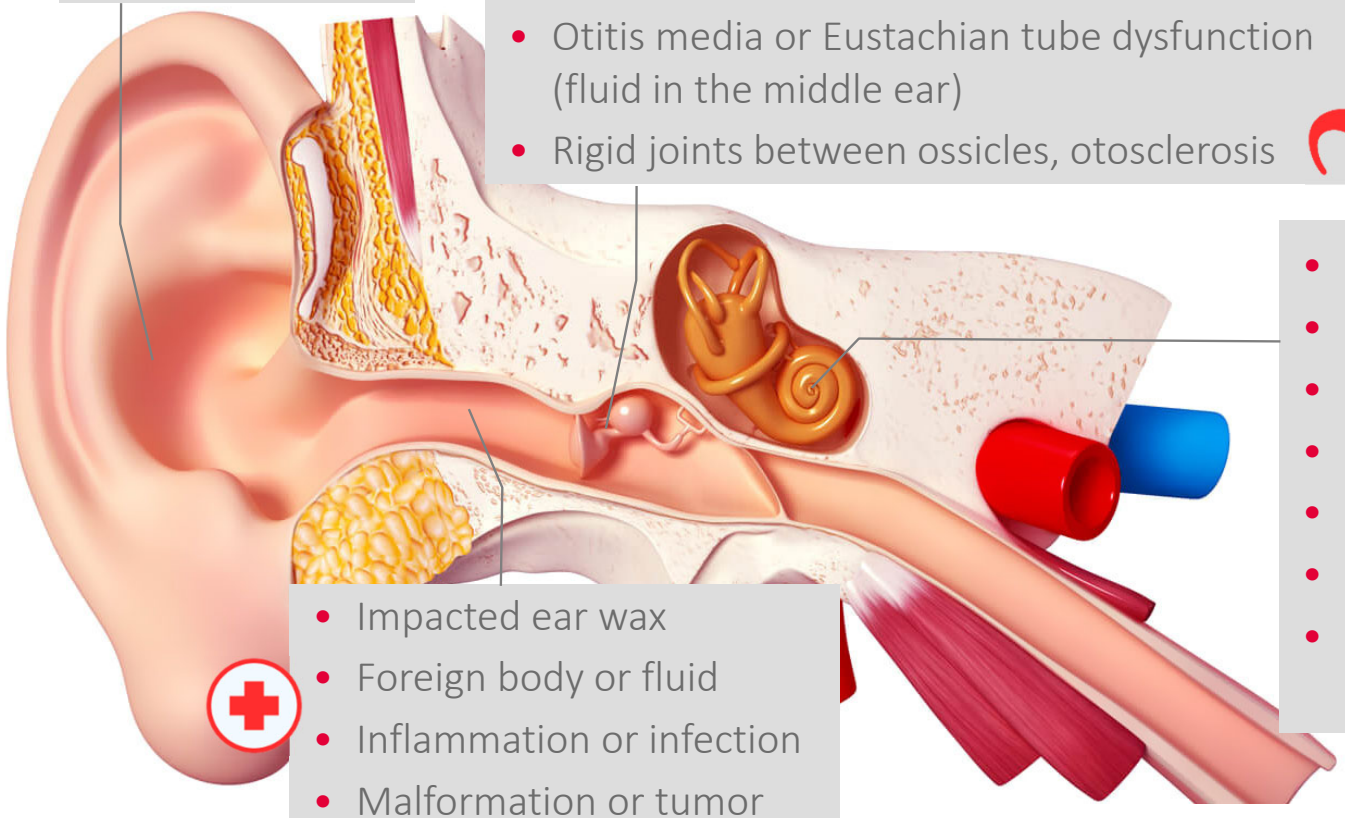

Questions:

- 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** with 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.

