Hearing Systems – Part 3 of 3

https://hearingsystems.github.io/

TU Ilmenau – Audio Signal Processing & Audio Systems

January 25, 2023

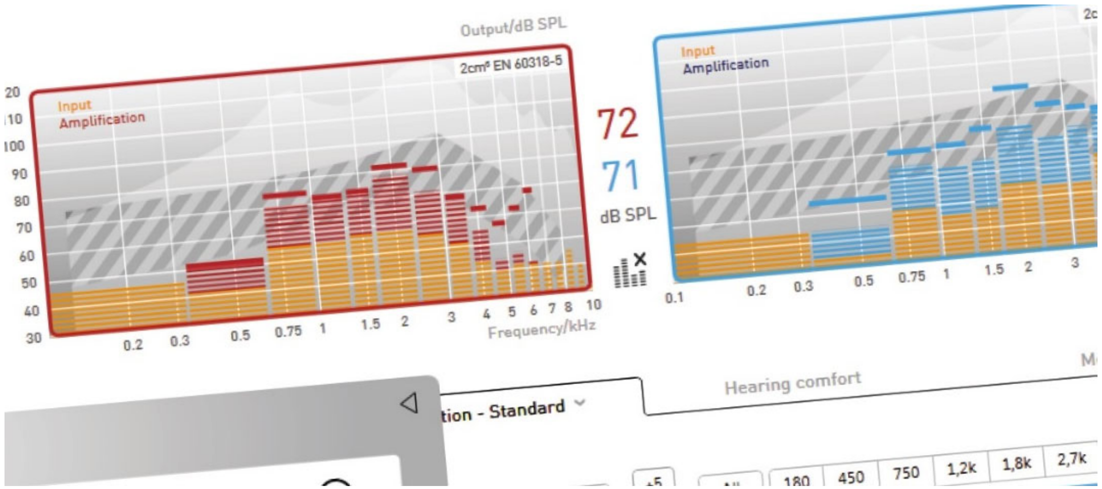
Dr.-Ing. Tamas Harczos

Recap: Hearing aids – Features

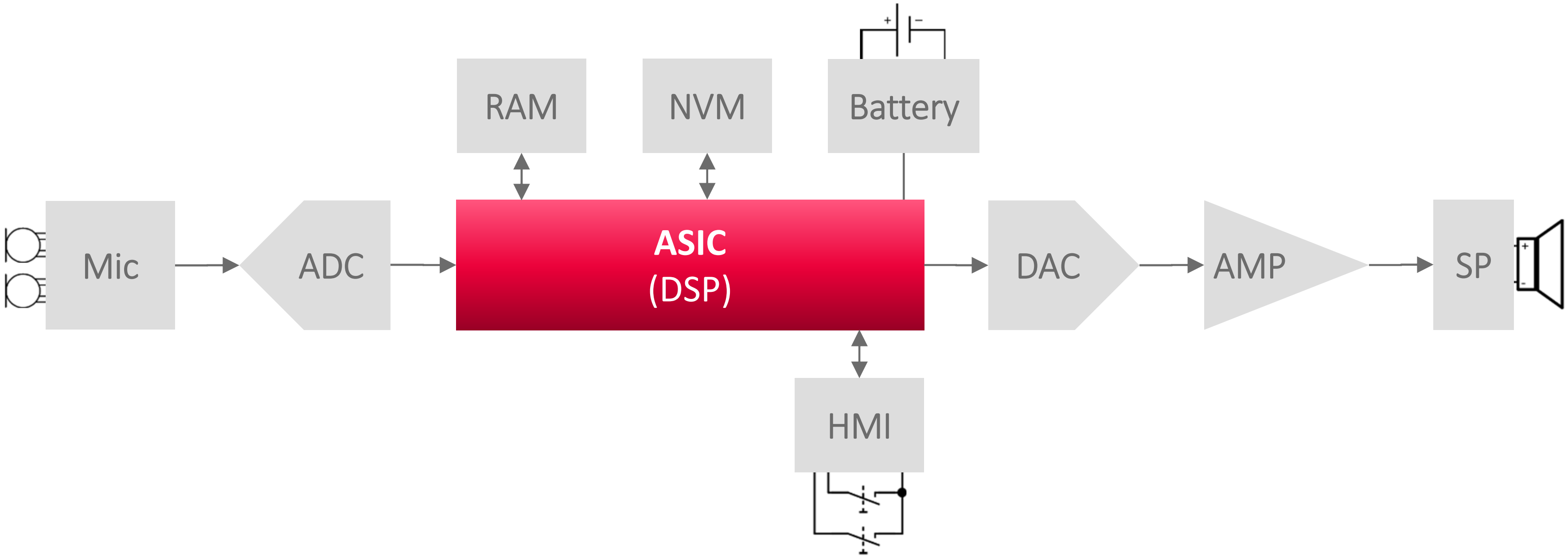
General:
- Small, lightweight, intuitive, discrete.
- Remote control, smartphone app.
- Wireless streaming (TV, remote microphone).
- Quickly rechargeable, long lasting battery.

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.

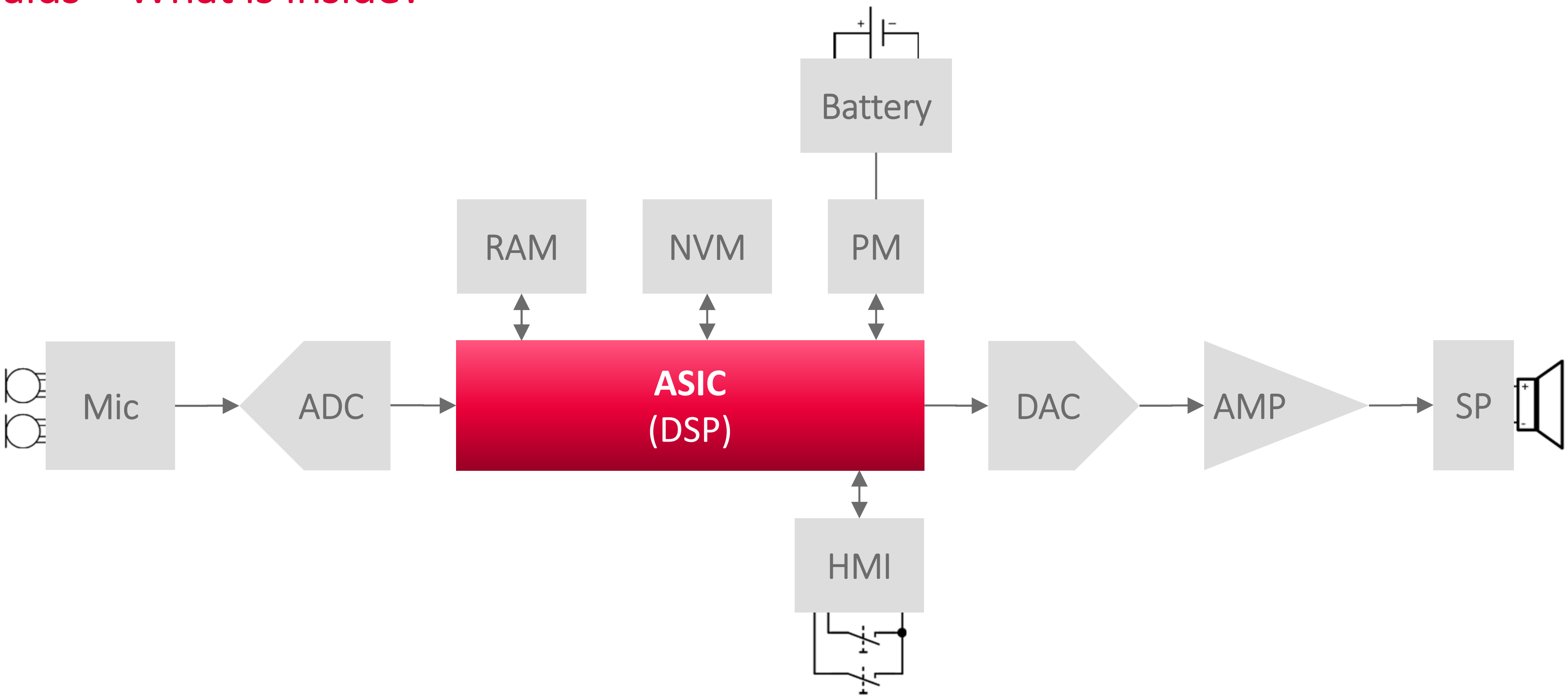


•• Hearing aids – What is inside?



