audifon
hearing systems

Hearing Systems – Part 2 of 3

https://hearingsystems.github.io/

TU Ilmenau – Audio Signal Processing & Audio Systems

January 23, 2024

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 (Electronics) and Ilmenau (Embedded Software);
  - about 220 employees.

- KIND:
  - KIND GmbH & Co. KG is specialized in hearing acoustics and optics;
  - headquarters located in Großburgwedel near Hanover;
  - around 750 specialist stores and over 3,000 employees;
  - KIND and audifon are both owned by the family Kind.

audifon
hearing systems

Introduction

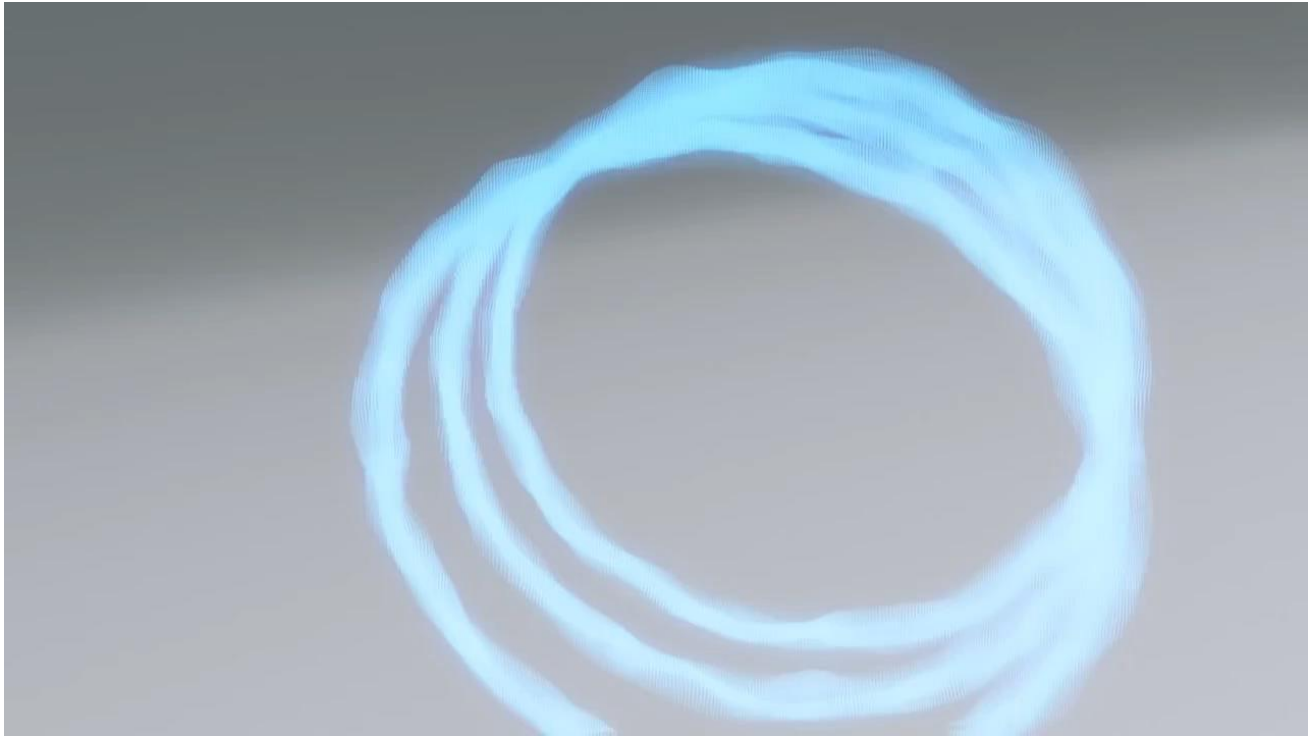
- Reminder:
  - Three lectures and one seminar.
  - Useful links:
    - https://hearingsystems.github.io/ (presentation slides and recordings),
    - https://moodle.tu-ilmenau.de/course/view.php?id=125.
- Topics we will cover today:
  - *Recap of the basics:* **units**, human hearing, **tonotopy**.
  - 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.

audifon hearing systems

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 with 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

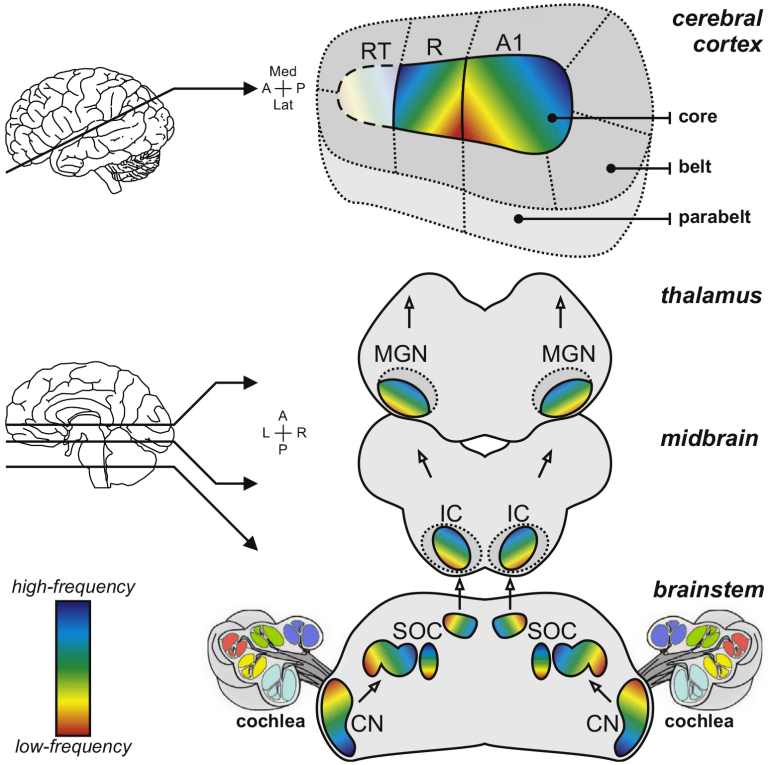


Source: youtube.com/@Signia-hearing, 2024.

•• Recap of the basics: tonotopy

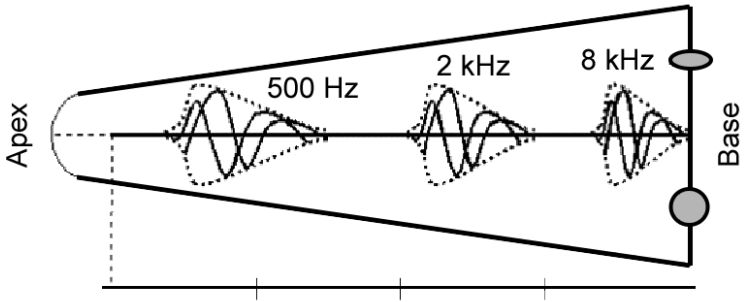
Source: HHMI, 2000.

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

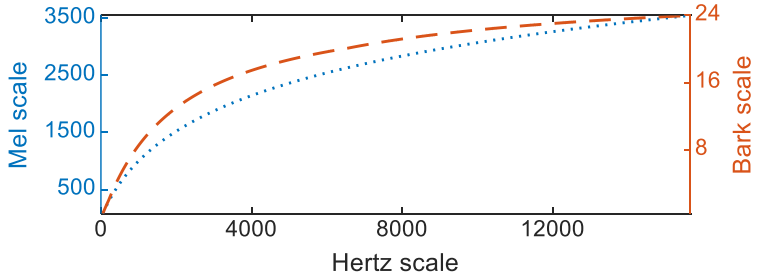


Source: Saenz & Langers, 2014.

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



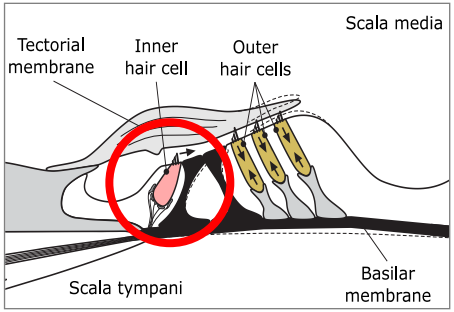
Frequency scale of the ear :

- 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.

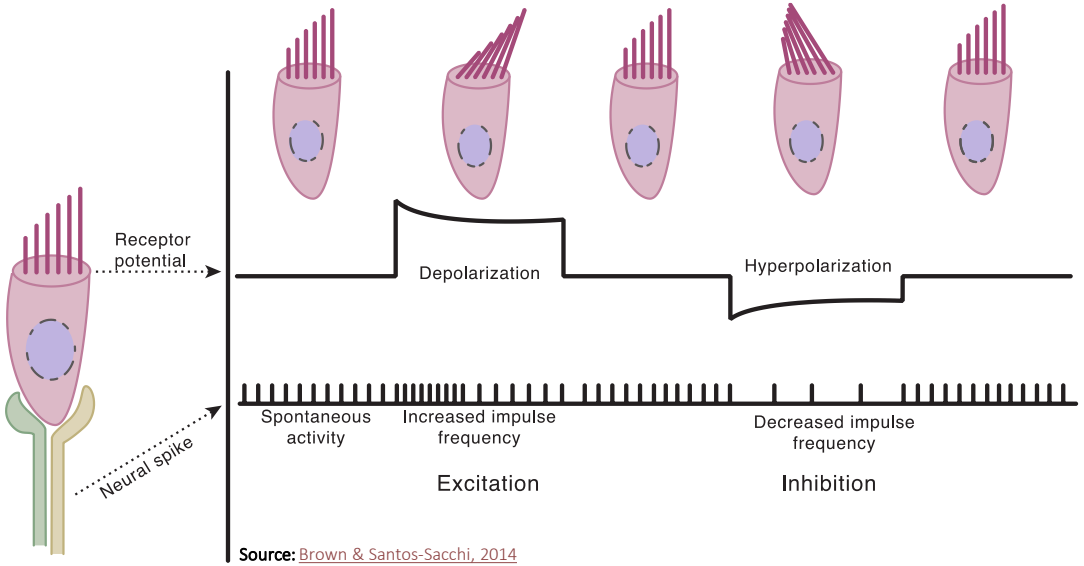

- Pitch difference of 1 Bark roughly equals to 1.3 mm on the BM; you only have around 150 IHCs along that cochlear section.