# 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



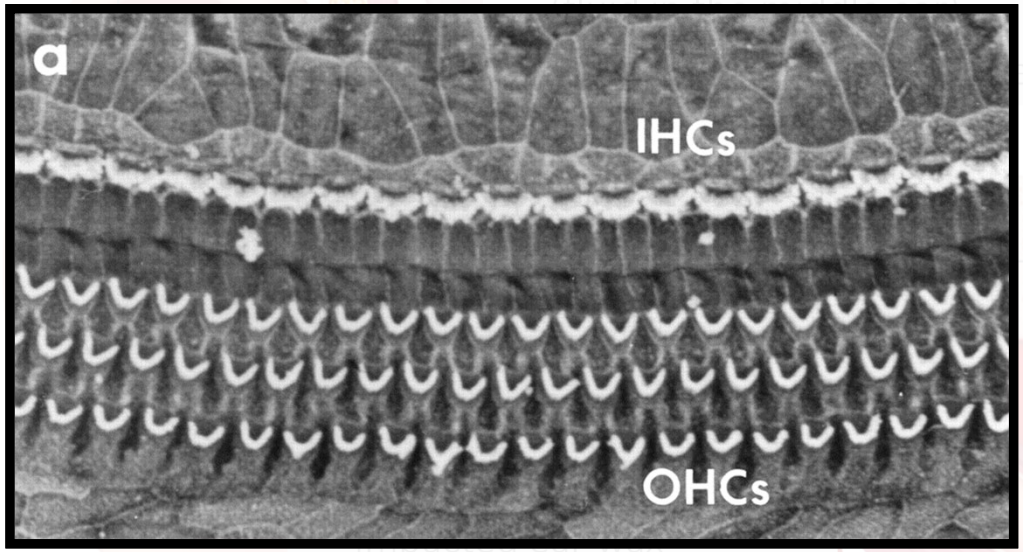
- Impacted ear wax
- Foreign body or fluid
- Inflammation or infection
- Malformation or tumor

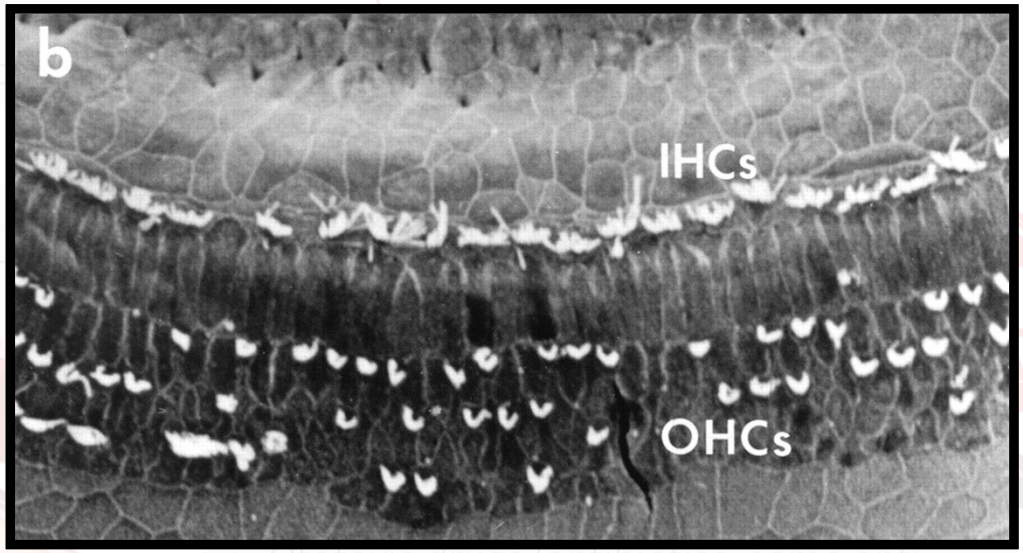
- Aging (presbyacusis)
- Exposure to loud noise
- Trauma / Barotrauma / Head injury
- Genetic or hereditary hearing loss
- Viral infection of the hearing nerve
- Malformation of the inner ear or tumor
- Ototoxic drugs (antibiotics, some anti-inflammatory drugs, chemotherapy)

Source: www.lobe.ca, 2021.