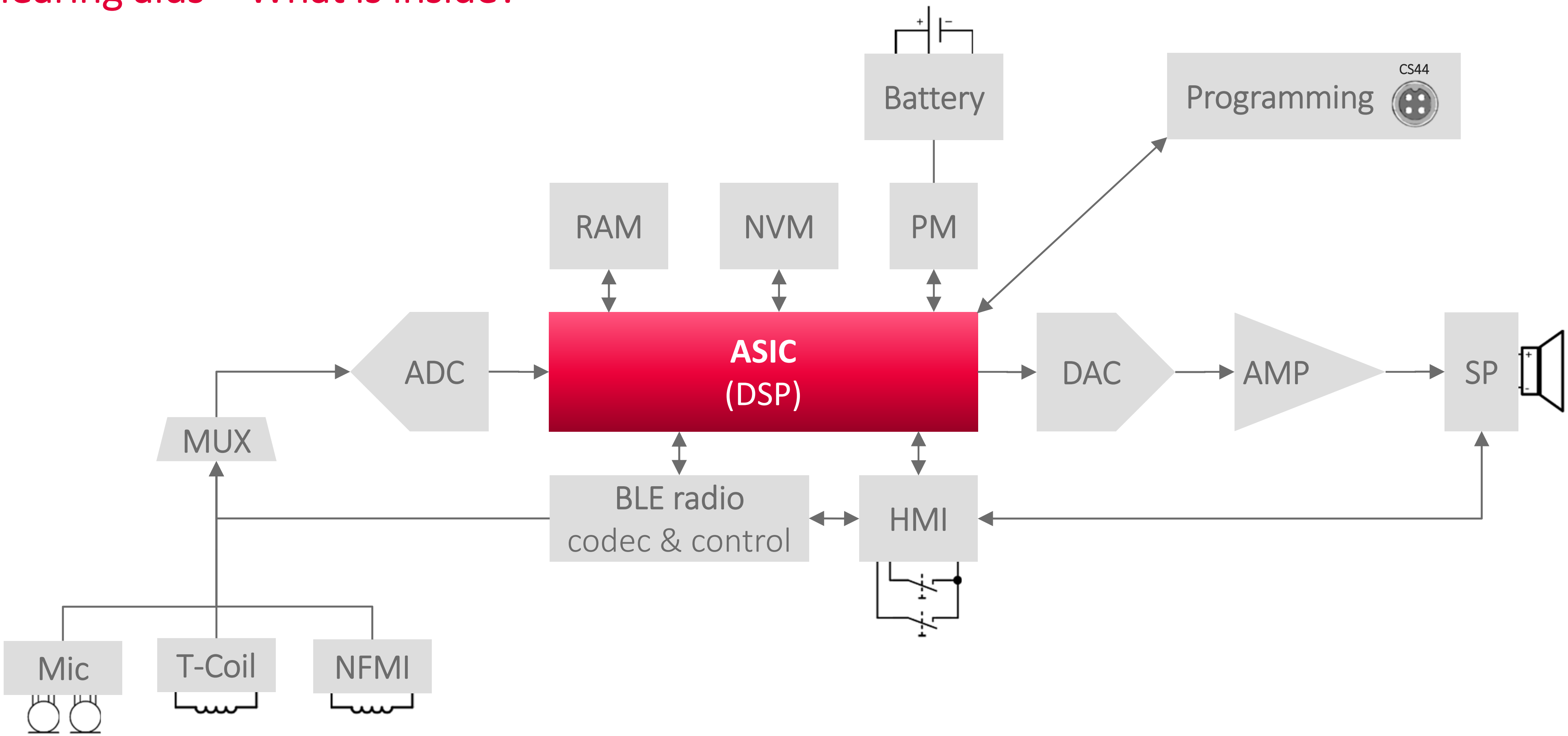
ASIC: application specific integrated circuit, **HMI**: human-machine interaction, **NVM**: non-volatile memory

•• 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

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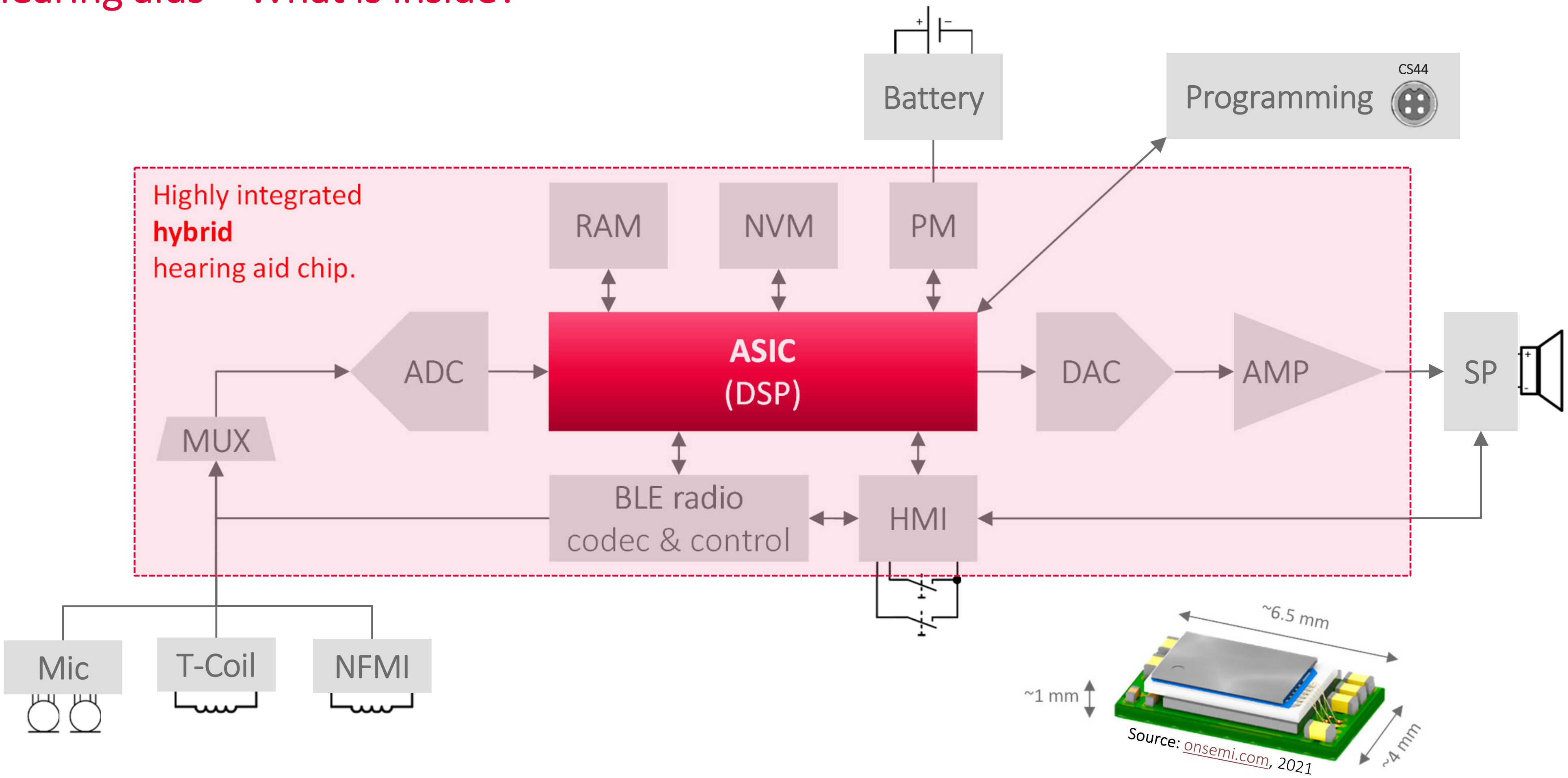
•• Hearing aids – What is inside?



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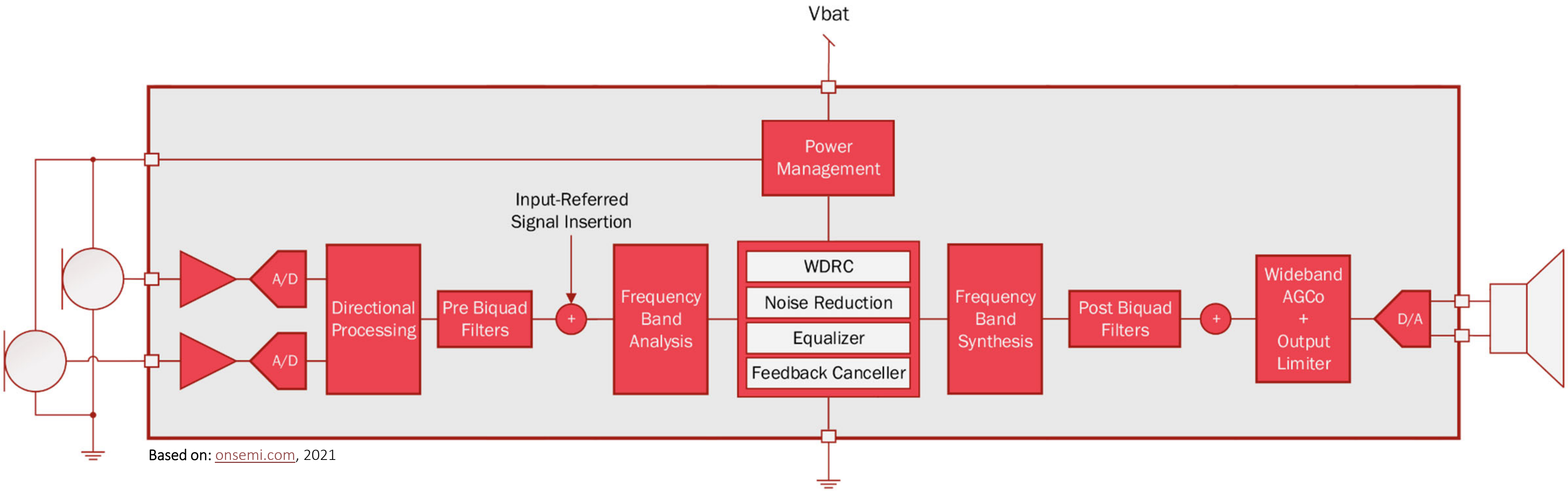
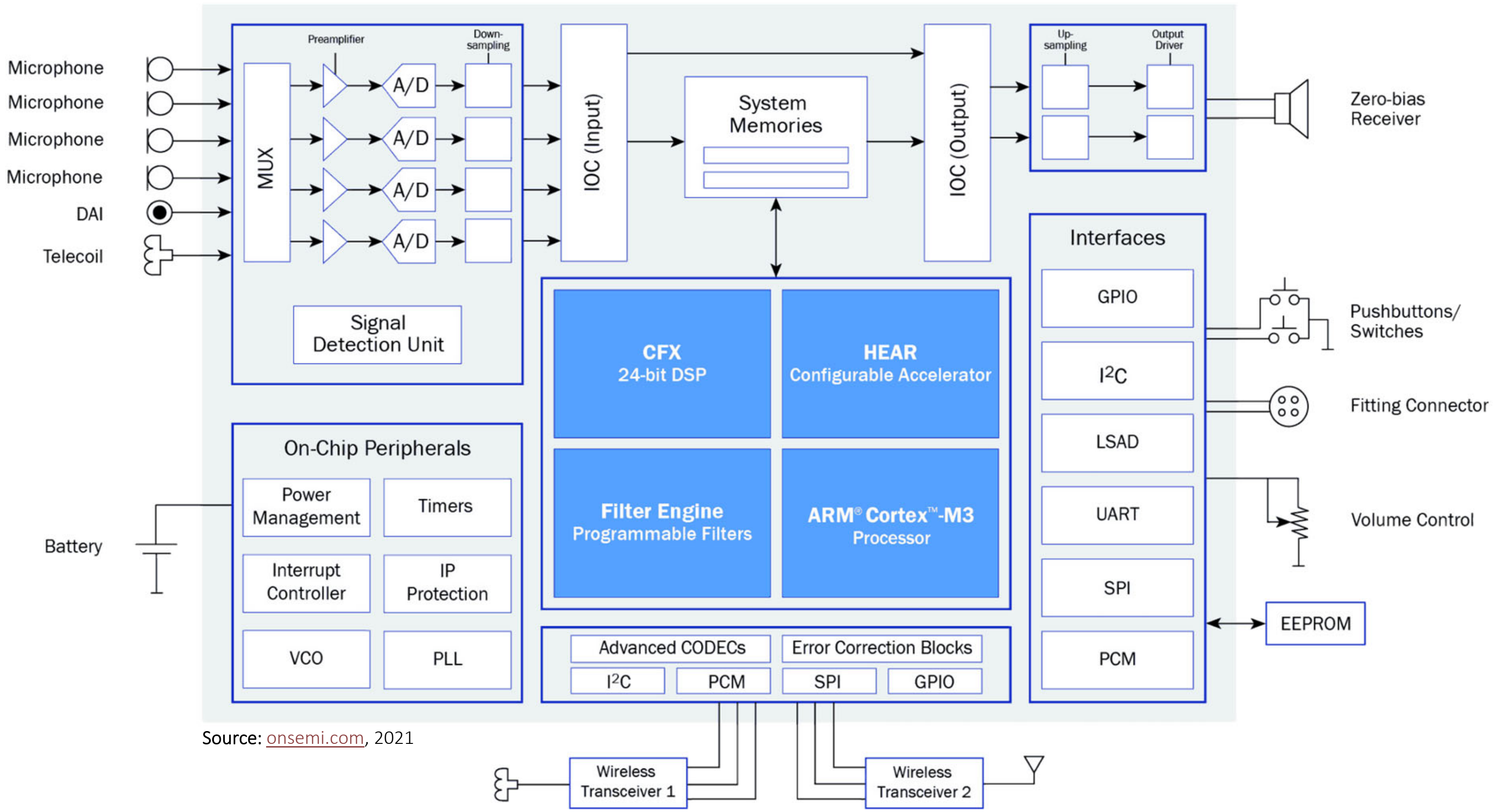
•• Hearing aids – Basic signal flow