How hearing works: Inner hair cells

Organ of Corti



Adapted from: Baumgarte, 2000



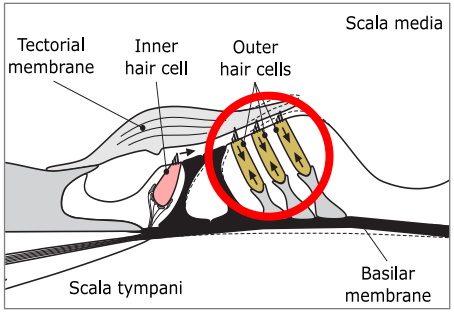
Source: Brown & Santos-Sacchi, 2014

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

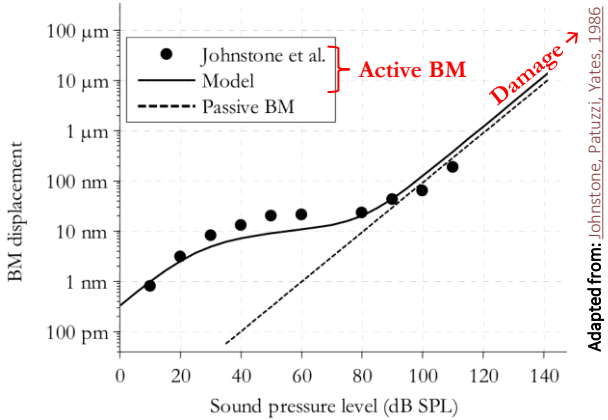


Adapted from: Baumgarte, 2000

OHC motility

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

BM nonlinearity



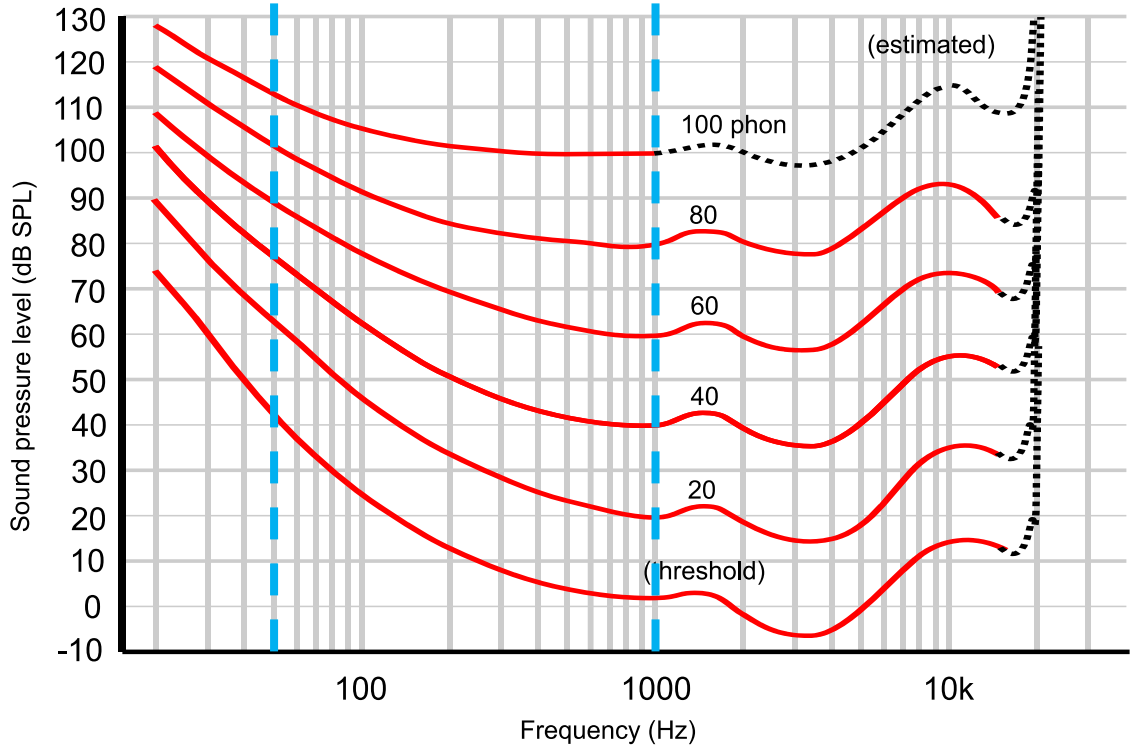
Adapted from: Johnstone, Patuzzi, Yates, 1986

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



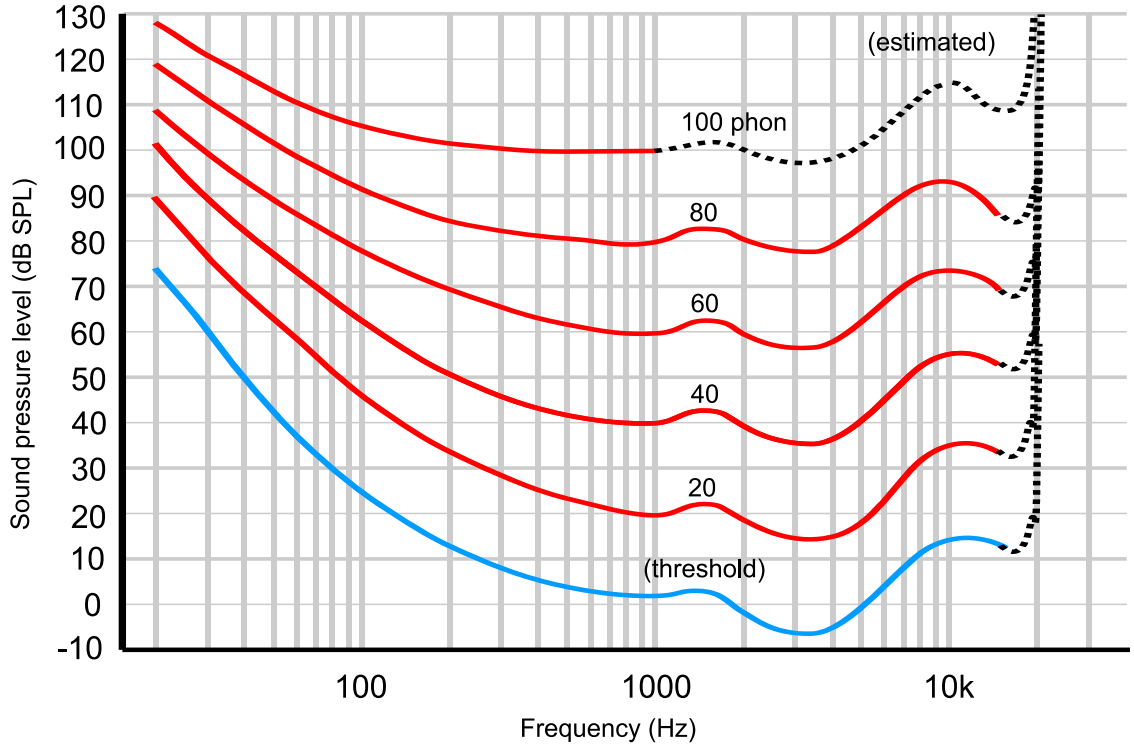
- 1933: Fletcher & Munson (*JASA*)
- 1956: Robinson & Dadson (*BJAP*)
- 2003: Multisite study, averaged over many normal hearing (NH) listeners → ISO 226:2003
- At 1000 Hz: dB SPL ≈ loudness.
- At other frequencies, e.g. at 50 Hz (mainly at higher levels) not.

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

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

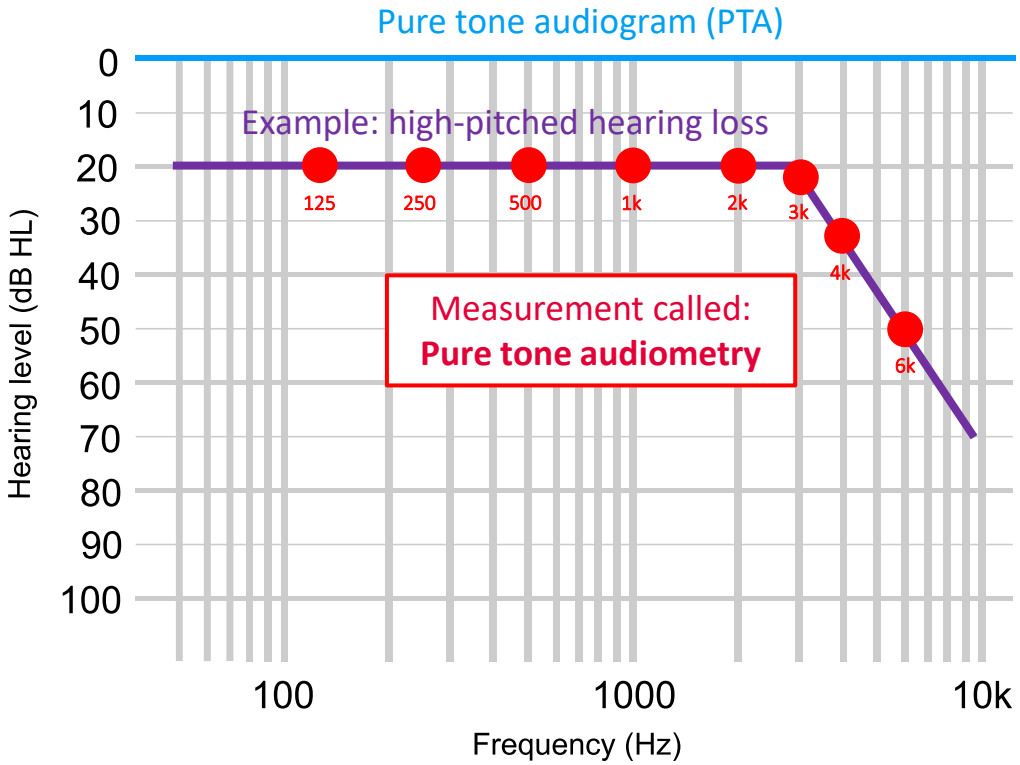
Equal loudness contours

Scales and units in audio signal processing: dB HL

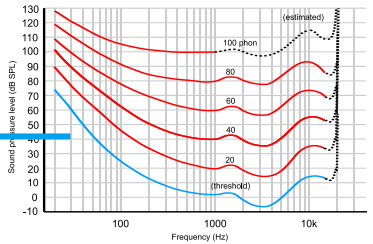


Source: https://upload.wikimedia.org/wikipedia/commons/4/49/Lindos4.svg

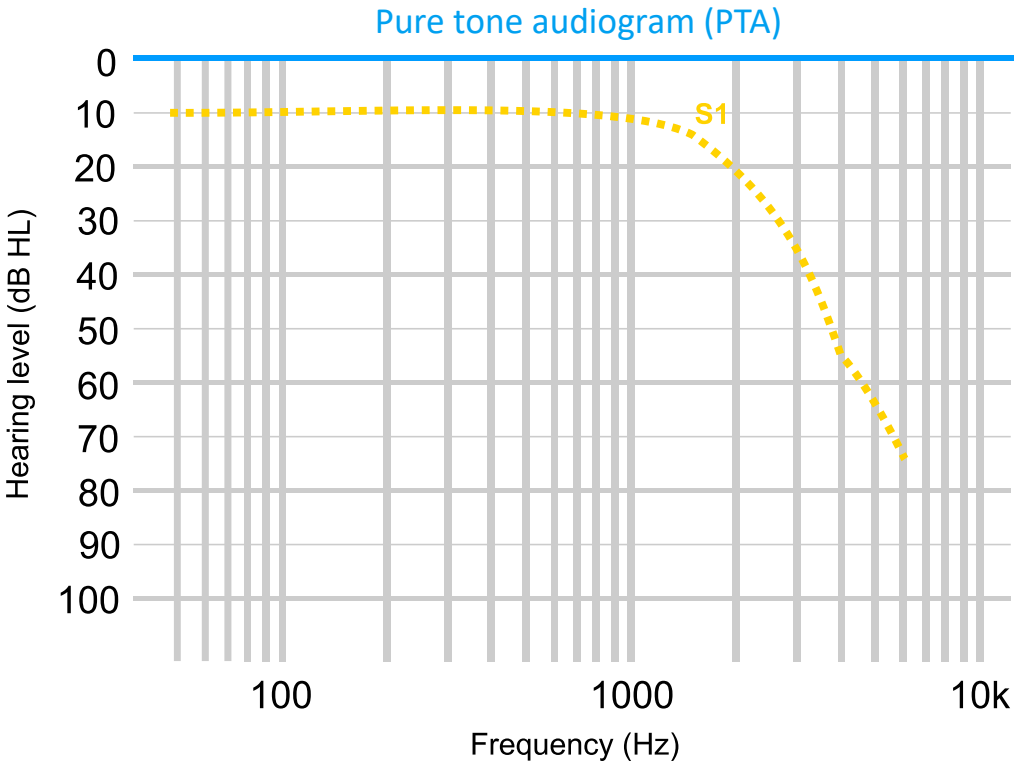
•• Scales and units in audio signal processing: dB HL