# •• Causes of hearing impairment

Exposure to high sound pressure level → **Hair cell damage**



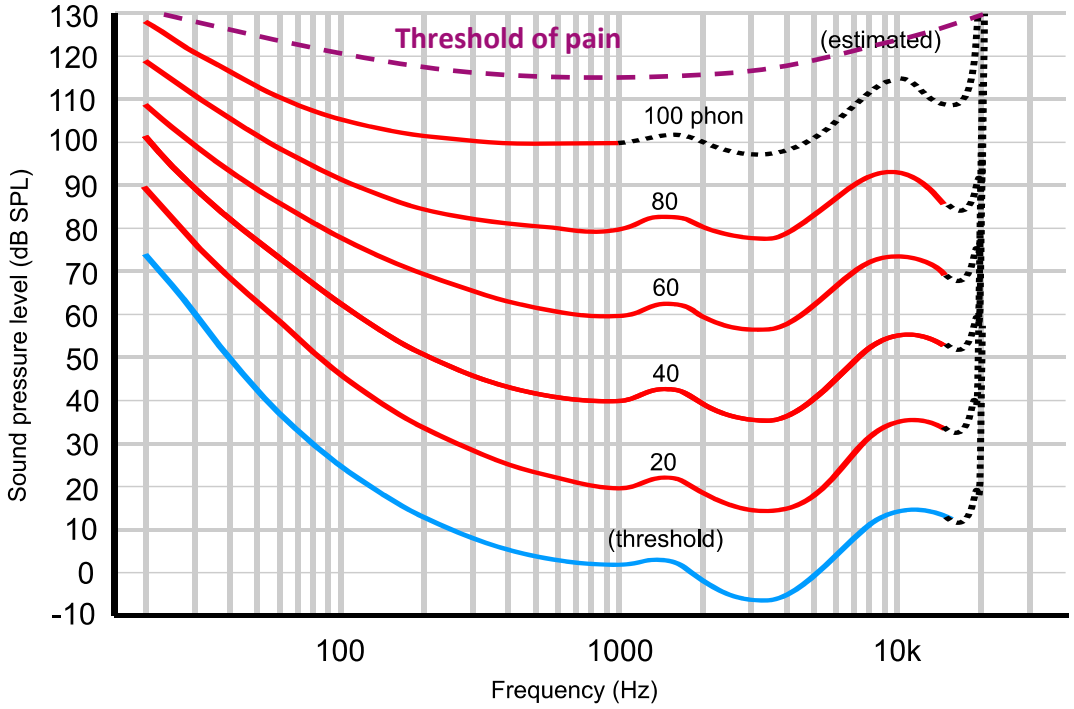

Source: Ryan, 2000

# 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.



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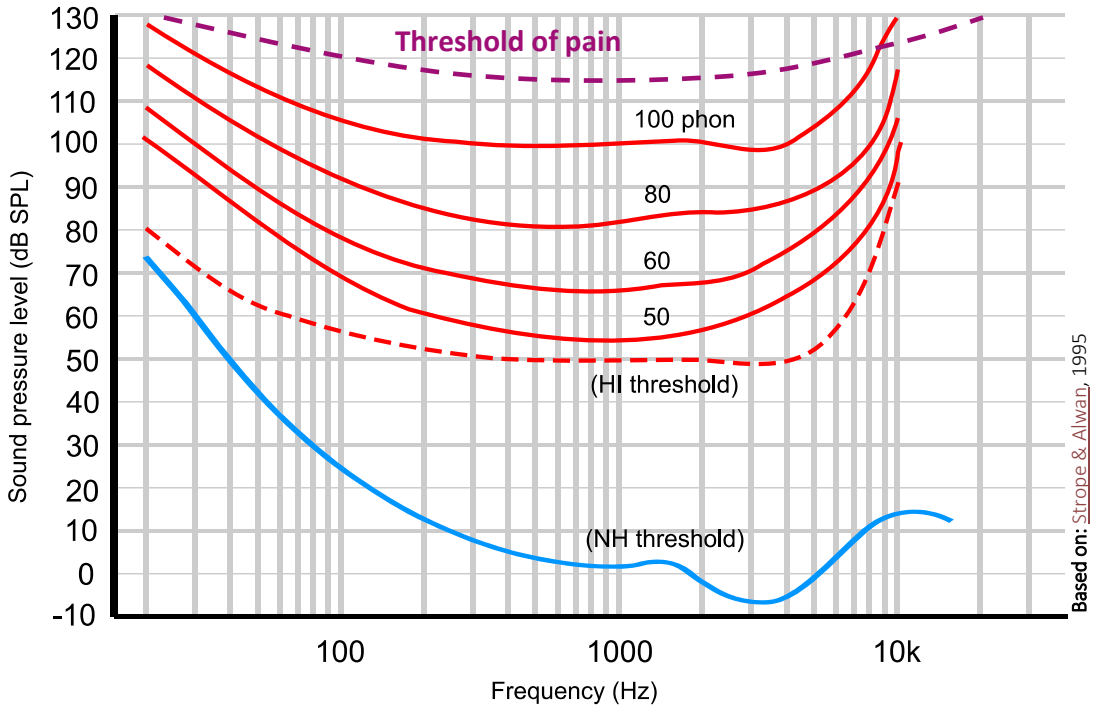
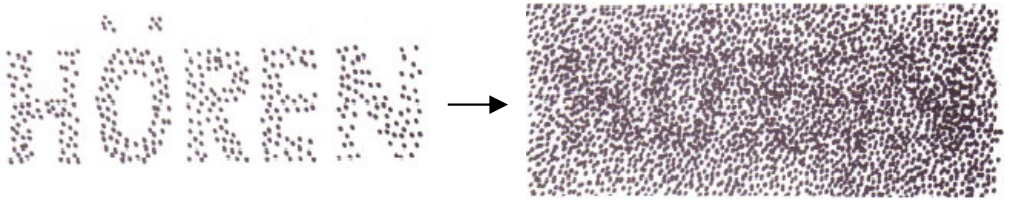
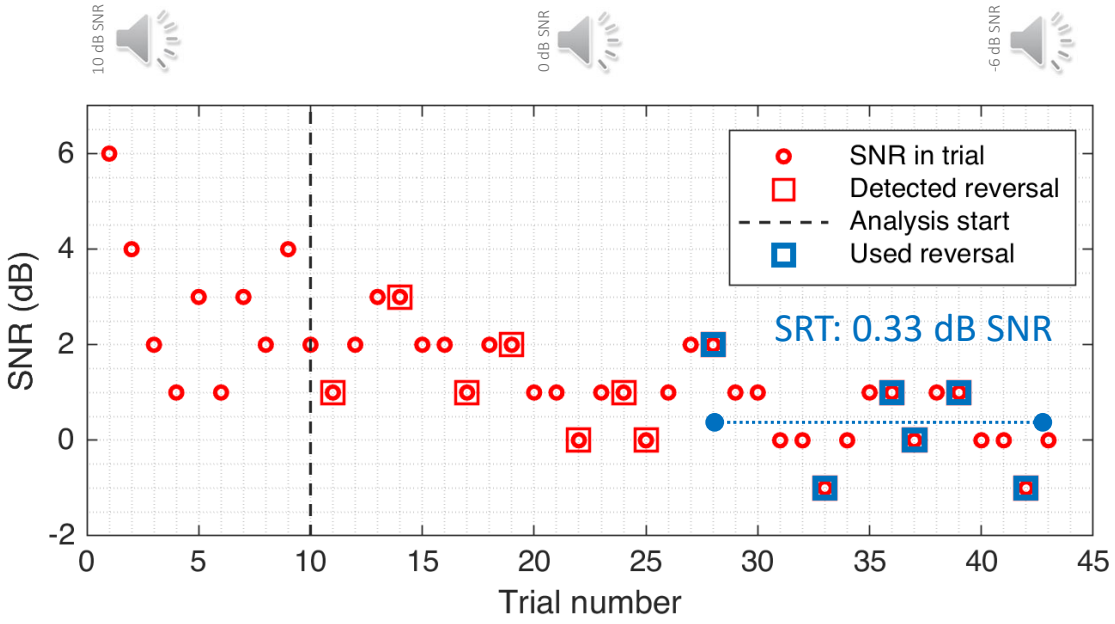



- **In most cases**, the amount of energy arriving at the IHCs is comparable to that of the NH (normal hearing) case.
- **Threshold of pain** is **unchanged** (and also the range of uncomfortably loud signals).
- The **dynamic range** (between threshold of hearing and threshold of pain) is **narrower**.
- In hearing assistive technology:
  - we need to **know the thresholds** (pure tone audiometry),
  - we 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 noise reduction algorithms.