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

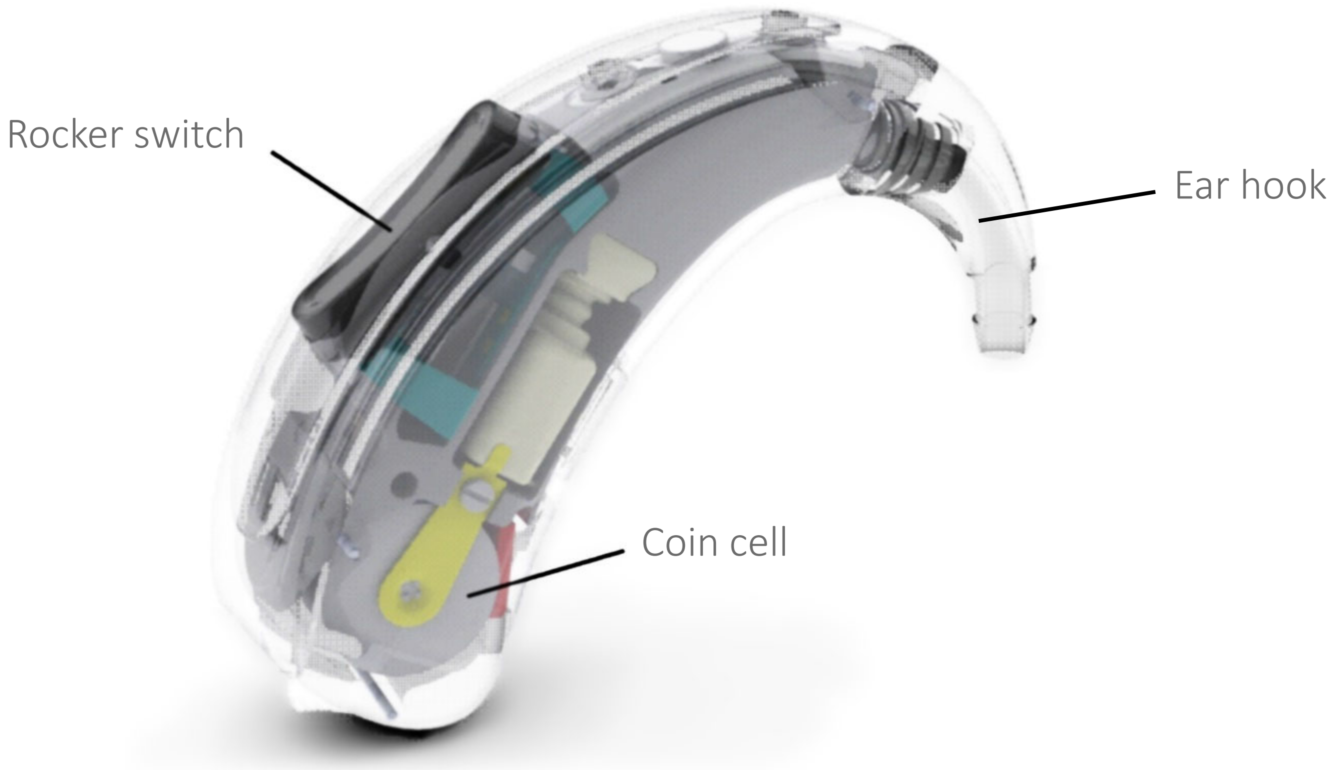
Rough estimates!

Source: jabra.com, 2021

Source: amd.com, 2021

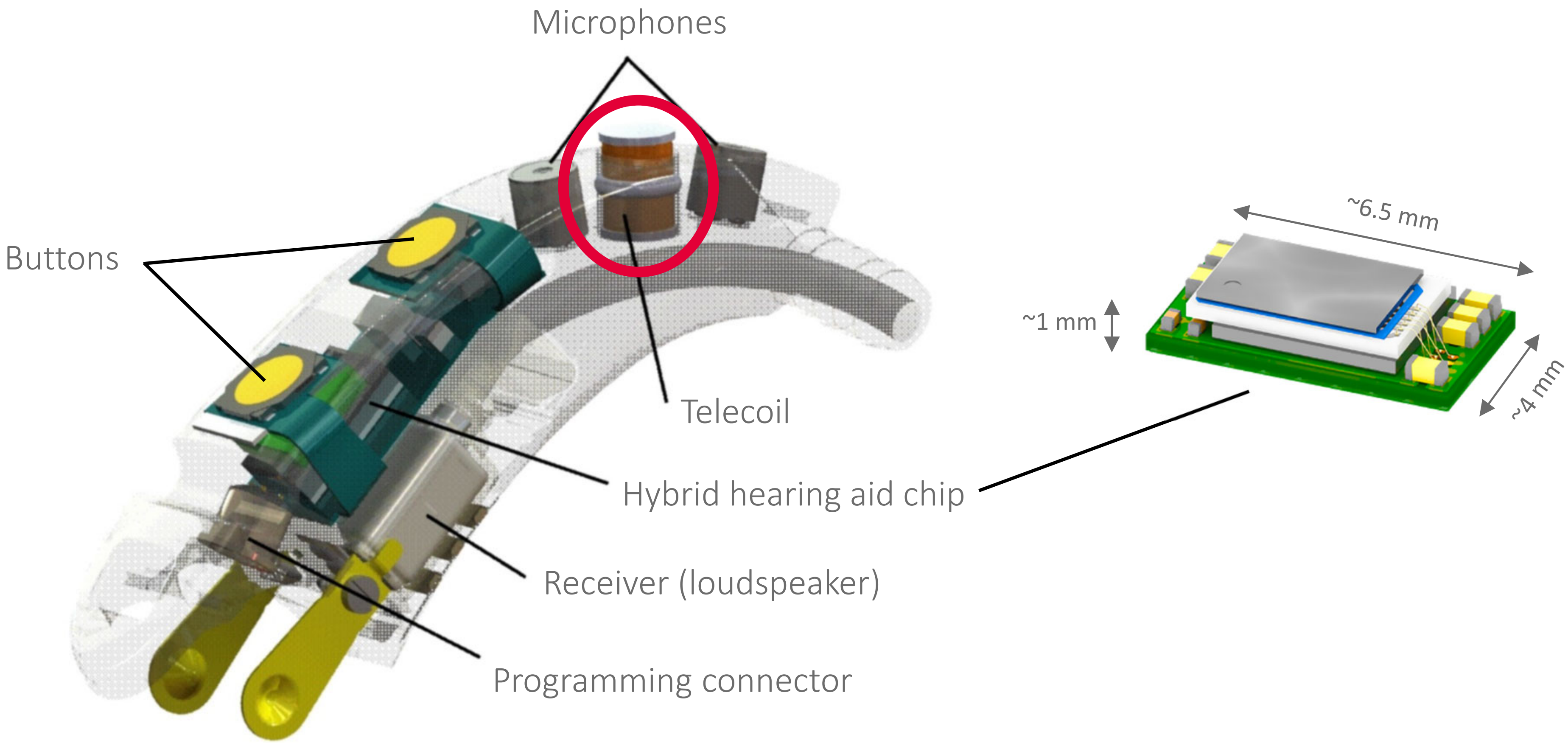
	Hearing aid ASIC	Hearable ASIC	PC CPU
Typical power consumption (algorithms on, wireless off)	~ **1-2 mW**	~ 15-50 mW	~ **35-125 W**
Typical power consumption (algorithms on, BLE in use)	+ 3-8 mW	+ 15-50 mW	
Clock speed	~ **10-60 MHz**	~ 20-200 MHz	~ **3000-4000 MHz**
MIPS @ max. clock speed	~ 400 MIPS	~ 1 000 MIPS	~ 200 000 MIPS
Typical dimensions	~ **4 x 7 x 1 mm = 28 mm³**	~ 5 x 8 x 1 mm = 40 mm³	~ **40 x 40 x 6 mm = 9.6 cm³**
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