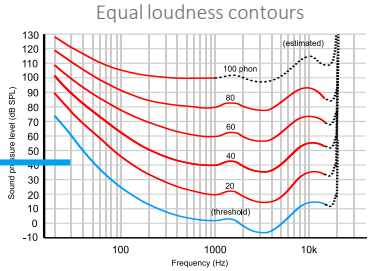
Equal loudness contours



Scales and units in audio signal processing: dB HL



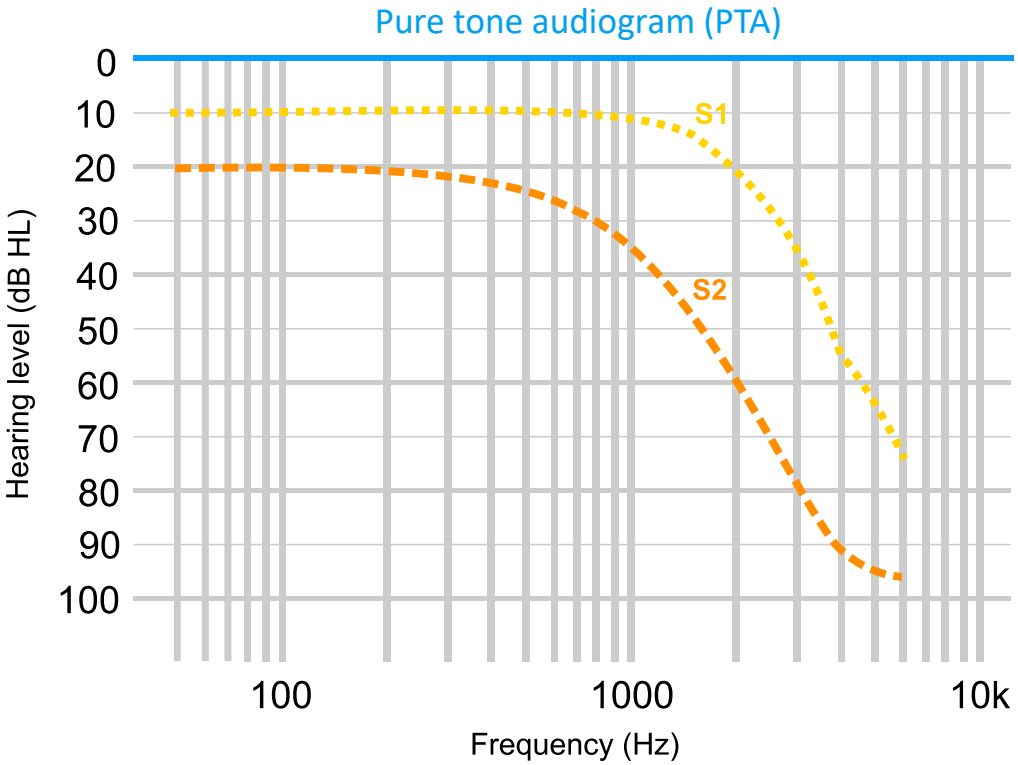
Equal loudness contours

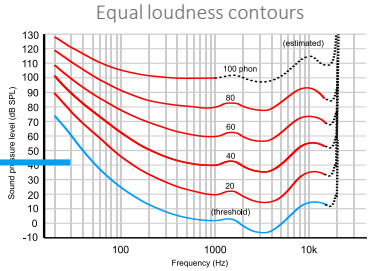


Bisgaard standard audiograms:

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

Scales and units in audio signal processing: dB HL

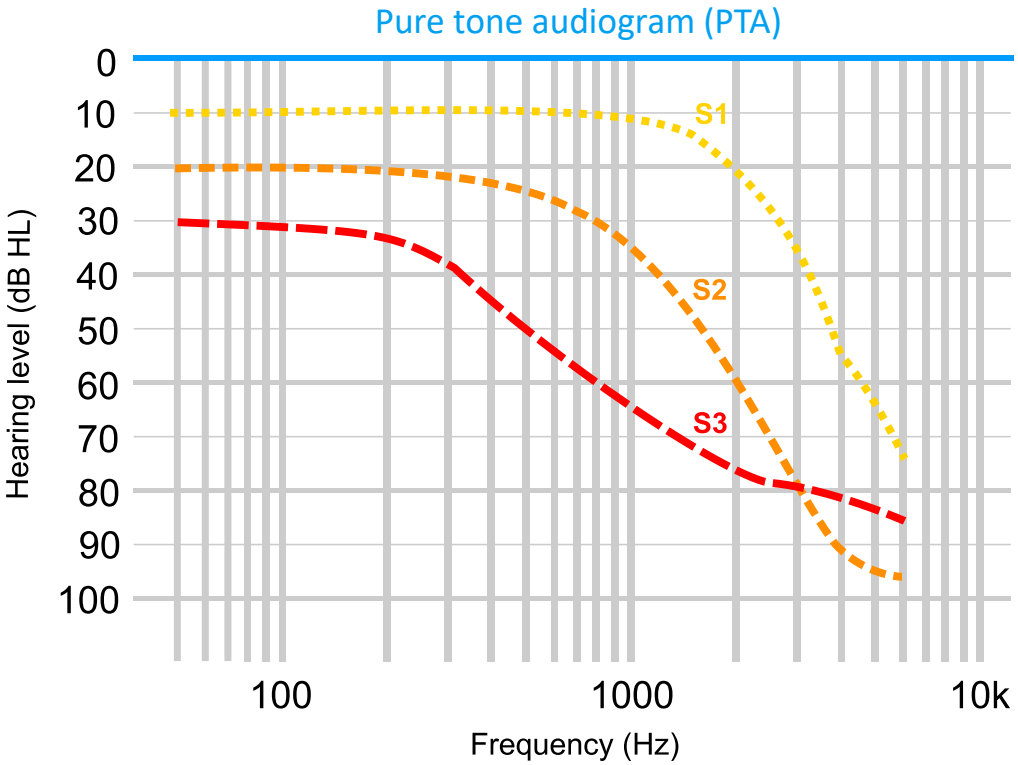




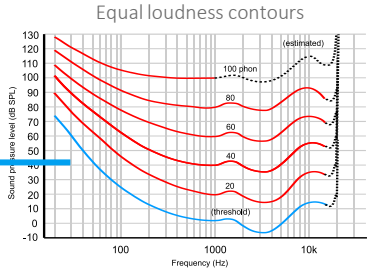
Bisgaard standard audiograms:

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

Scales and units in audio signal processing: dB HL



Equal loudness contours

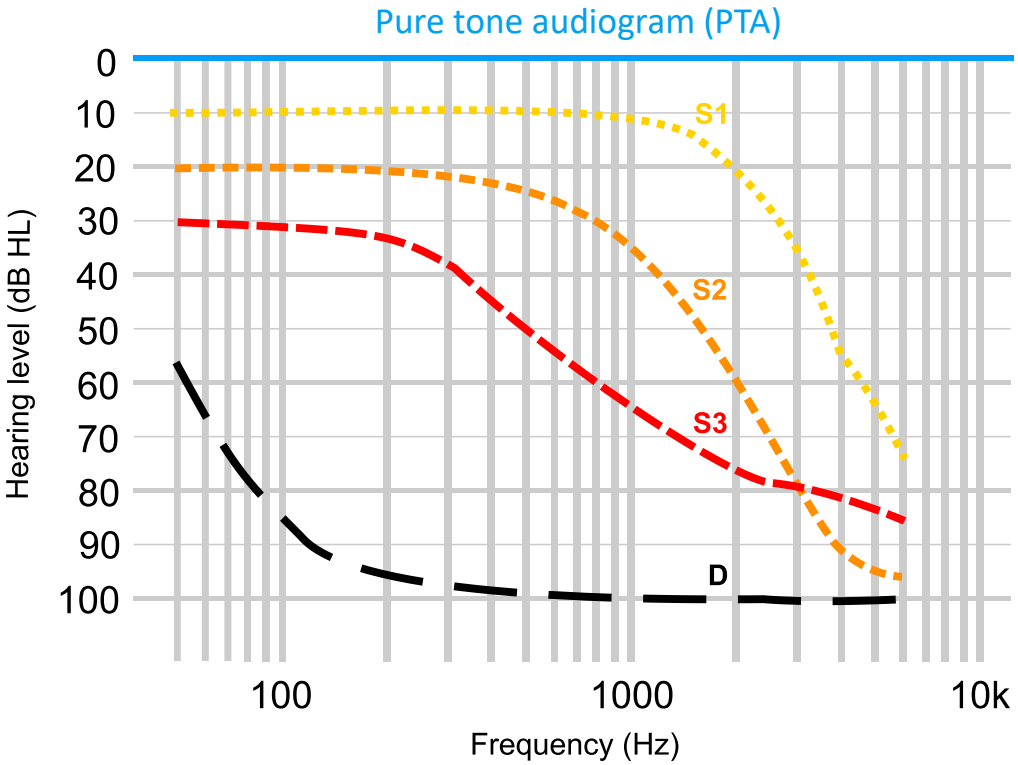


Bisgaard standard audiograms:

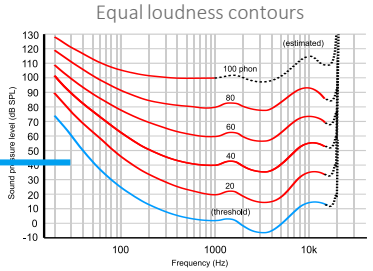
- S1: very mild *(degree of hearing loss)*
- S2: mild
- S3: severe

Source: Bisgaard et al. (2010)