# Hearing aids – Early history

Source: hearingaidmuseum.com, 2021

**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)

# •• 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 – 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:

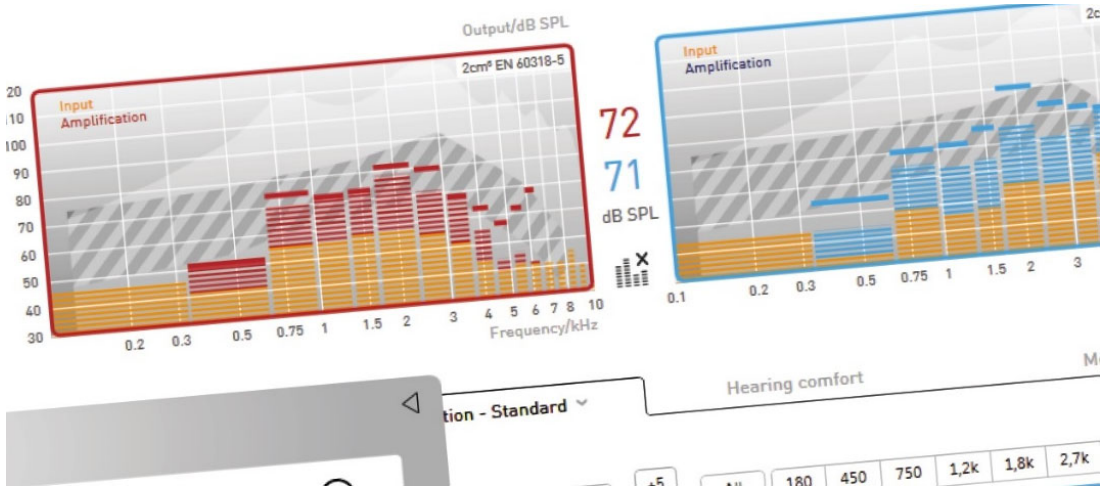
- Small, lightweight, intuitive, discrete*.
- Remote control, smartphone app.
- Wireless streaming (TV, remote microphone).
- Quickly rechargeable, long lasting battery.

## Audiological features:

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

Discrete vs. Fancy





# Hearing aids – Medical features

General:

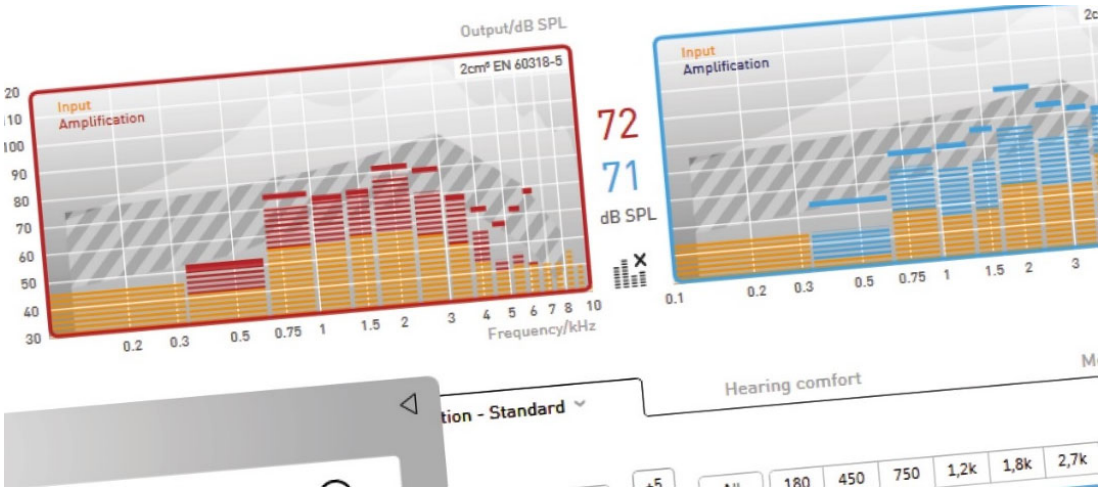
- Small, lightweight, intuitive, discrete.
- Remote control, smartphone app.
- Wireless streaming (TV, remote microphone).
- Quickly rechargeable, long lasting battery.

Audiological features:

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

Fitness and medical features:

- Fitness tracking (step counter, pulse rate etc.).
- Blood pressure monitoring (Sonion BiometRIC).
- On-demand activity log.
- Fall detection.



## Hear

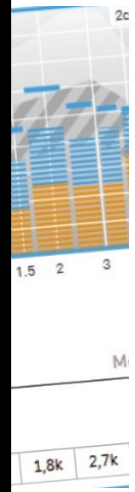
[redacted]

Gener

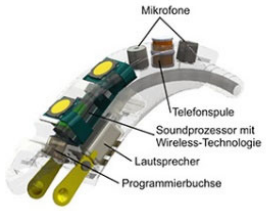
- Sma
- Rem
- Wir
- Qui

Audio

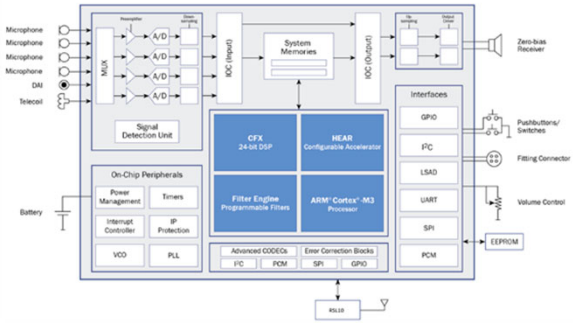
- Low
- 10+
- Ada
- Noi
- Env
- Adv
- Fre
- Low