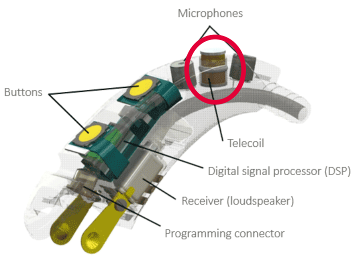
Source: kind.com, 2021

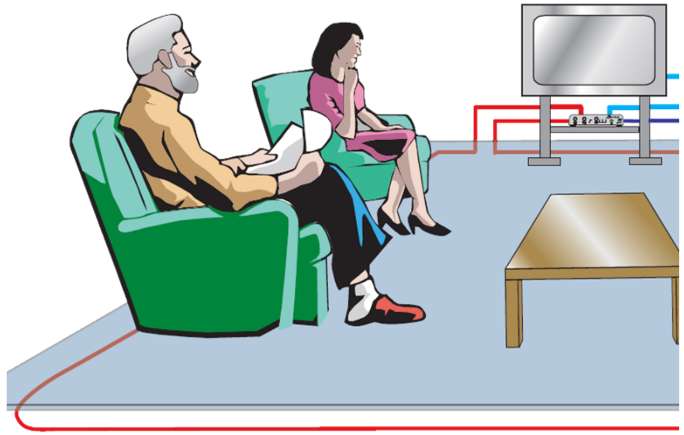
•• Hearing aids – Construction of a hearing aid

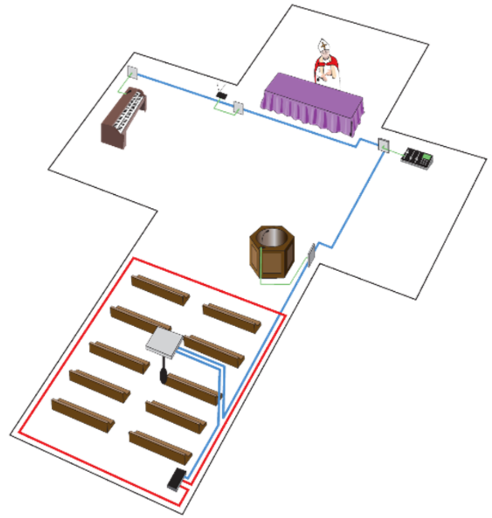


Source: kind.com, 2021

Excursion: Telecoil



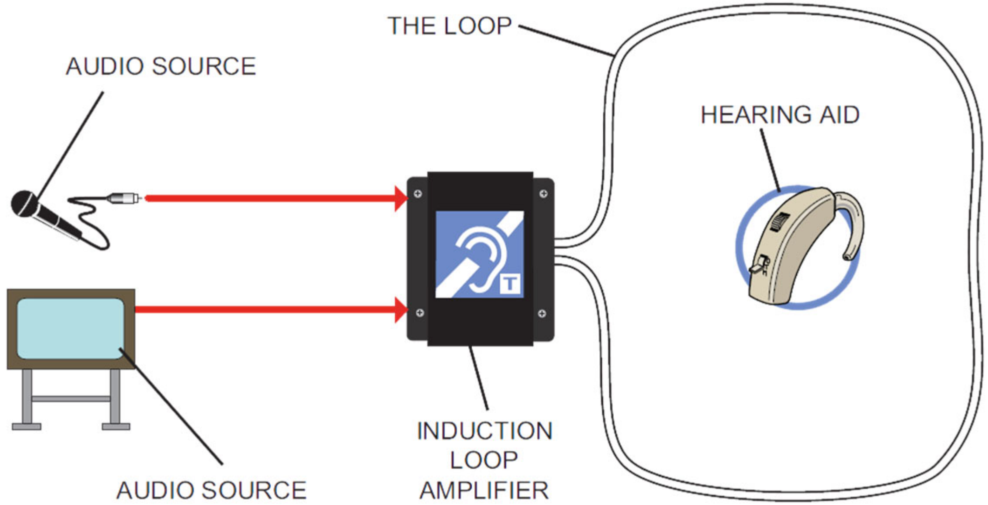




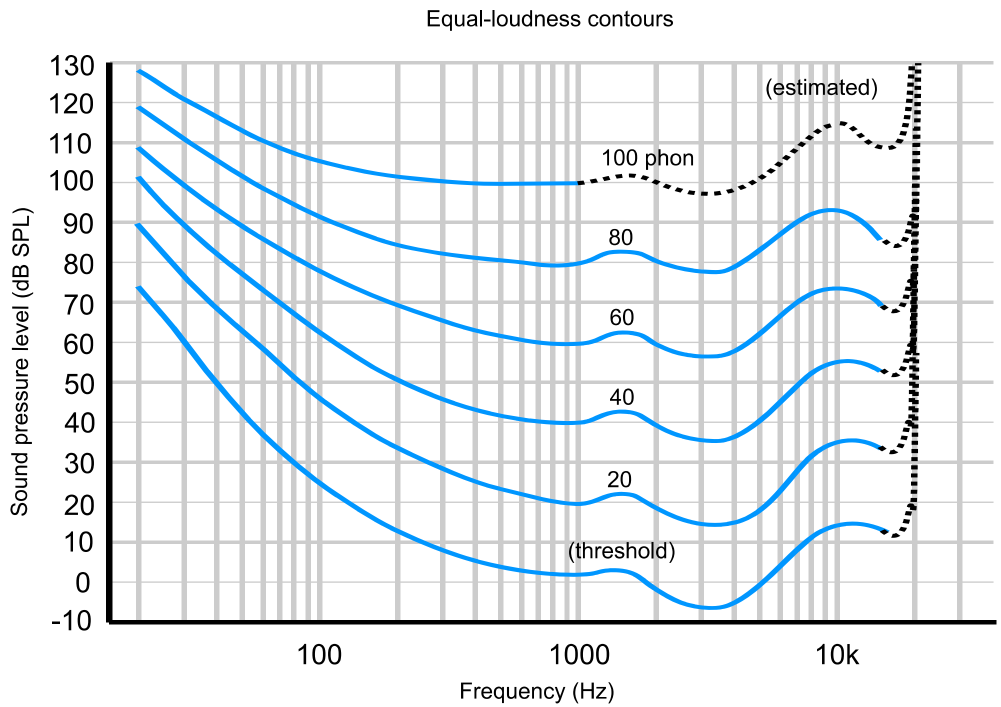
Source: signet-ac.co.uk, 2021

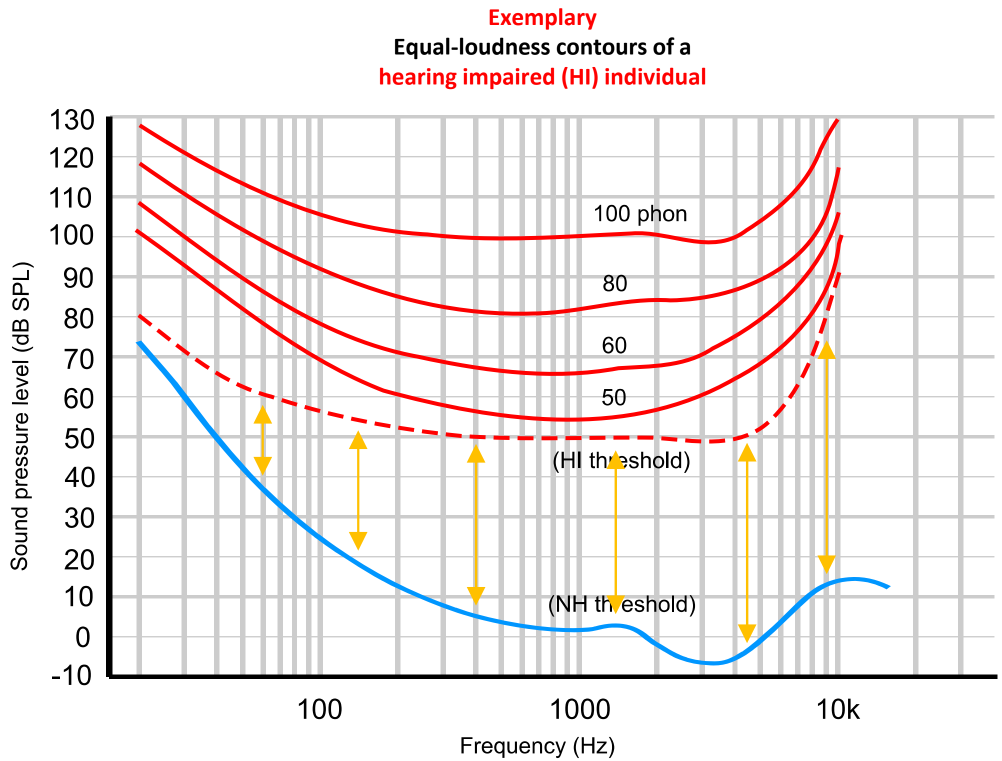
T-coil or induction loop receiver:

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



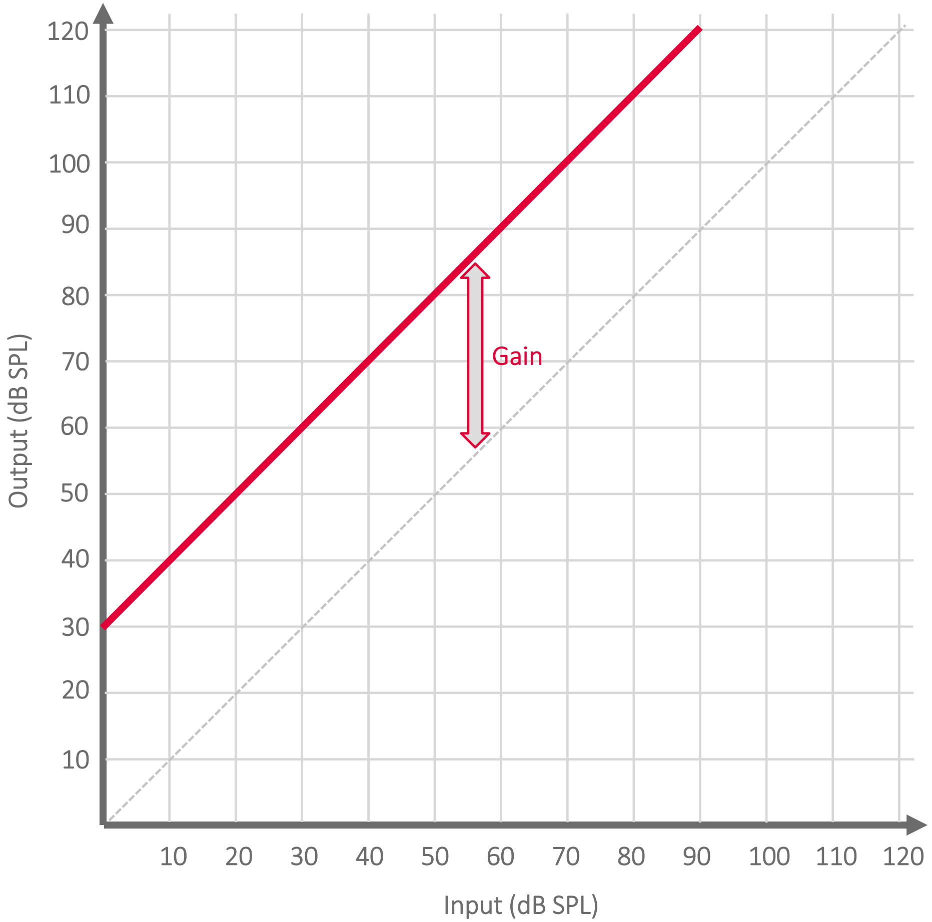
Recap: Equal-loudness contours





Based on: Strope & Alwan, 1995

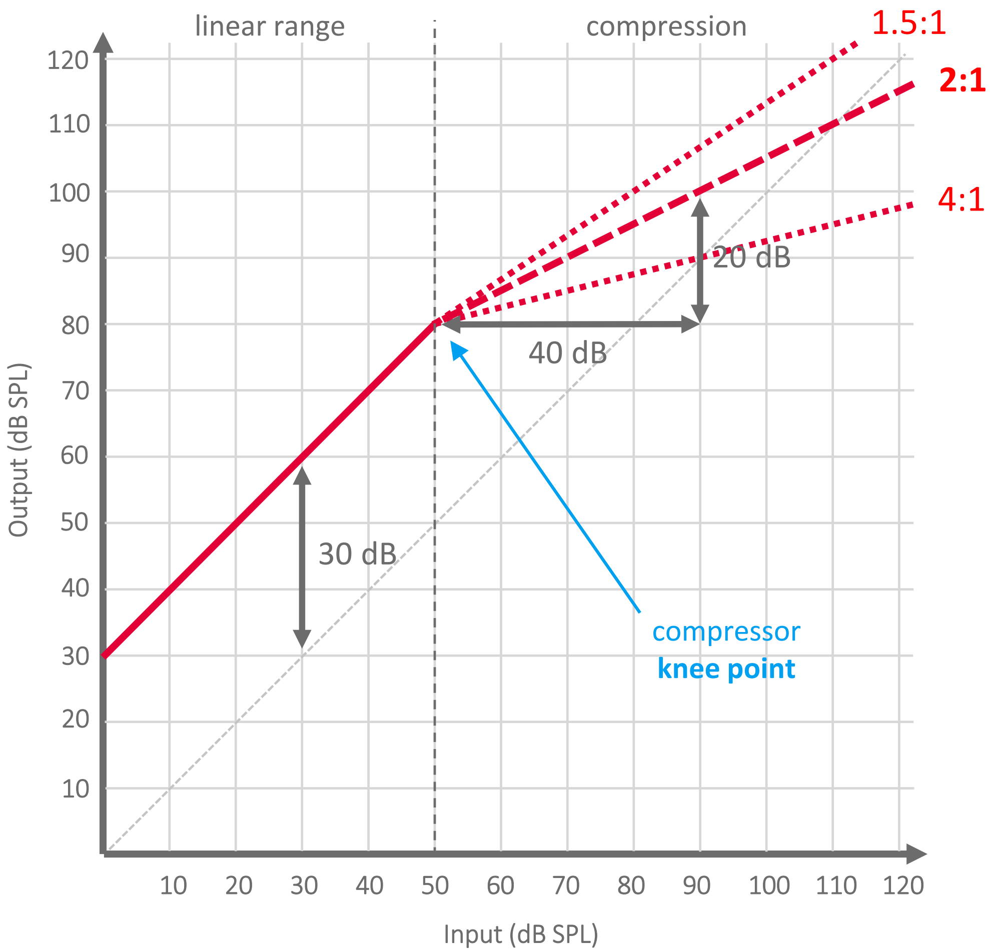
Hearing aids – Wide dynamic range compression



<u>Linear amplification alone:</u>

- Increases amplitude always with the same gain.
- Not conform with loudness perception of hearing impaired. (Will often cause uncomfortably loud percept.)
- Can lead to more hearing impairment.

•• Hearing aids – Wide dynamic range compression



Compression:

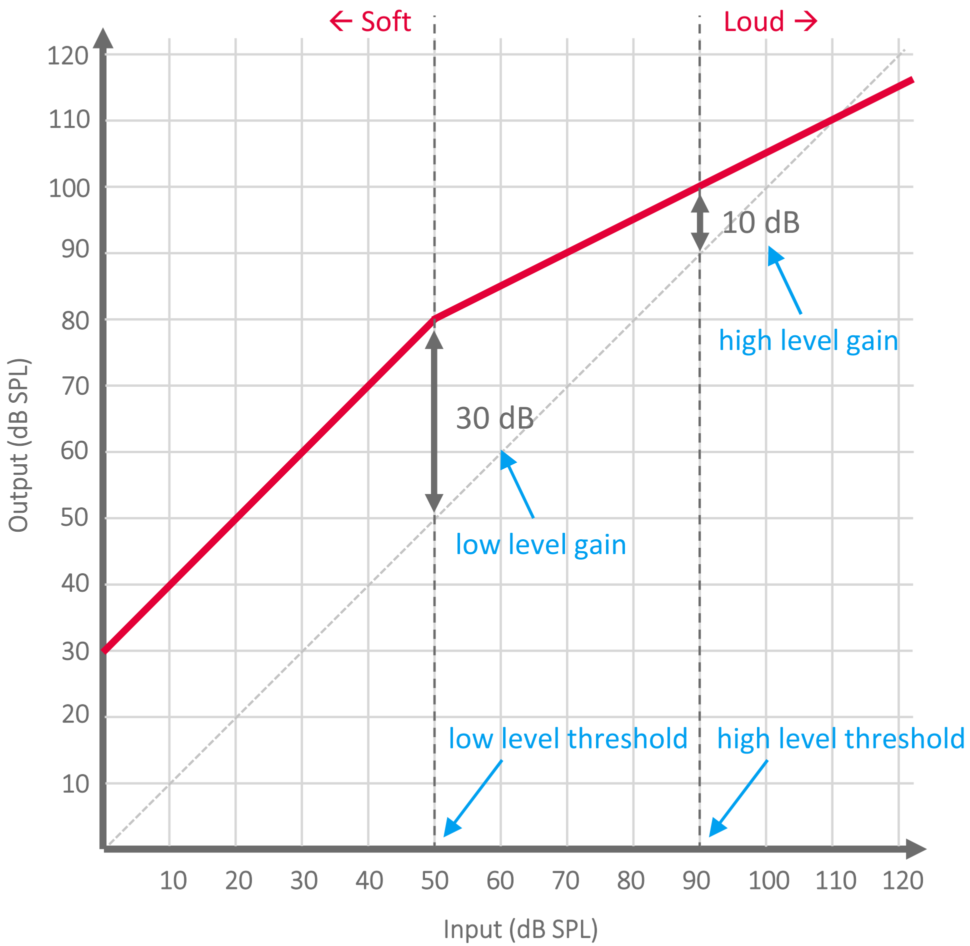
- Example:

  40 dB increase in the input leads to
  20 dB increase in the output, i.e.,

  → **compression ratio**: 40 dB : 20 dB = **2**:1

- Compression ratio can vary, but usually does not exceed 4:1 in the hearing aid field.

•• Hearing aids – Wide dynamic range compression



Compression:

- Low level gain: gain at ca. 50 dB SPL input
- High level gain: gain at ca. 90 dB SPL input

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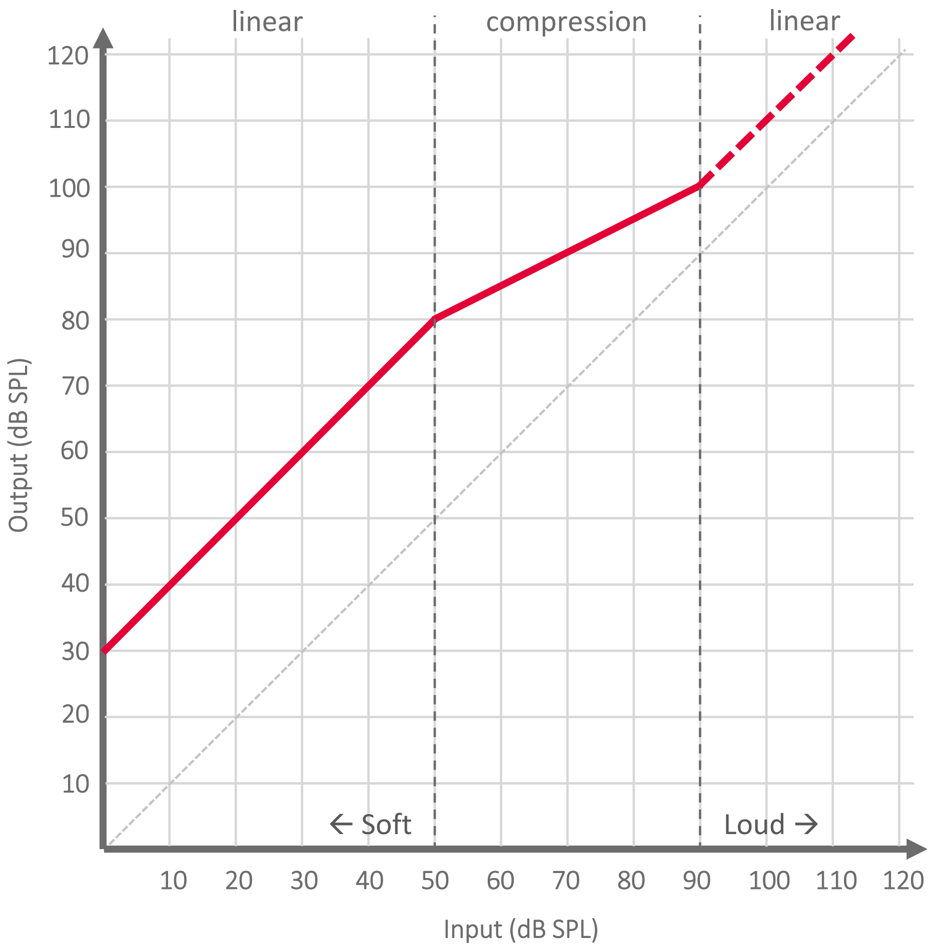
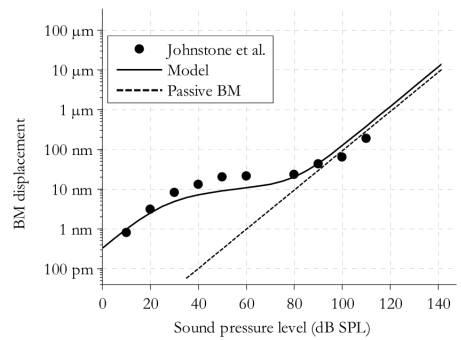
•• Hearing aids – Wide dynamic range compression