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



Equal loudness contours



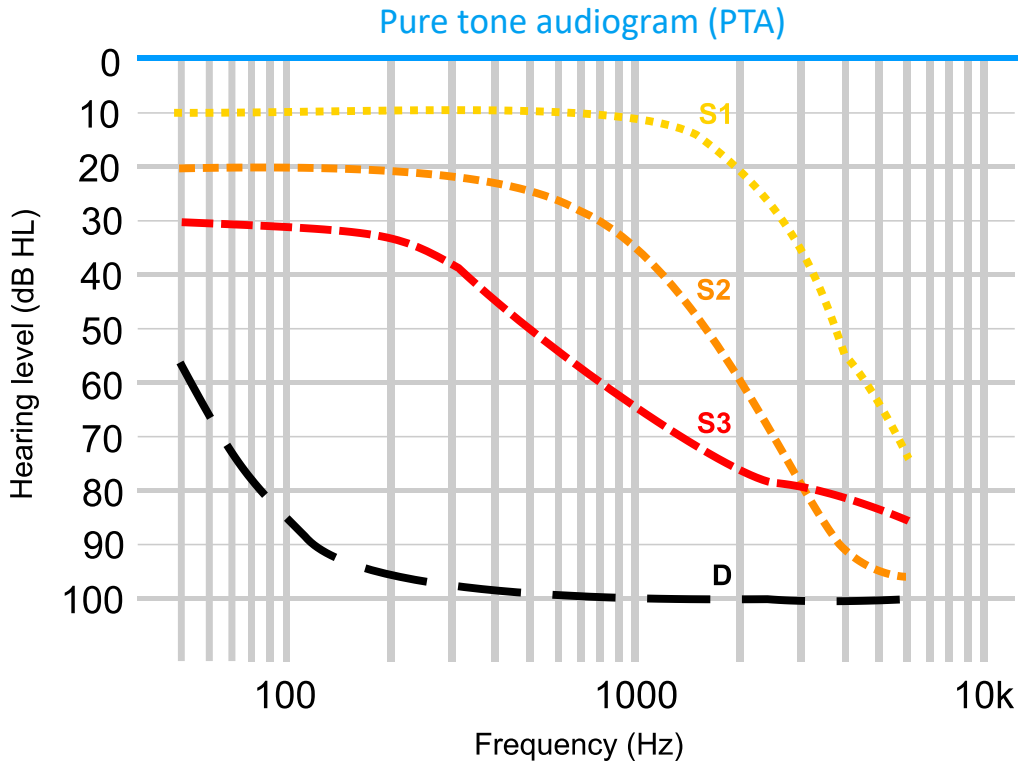
Bisgaard standard audiograms:

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

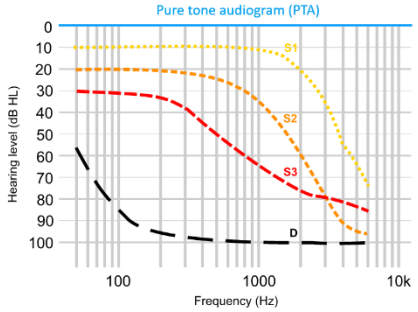
Source: Bisgaard et al. (2010)

- D: hearing loss bordering on deafness

Hearing and hearing impairments



Hearing and hearing impairments



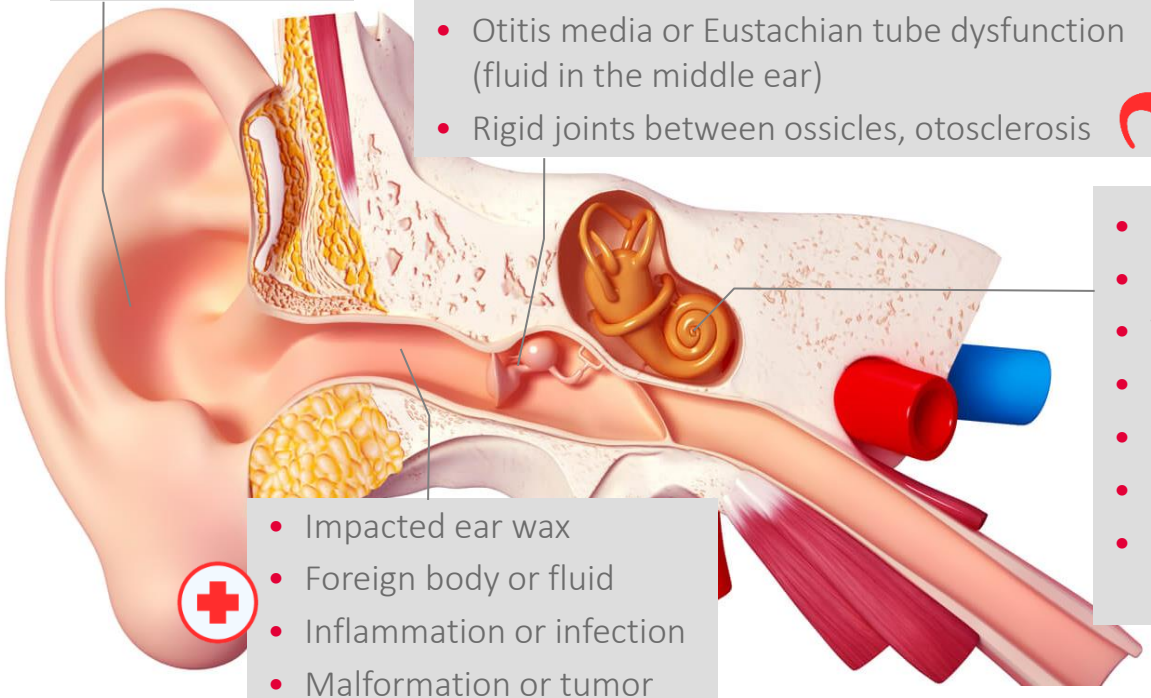
Questions:

- 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

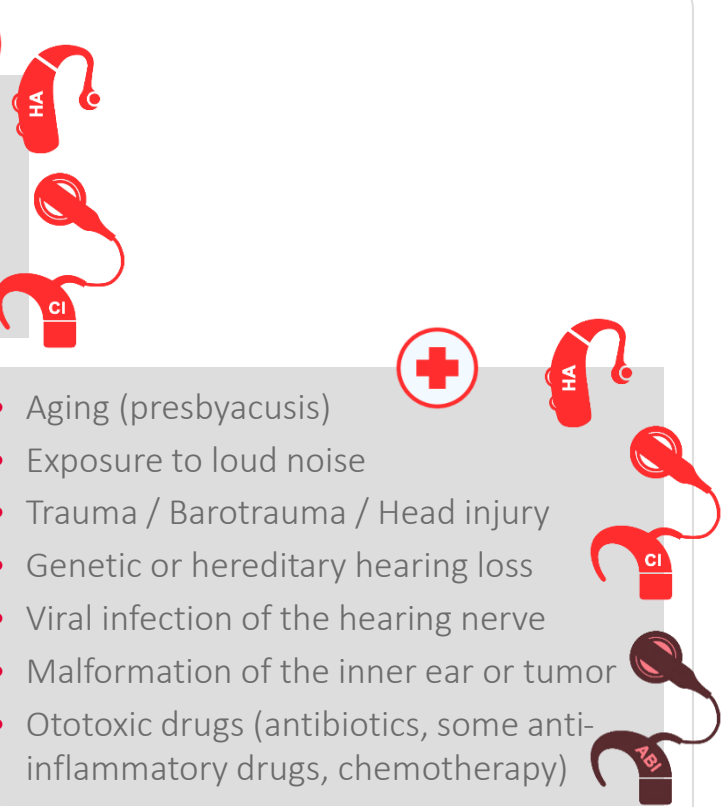
- Malformation
- Foreign body

- 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

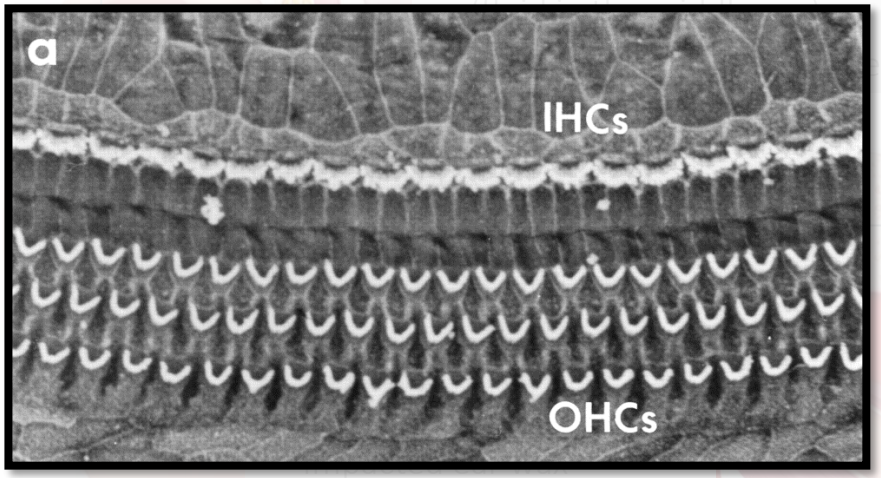
- Aging (presbyacusis)
- Exposure to loud noise
- Trauma / Barotrauma / Head injury
- Genetic or hereditary hearing loss
- Viral infection of the hearing nerve
- Malformation of the inner ear or tumor
- Ototoxic drugs (antibiotics, some anti-inflammatory drugs, chemotherapy)

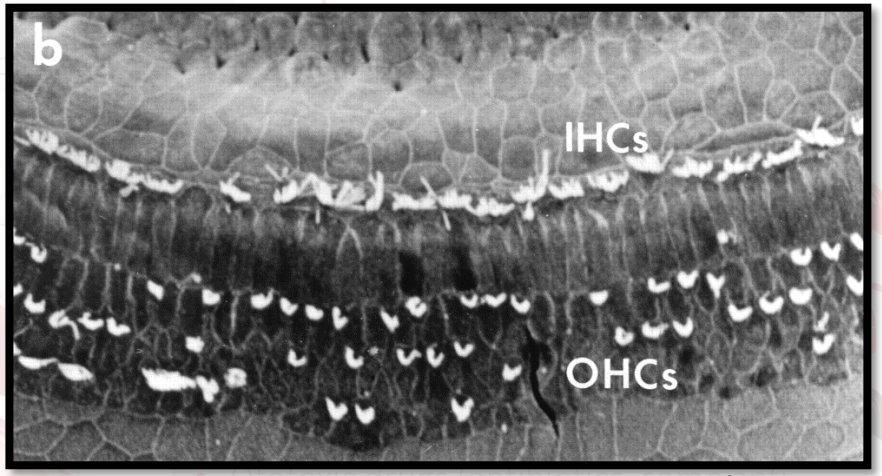


Source: www.lobe.ca, 2021.

•• Causes of hearing impairment

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





Source: Ryan, 2000

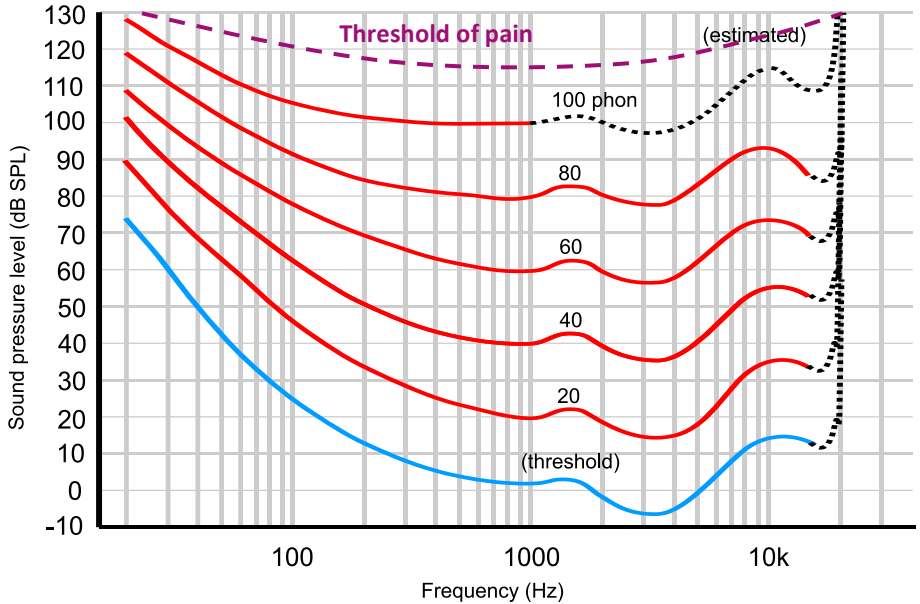
Consequences of hearing impairment

- 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. [FJ23]
- Danger: dementia. [FJ23]

[FJ23] F. Jiang et al., "Association between hearing aid use and all-cause and cause-specific dementia: an analysis of the UK Biobank cohort," *The Lancet*, vol. 8, no. 5, doi: 10.1016/S2468-2667(23)00048-8, 2023.