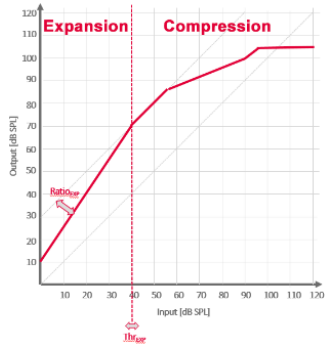


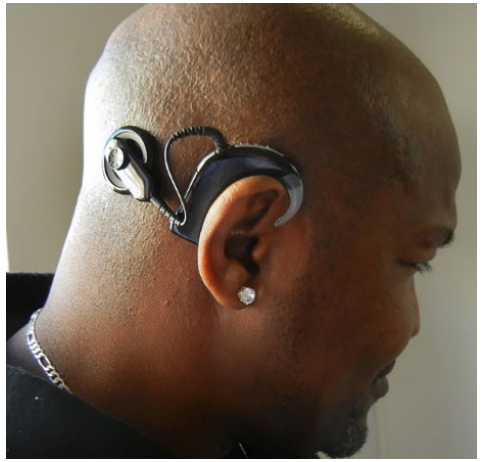
# •• Next time

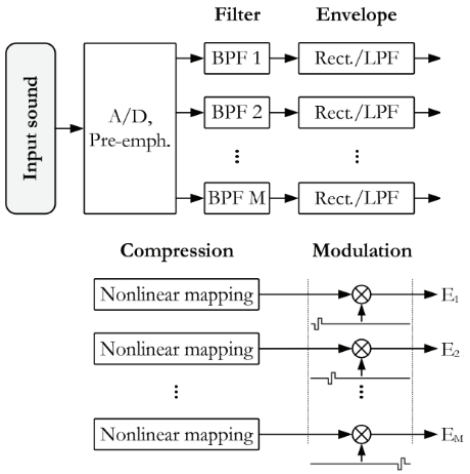

Mikrofone
Telefonspule
Soundprozessor mit
Wireless-Technologie
Lautsprecher
Programmierbuchse

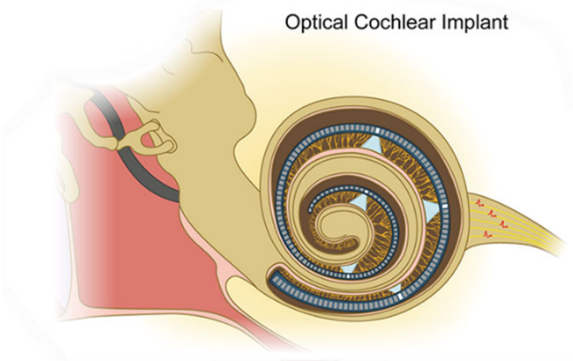

Schalter
Batterie


Microphone
Microphone
Microphone
Microphone
DAI
Telecoil
Battery
MUX
A/D
I²C (Input)
System Memories
I²C (Output)
Signal Detection Unit
CFX 24-bit DSP
HEAR Configurable Accelerator
Filter Engine Programmable Filters
ARM® Cortex®-M3 Processor
On-Chip Peripherals
Power Management
Timers
Interrupt Controller
IP Protection
VCO
PLL
Advanced CODECs
Error Correction Blocks
I²C
PCM
SPI
GPIO
Interfaces
GPIO
I²C
LSAD
UART
SPI
PCM
Zero-bias Receiver
Pushbuttons/ Switches
Fitting Connector
Volume Control
EEPROM


Expansion
Compression
Output [dB SPL]
Input [dB SPL]
Ratio
Thr




Filter
Envelope
Input sound
A/D, Pre-emph.
BPF 1
BPF 2
BPF M
Rect./LPF
Rect./LPF
Rect./LPF
Compression
Modulation
Nonlinear mapping
Nonlinear mapping
Nonlinear mapping
E1
E2
EM


Optical Cochlear Implant

audifon
hearing systems

# Thank you very much!
# Questions?

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