Second linear range:

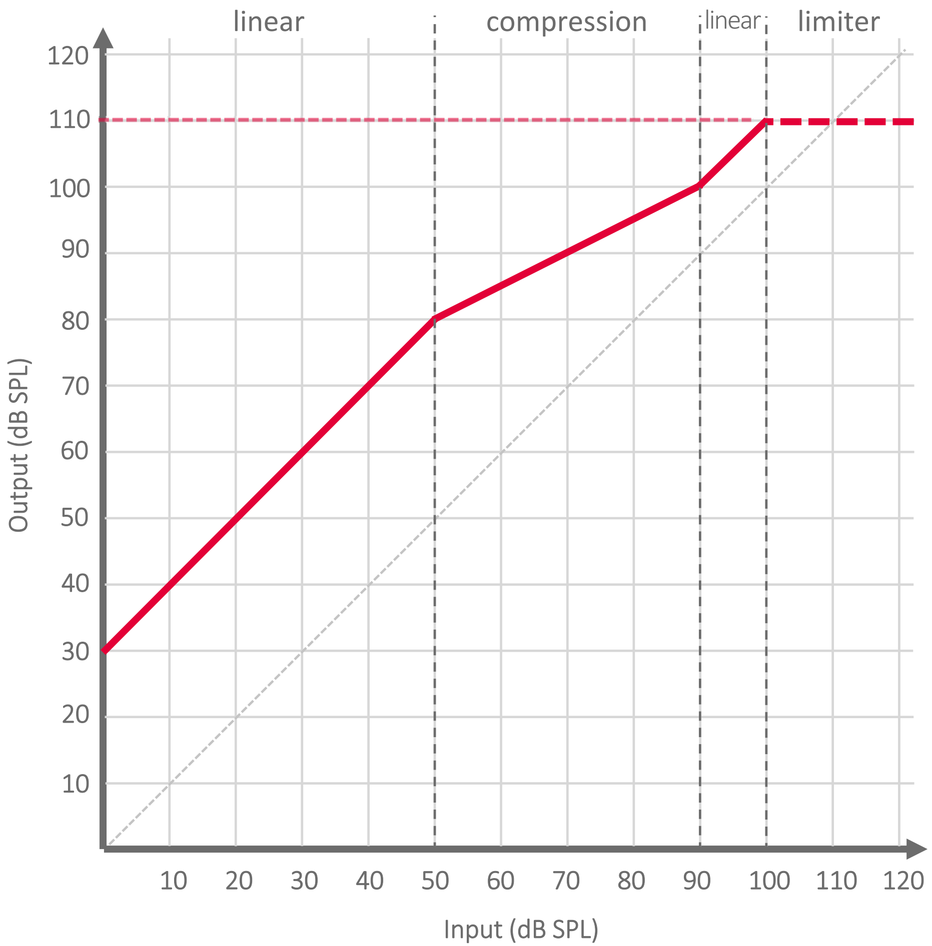
- Can be useful to allow the listener to realize that the input is very loud.
- Should be verified to not extend into the threshold of pain. (See "limiter" on next slide.)
- Remember the normal hearing ear handles loud noises very similarly! Basilar membrane nonlinarity:

Reminder



Adapted from: Johnstone et al., 1986

•• Hearing aids – Wide dynamic range compression



Limiter:

- Ensures not to cross the threshold of pain.
- Ensures technical limits not to be exceeded.

  (MPO: maximum power output of a hearing device. Limited for example by the power source, amplifier, and receiver.)
- Is equivalent to a compressor with ∞:1 compression rate.

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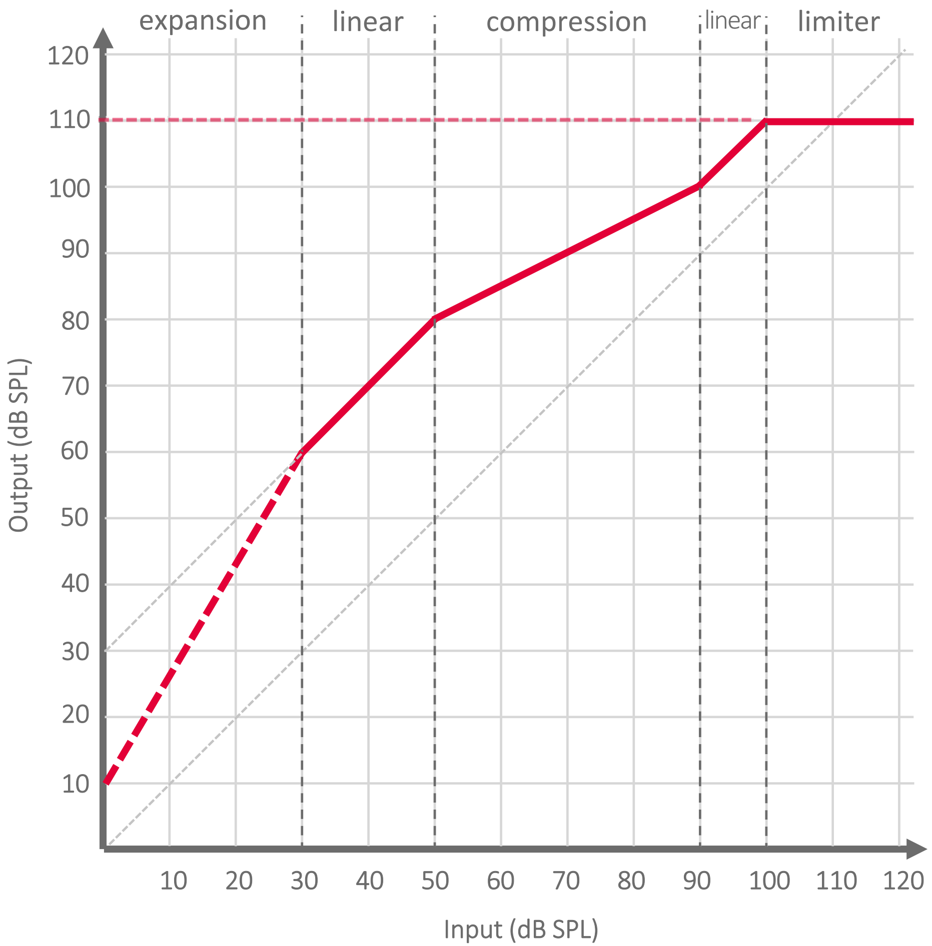
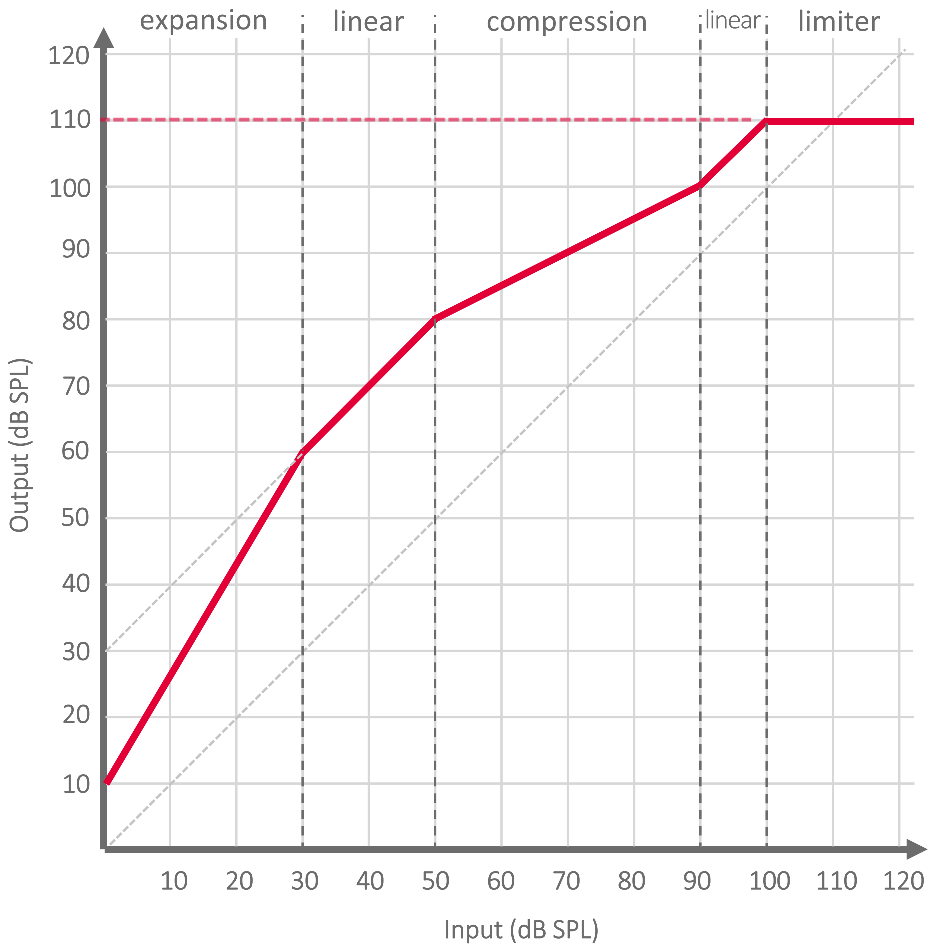
•• Hearing aids – Wide dynamic range compression



Expansion:

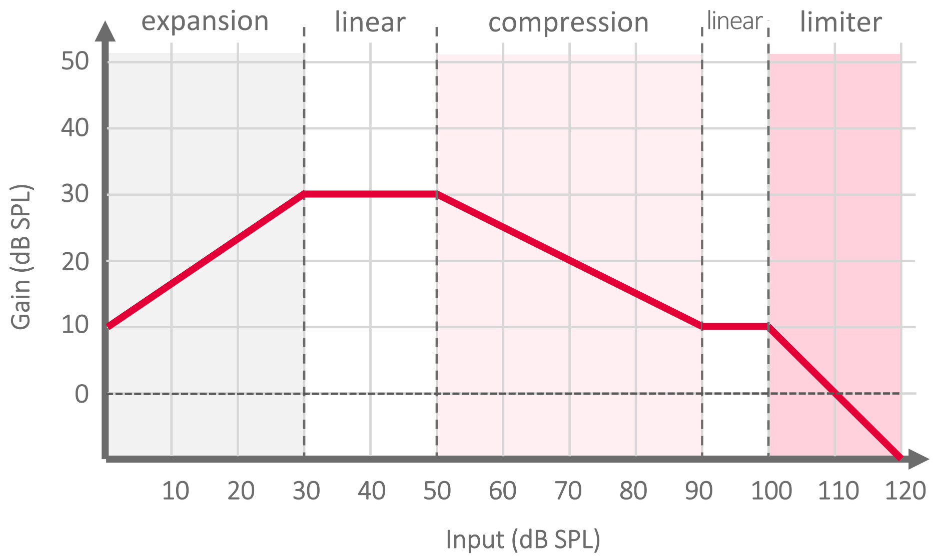
- Usually employed in the low SPL range.
  → Less gain added to soft noises.
- Reduces inherent noise of the system (e.g. that of microphones or preamps).
- Reduces irrelevant background noise.
  → Increases overall SNR.
- Typical expansion rate: 1:1.5 - 1:3.
  (1:1.66 in the graph on the left.)

•• Hearing aids – Wide dynamic range compression

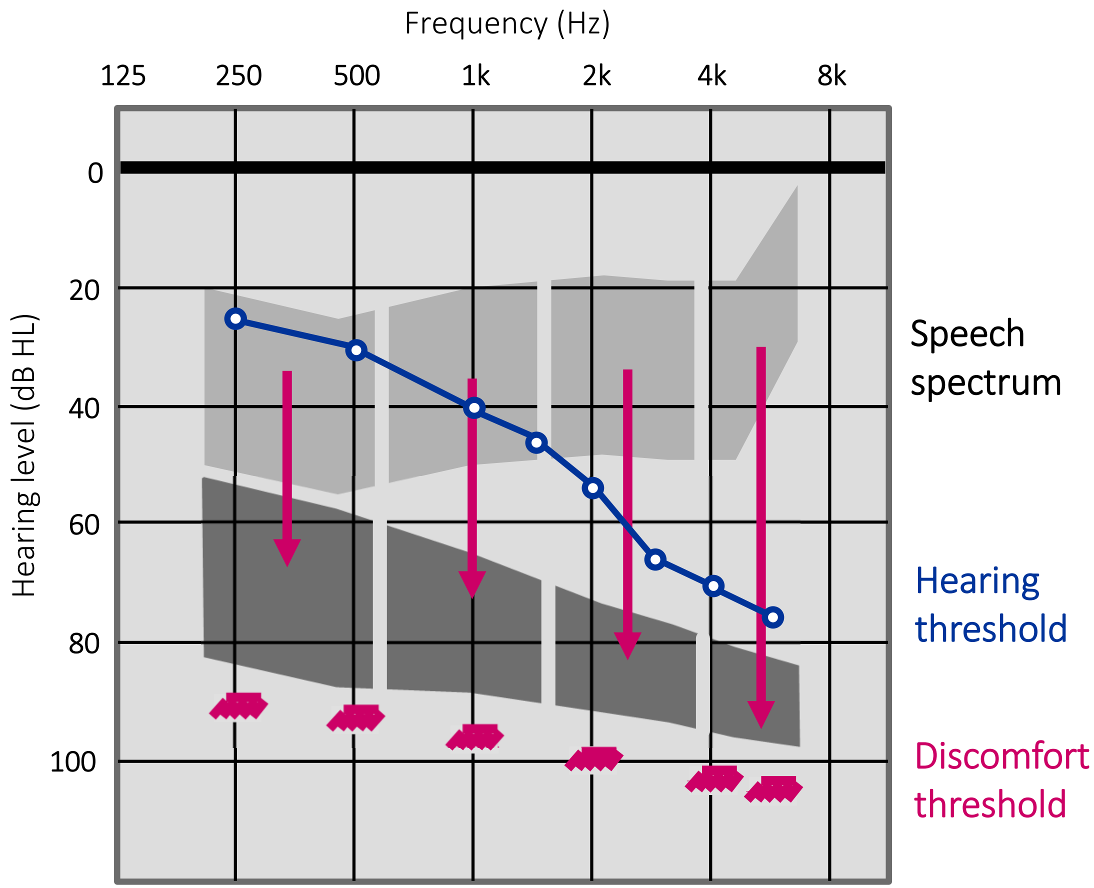


Gain plot:

- A shorter / compacter way to describe compression-expansion curves.



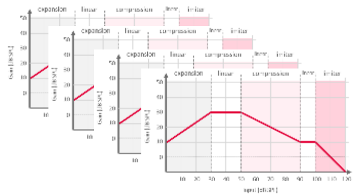
•• Hearing aids – Multi-channel WDRC



Adapted from: Kiessling & Steffens, 1991

Multi-channel compression:

- The normal dynamic range of speech varies across frequency.
- The amount of hearing loss also varies across frequency, individually.
- Solution: use multiple dynamic compressors, each fitted for a distinct frequency range.

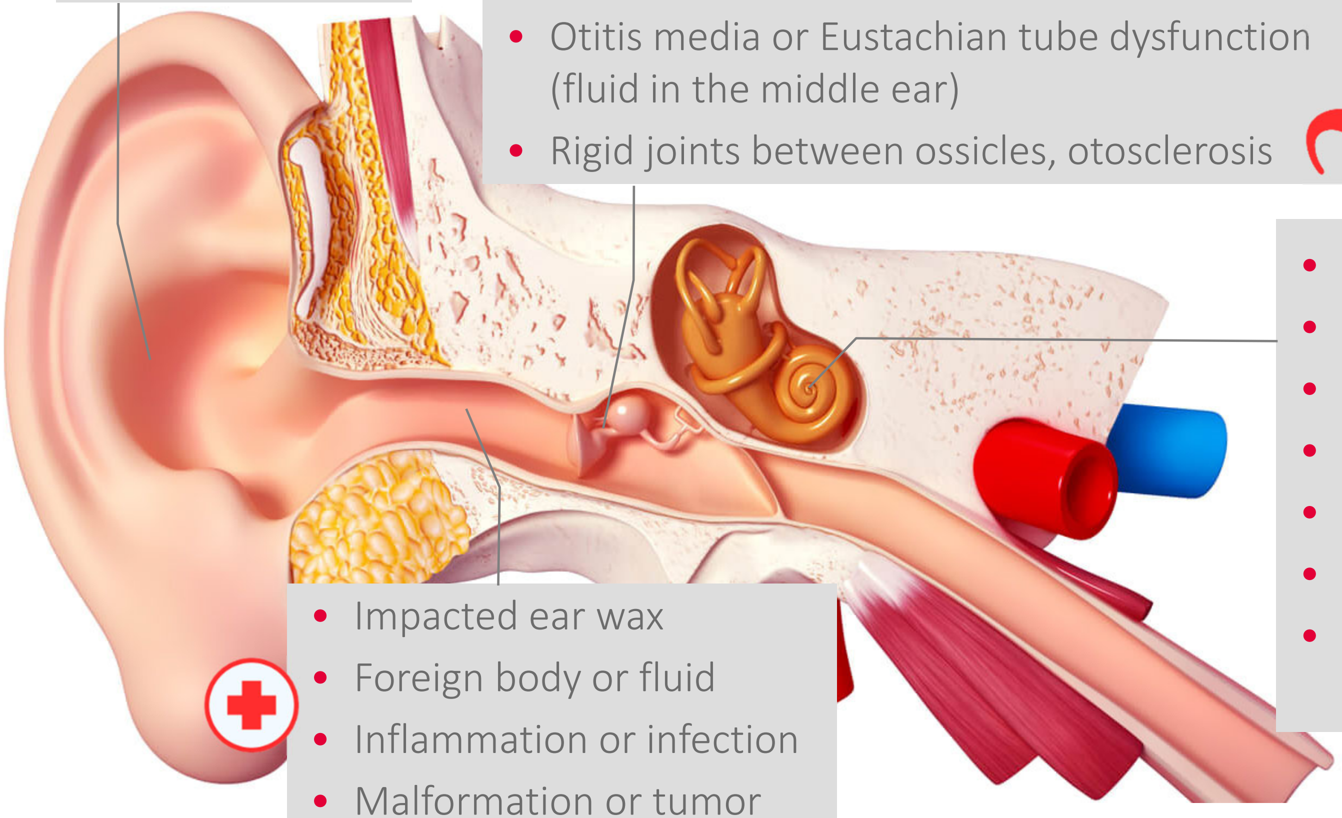


- A computationally cheap, but high quality filter-bank with almost perfect reconstruction is needed.
- (Keywords for searching further information: FFT-based WOLA filter-banks and warped filters.)

Recap: 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.