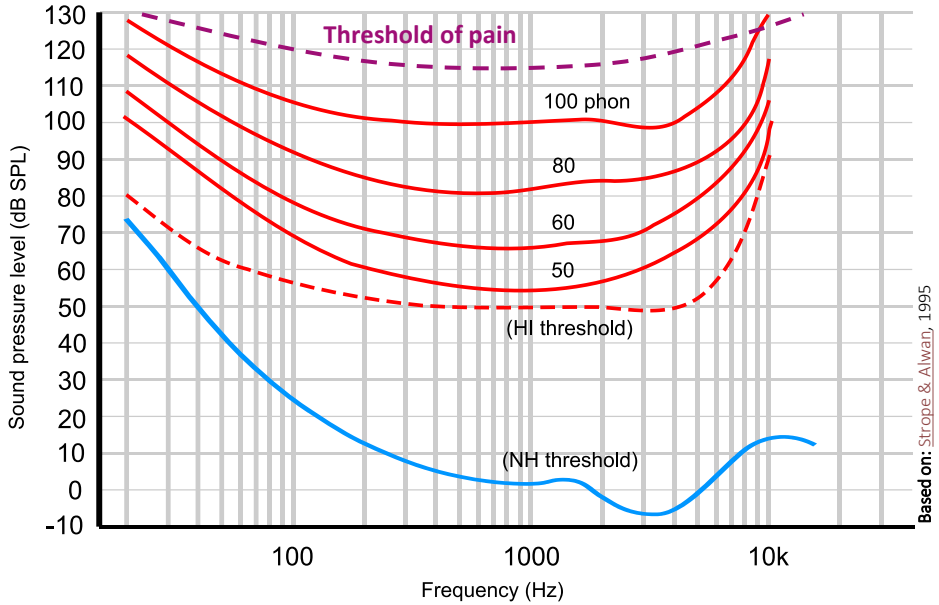
First signs of a hearing impairment #1

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



First signs of a hearing impairment #1

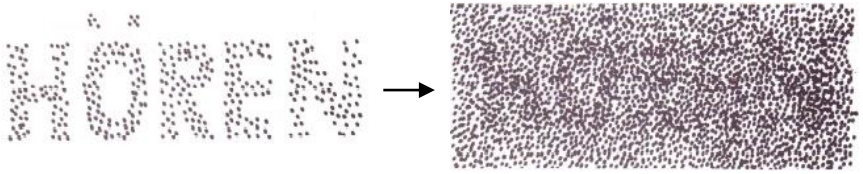
- Speech at moderate level not always understood, but **loud speech becomes disturbing** and misinterpreted as offensive.

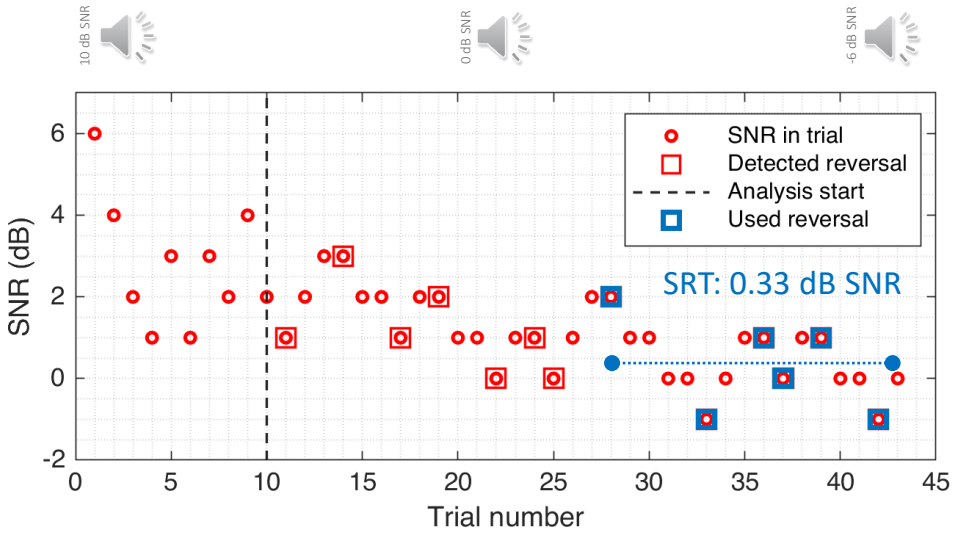


- **In most cases**, the amount of energy arriving at the IHCs is comparable to that of the NH (normal hearing) case.
- **Threshold of pain** is **unchanged** (and also the range of uncomfortably loud signals).
- The **dynamic range** (between threshold of hearing and threshold of pain) is **narrower**.
- 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 | 1984 | 1996

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

Disability:

35+ dB hearing loss in better ear confirmed by a medical doctor

- Attested hearing impairment is a **disability**.
- Health insurance (in Germany) pays for an adequate hearing aid system. **Technical requirements** (as of 2023):
  - digital technology;
  - a minimum of 6 frequency channels with compression;
  - a minimum of 4 selectable, individualized programs (=*settings*);
  - directional microphones (to help separate speech and noise);
  - availability of feedback suppression method.

- 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.

Co-payments for hearing systems in Germany

Co-payment for hearing aid provision has existed in Germany since the health reform of 1989 (effective from 1993).

In 2023, the statutory health insurance funds [GK22] generally cover a contract price of

- €685 per hearing aid, plus
- a standard fee for custom-made earpieces of €33.50 and
- a flat-rate service fee for repair work of approximately €125.

Contract price generally covers standard hearing aid models (→ *Nulltarif*), but patients can pay extra to purchase premium products.

Cochlear implants are usually covered 100% by the health insurance.

[GK22] GKV-Hilfsmittelverzeichnis, "Festbeträge für Hörhilfen," 2022

Hearing aids – Expected features

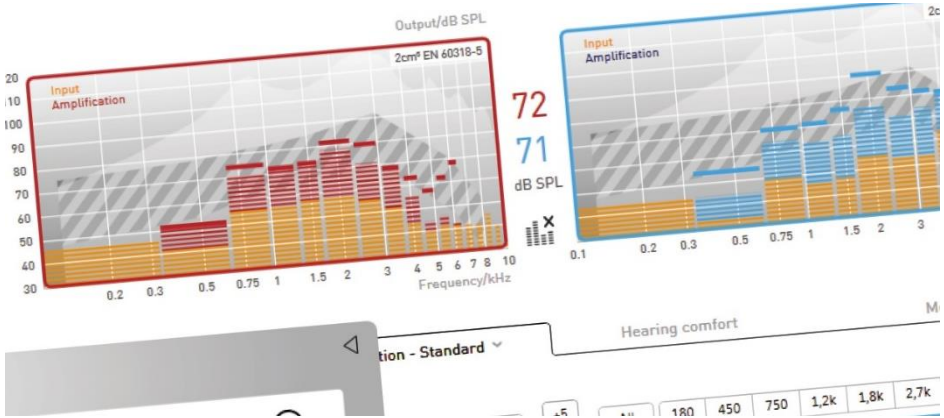
General:

- 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:

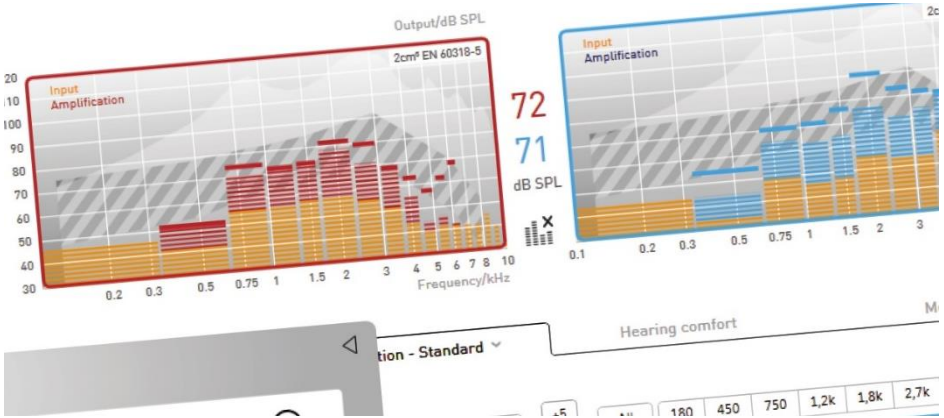
- Small, lightweight, intuitive, discrete.
- Remote control, smartphone app.
- Wireless streaming (TV, remote microphone).
- Quickly rechargeable, long-lasting battery.

Audiological features:

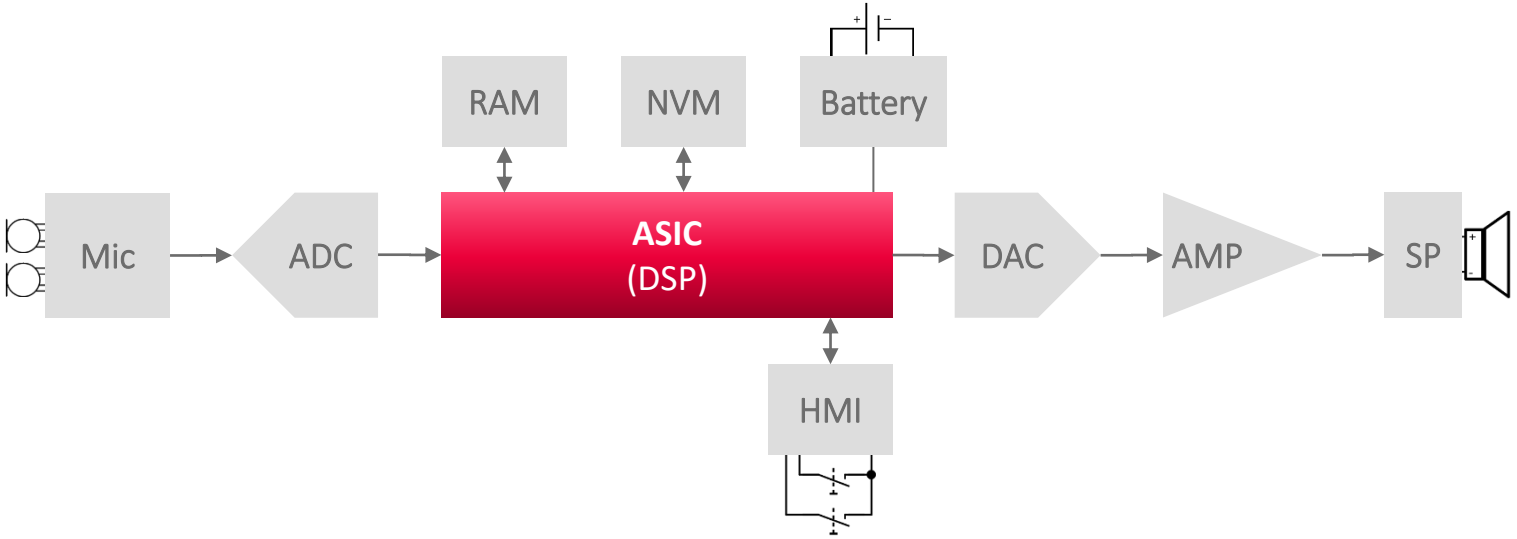
- Low noise, high gain, high bandwidth (10 kHz+).
- 10+ frequency channels for DRC.
- Adaptive microphone directionality.
- Noise reduction: ambient, wind, impulse.
- Environment classification.
- Advanced feedback cancelation.
- Frequency shifting.
- Low latency (<< 10 ms), binaural algorithms.

Fitness and medical features:

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

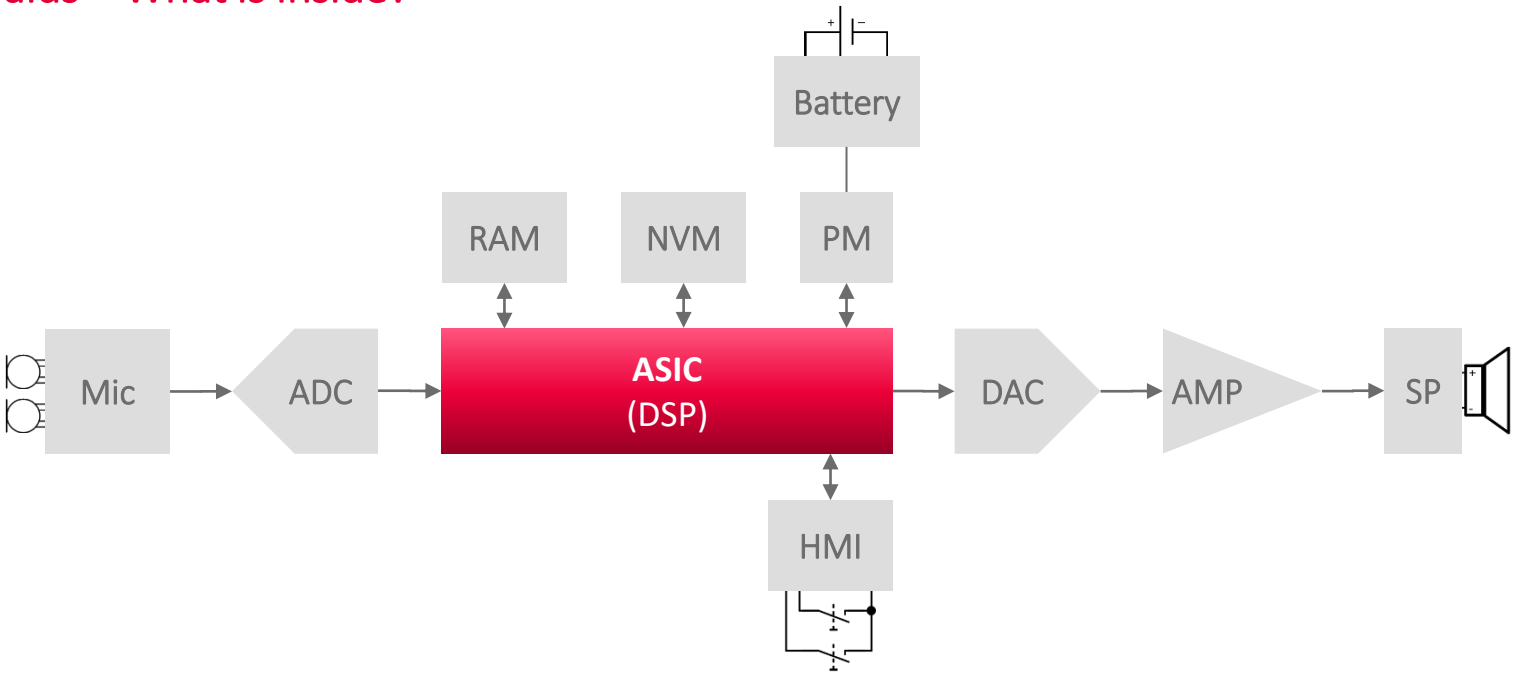


Hearing aids – What is inside?



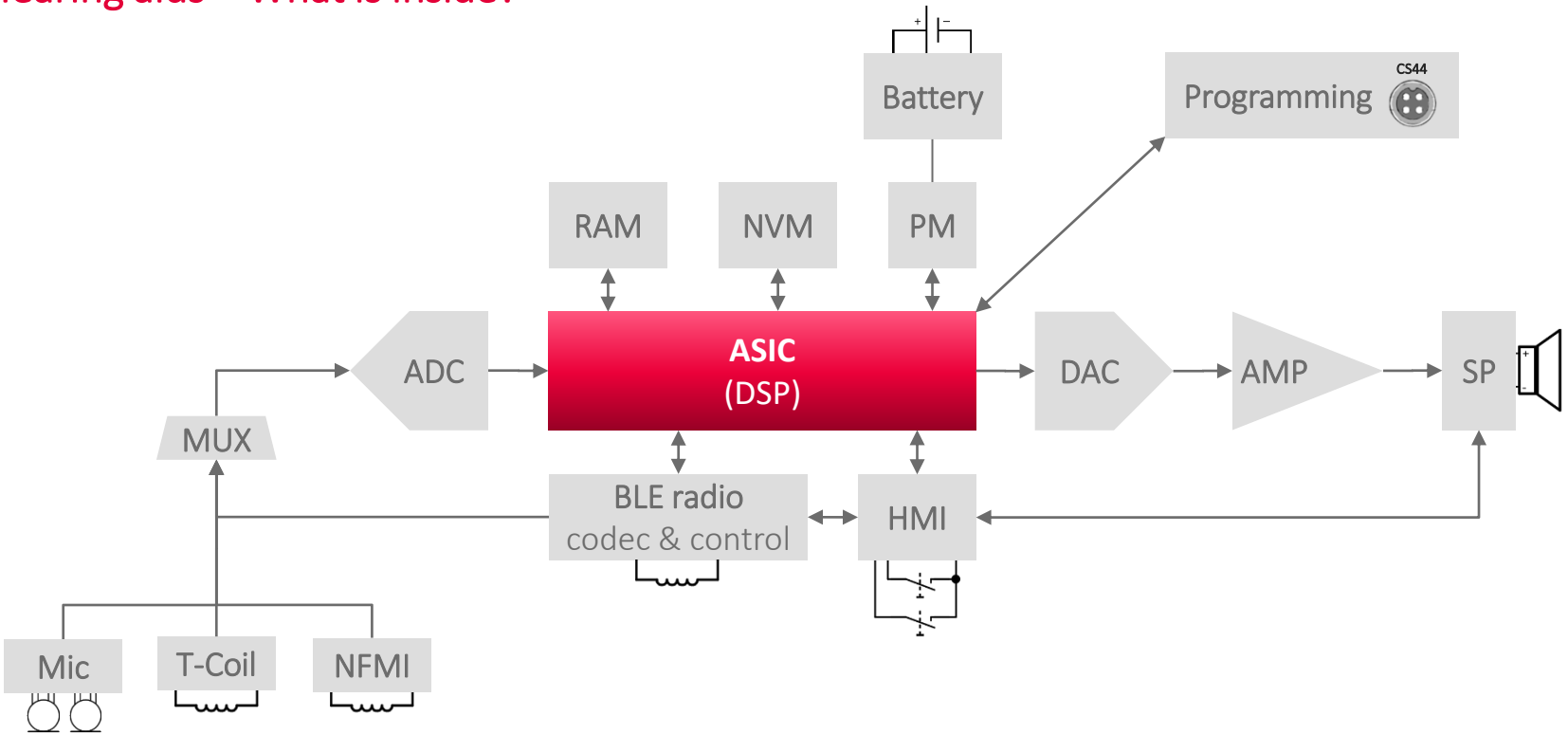
ASIC: application specific integrated circuit, **HMI**: human-machine interaction, **NVM**: non-volatile memory

Hearing aids – What is inside?



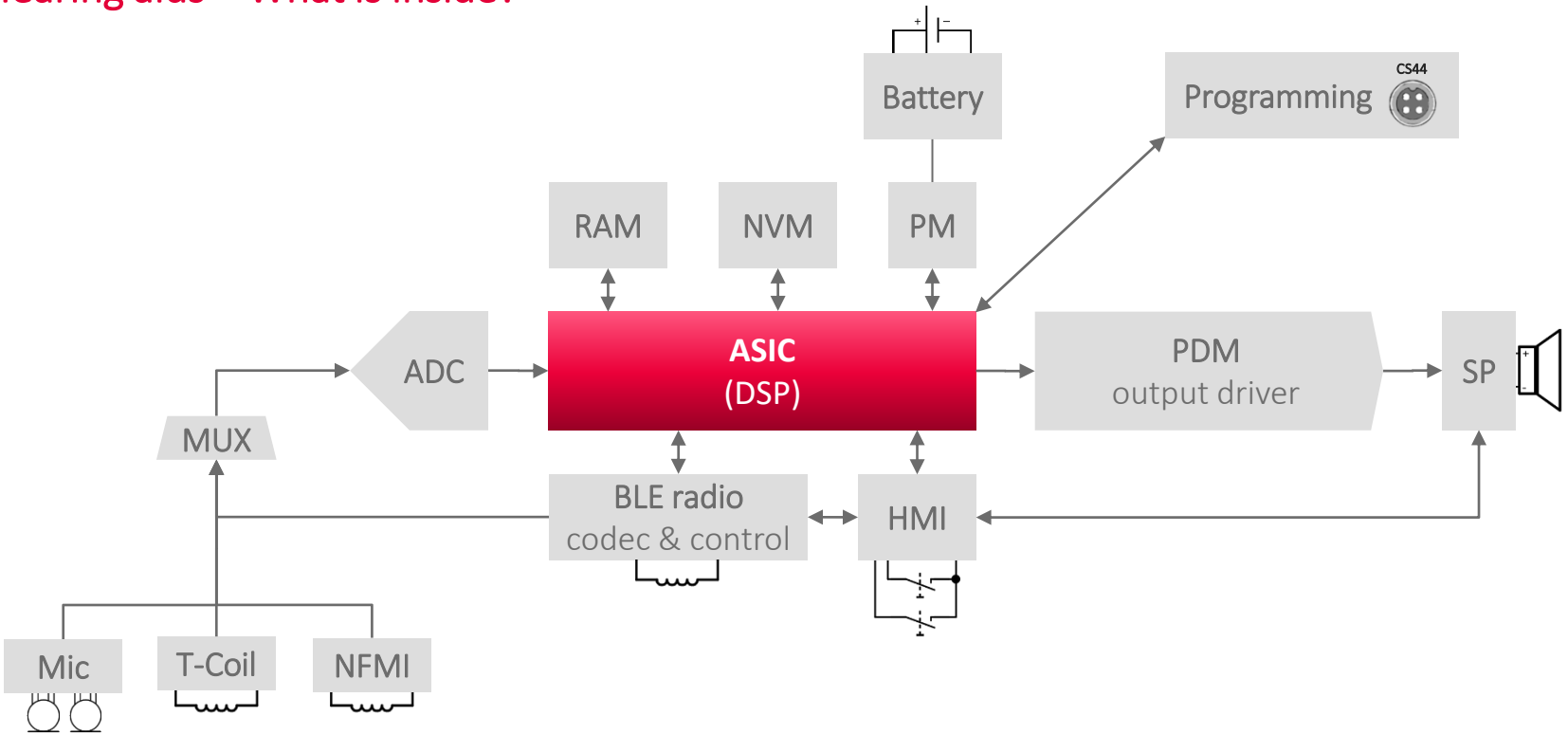
ASIC: application specific integrated circuit, **HMI**: human-machine interaction, **NVM**: non-volatile memory, **PM**: power management

Hearing aids – What is inside?



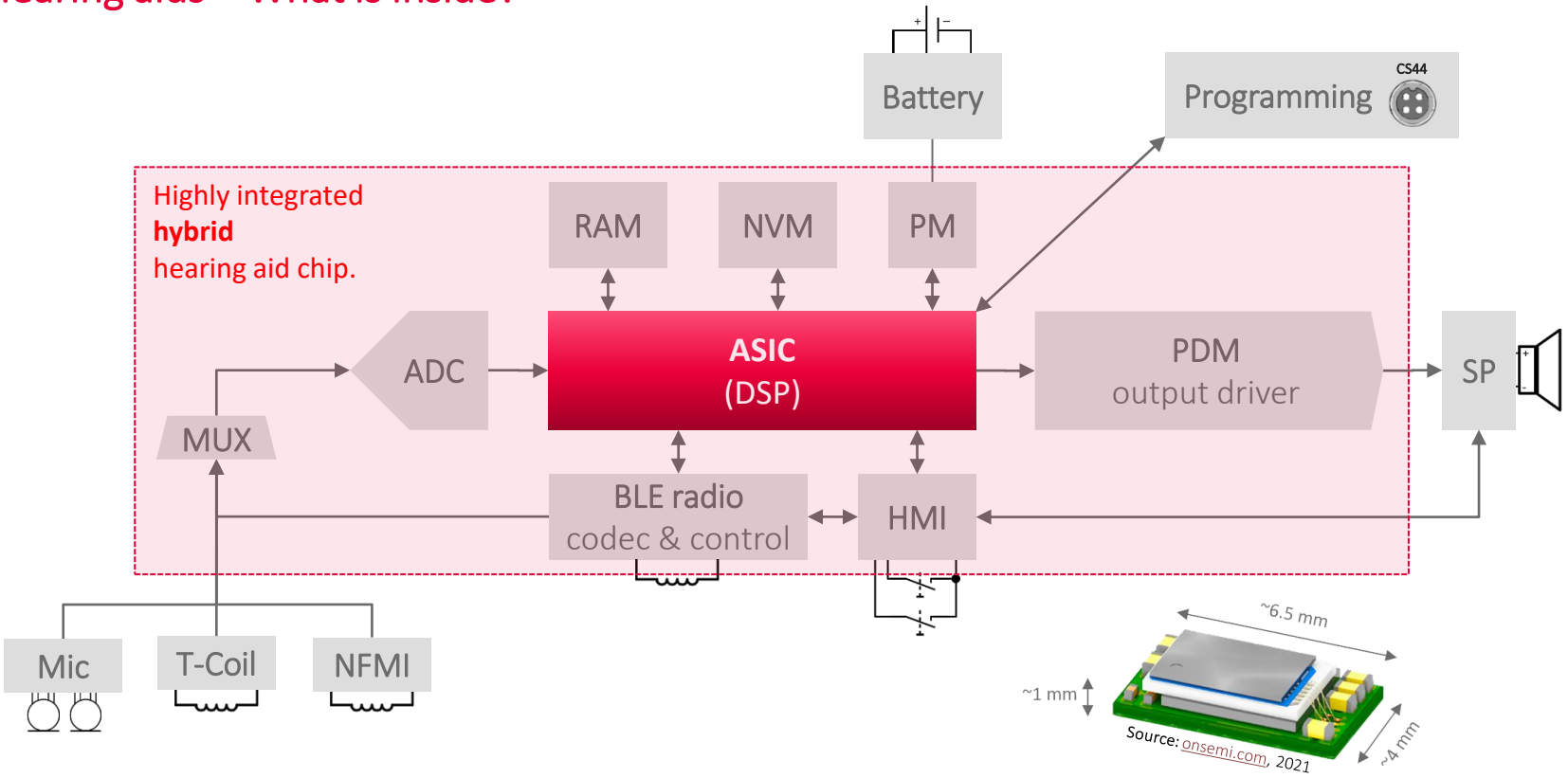
ASIC: application specific integrated circuit, **HMI**: human-machine interaction, **MUX**: multiplexer, **NFMI**: near-field magnetic induction, **NVM**: non-volatile memory, **PM**: power management, **T-Coil**: Telecoil (receiver for inductive loop), **WL**: (other) wireless technology

Hearing aids – What is inside?



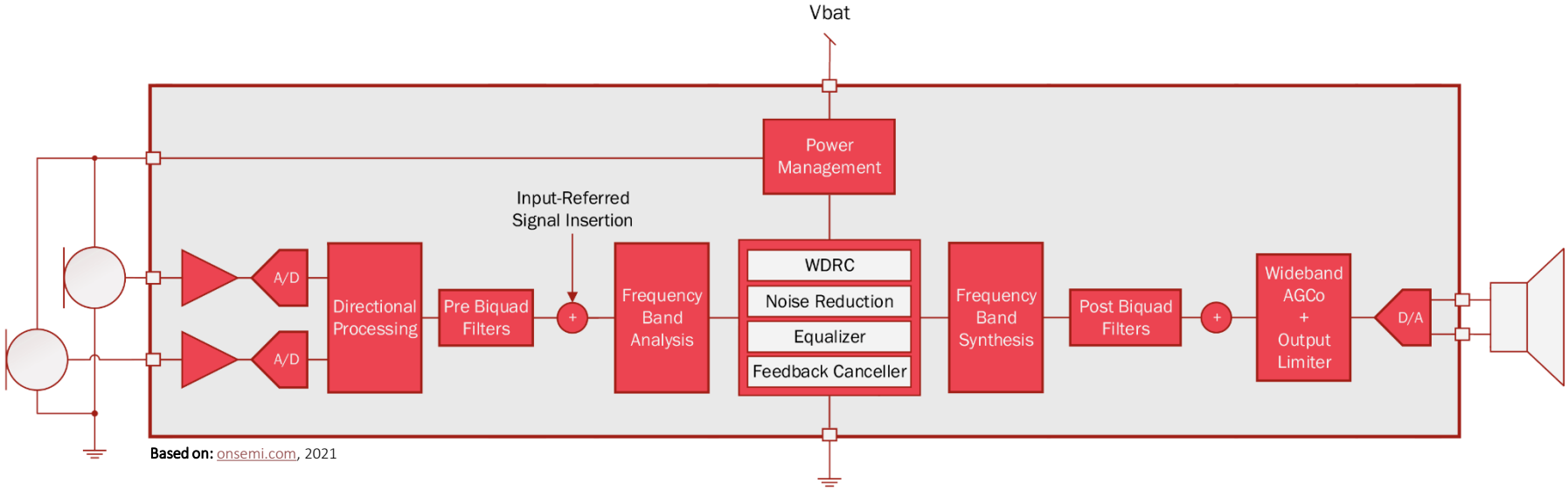
ASIC: application specific integrated circuit, **HMI**: human-machine interaction, **MUX**: multiplexer, **NFMI**: near-field magnetic induction, **NVM**: non-volatile memory, **PDM**: pulse density modulation, **PM**: power management, **T-Coil**: Telecoil (receiver for inductive loop), **WL**: (other) wireless technology

•• Hearing aids – What is inside?



ASIC: application specific integrated circuit, **HMI**: human-machine interaction, **MUX**: multiplexer, **NFMI**: near-field magnetic induction, **NVM**: non-volatile memory, **PDM**: pulse density modulation, **PM**: power management, **T-Coil**: Telecoil (receiver for inductive loop), **WL**: (other) wireless technology

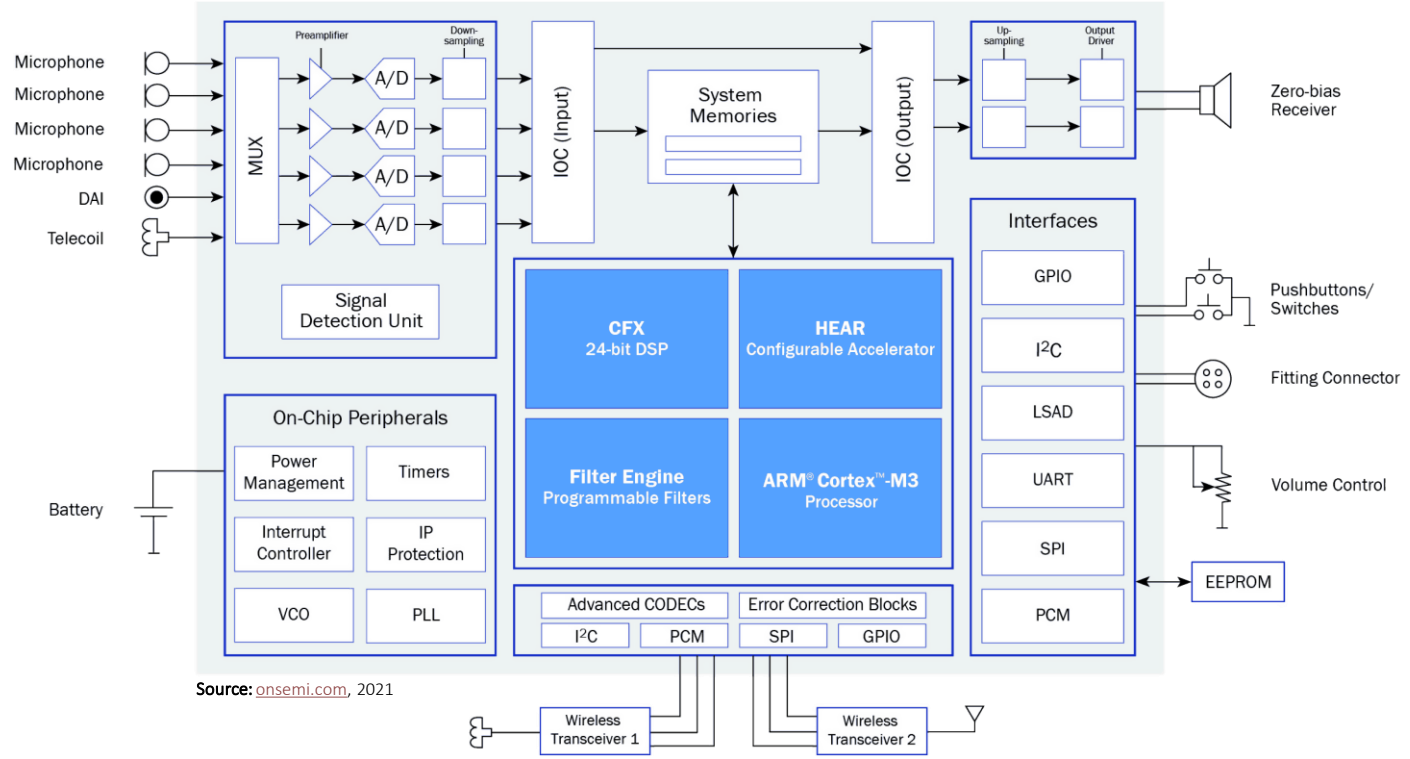
Hearing aids – Basic signal flow



Based on: onsemi.com, 2021

AGCo: automatic gain control for output, **WDRC**: wide dynamic range compression

•• Hearing aids – Architecture of a hearing aid ASIC



Source: onsemi.com, 2021

ASIC: application specific IC, **DAI**: digital audio input, **EEPROM**: electrically erasable programmable read-only memory, **GPIO**: general purpose input/output, **I²C**: inter-integrated circuit, **IOC**: input/output controller, **IP**: intellectual property, **LSAD**: low-speed A/D converter, **PCM**: pulse code modulation, **SPI**: serial peripheral interface, **UART**: universal asynchronous receiver transmitter, **WL**: (other) wireless technology

•• Hearing aids – Basic specifications

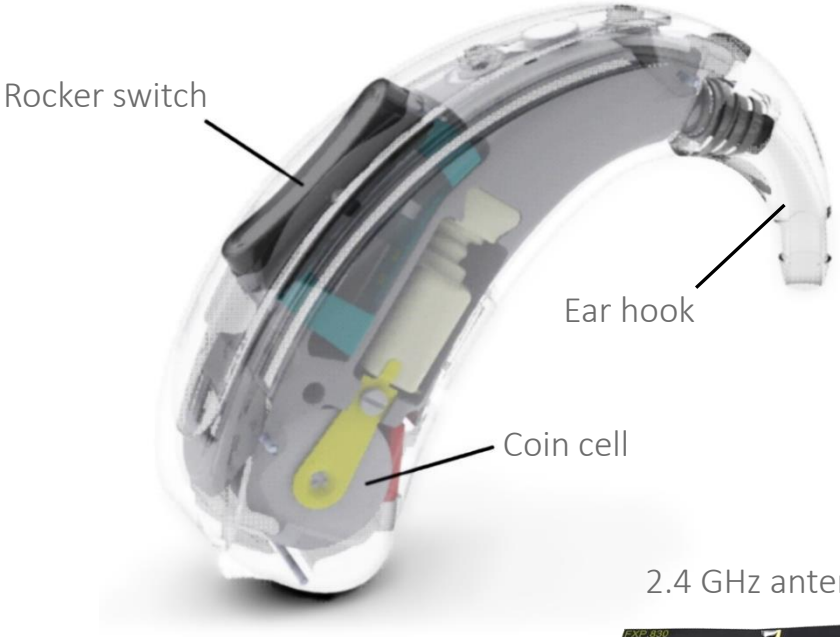
Rough estimates!

Source: jabra.com, 2021

Source: amd.com, 2021

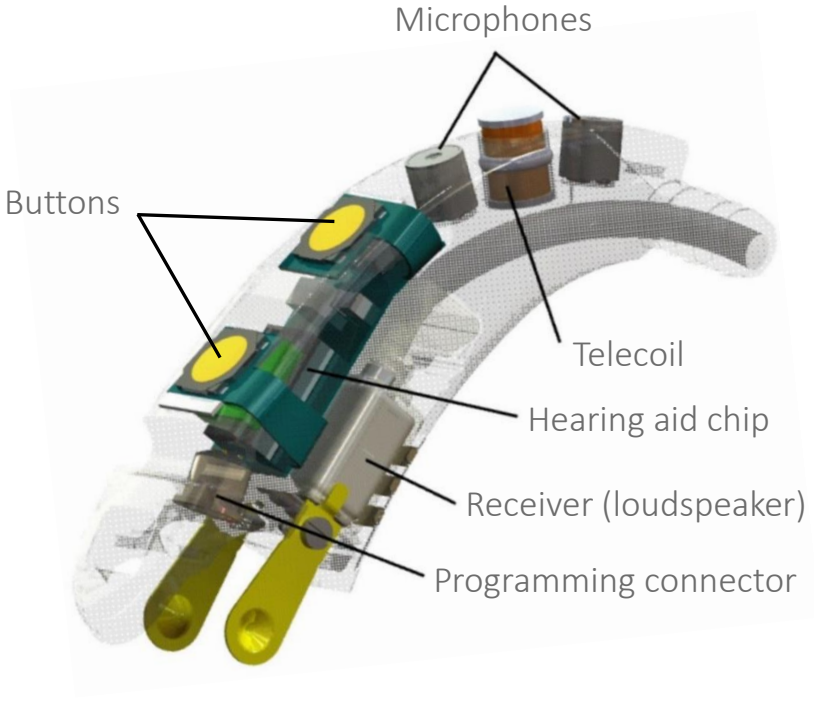
	Hearing aid ASIC	Hearable ASIC	PC CPU
Typical power consumption (algorithms on, wireless off)	**~ 1-2 mW**	~ 15-50 mW	**~ 35-125 W**
Typical power consumption (algorithms on, BLE in use)	+ 3-8 mW	+ 15-50 mW	
Clock speed	**~ 10-60 MHz**	~ 20-200 MHz	**~ 3000-4000 MHz**
MIPS @ max. clock speed	~ 400 MIPS	~ 1 000 MIPS	~ 200 000 MIPS
Typical dimensions	**~ 4 x 6.5 x 1 mm = 26 mm^3**	~ 5 x 8 x 1 mm = 40 mm^3	**~ 40 x 40 x 6 mm = 9.6 cm^3**
Number of cores	~ 2-8	~ 4-8	~ 2-32
Fabrication process	~ 45-22 nm	~ 45-22 nm	~ 14-7 nm

•• Hearing aids – Construction of a hearing aid



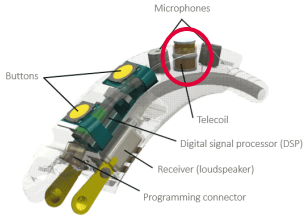
Source: kind.com, 2021

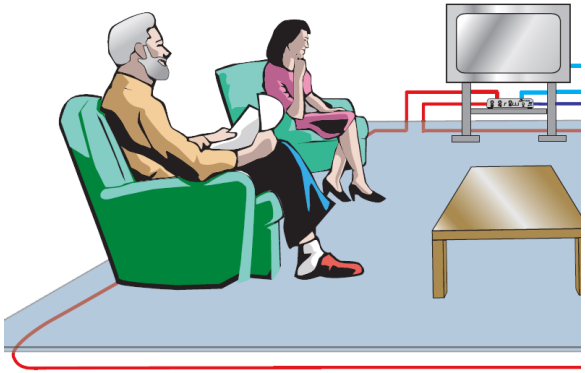
Source: taoglas.com, 2024

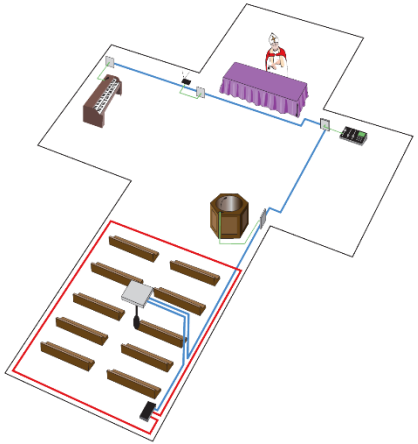


Source: kind.com, 2021

Excursion: Telecoil



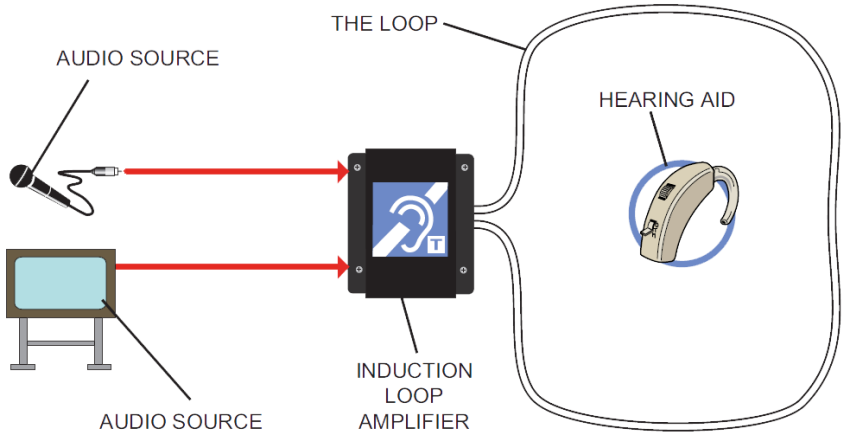




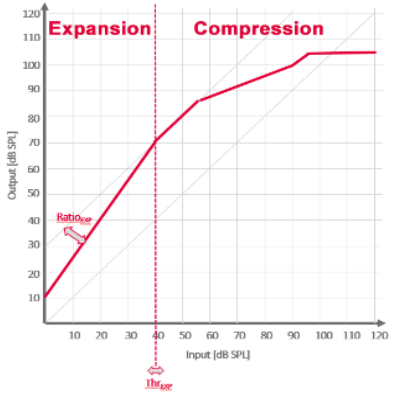
Source: signet-ac.co.uk, 2021

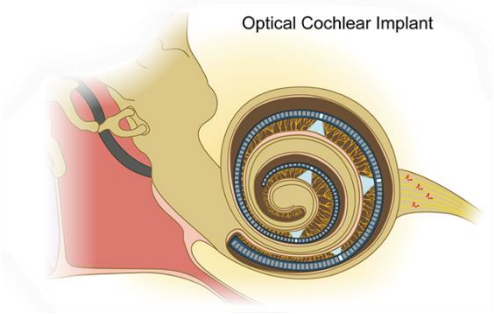
T-coil or induction loop receiver:

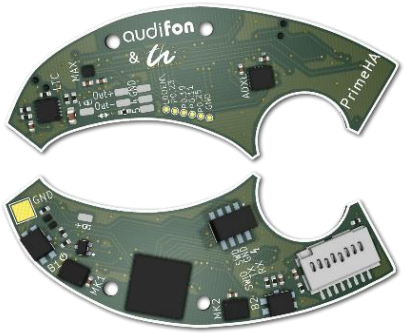
- Operating at audio frequencies, no RF.
- Induction loop parts:
  - constant current amplifier,
  - closed loop cable.
- Attention (privacy):
  - EM-field bleeding.
  - Always broadcast.



•• Next time


Expansion
Compression
Output [dB SPL]
Input [dB SPL]
120
110
100
90
80
70
60
50
40
30
20
10
10 20 30 40 50 60 70 80 90 100 110 120


Optical Cochlear Implant


audifon
& Ti
PrimeHA

Thank you very much!
Questions?

Dr.-Ing. Tamas Harczos
tamas.harczos@audifon.com

audifon GmbH & Co. KG