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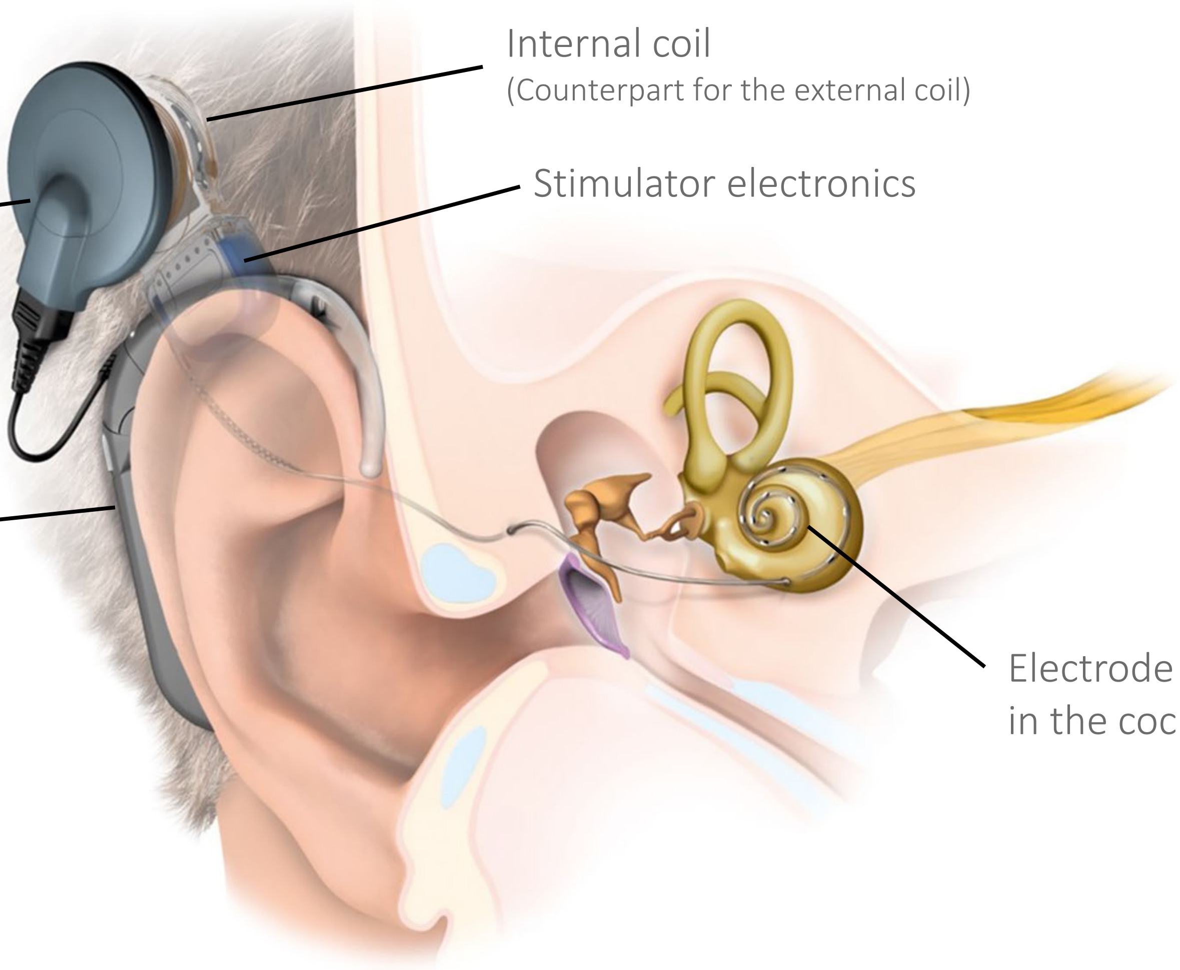
•• Cochlear implants



Source: medel.com, 2016

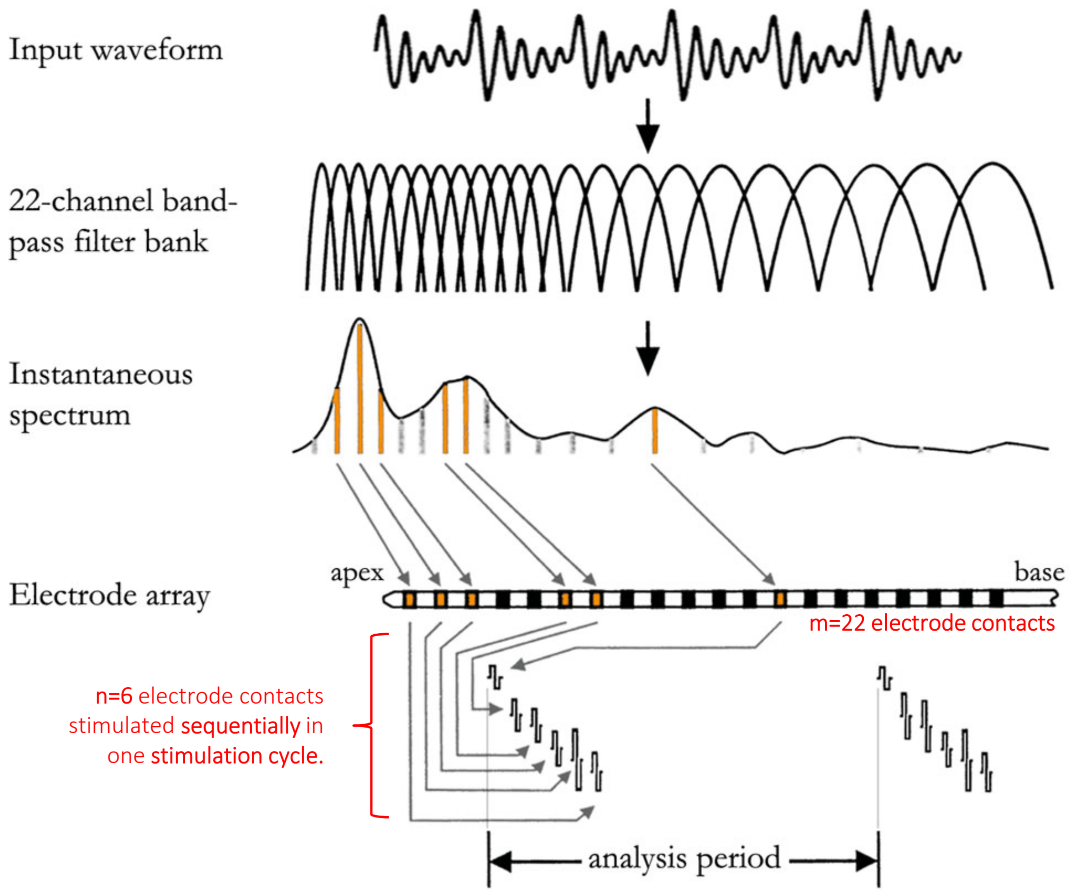
•• Cochlear implants

Source: cochlear.com, 2021

•• Cochlear implants

Source: cochlear.com, 2021 (unprocessed sound)

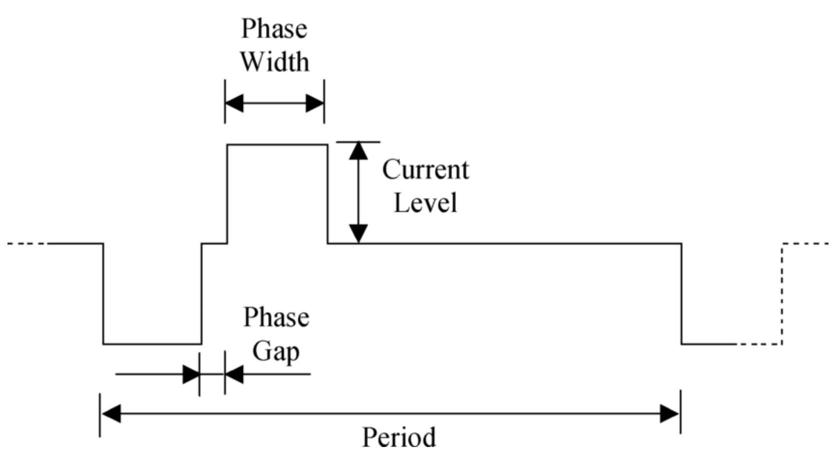
•• Cochlear implants – Signal processing strategy



Source: G. Clark, *Cochlear Implants*, 2003

ACE signal processing strategy
(advanced combination encoder)

Biphasic, charge balanced pulses



Source: Tognola et al., 2005

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Cochlear implants – Early history

Source: hearinghealthmatters.org, 2021

Alessandro Volta
50 V DC ear-to-ear

Lundberg (1950),
Djourno & Eyries (1957)

Direct electrical stimulation of the auditory nerve with distinguishable percepts in human.

House's first clinical multi-channel CI

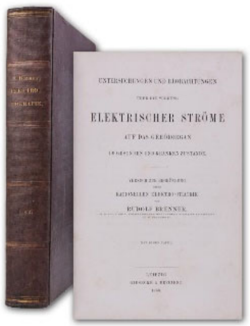
Source: Clark, 2013

Clarion implant
Advanced Bionics
(USA)

Source: cochlear.com, 2021

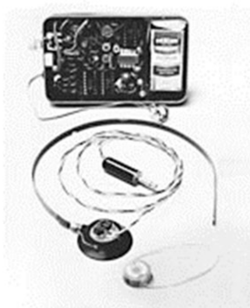
1790s | 1868 | 1950-57 | 1961 | 1982 | 1985 | 1996 | 2001

Source: abebooks.com, 2021



Rudolf Brenner's
AC stimulation

Source: Eisenberg, 2005



William F. House's
single-channel CI

Nucleus implant
Cochlear Ltd. (AU)

Combi40+ implant
MED-EL GmbH (AT)

Commercialization →

•• Hearing aids (HA) vs. Cochlear implants (CI)

- System size
  BTE processor is about the same size for both, but **CI has more system parts**
  (RF link, implanted stimulator, implanted electrode array).
- Power consumption
  Signal processing requires about the same power for both, but **CIs need extra current** for electrical stimuli and RF link.
- Core signal processing
  Both do spectral decomposition via an analysis filter-bank, but while HAs need to synthesize audio on the output, CIs calculate parameter for electrical stimuli.
- Additional algorithms / features
  Very similar: directionality, dynamic range compression, noise reduction, binaural algorithms, but
  CIs do not need feedback canceller. Both can be streamed to wirelessly and be remote controlled.
- Current issues
  Both: speech in noise enhancement, power consumption and size, connectivity, user-friendly handling.
  *CIs: reverb, **pitch discrimination*** (12/16/22/24 channels, does not matter ← ***current spread***).

Cochlear implants – Ways to improve pitch sensitivity

- Train cochlear implant users
  Use the brain's plasticity. Needed anyway in CI therapy, but has its limits.
- Enhance pitch changes
  Smart preprocessing can increase speech melody changes in real-time (PREX project, Fraunhofer IDMT).
- Improve temporal pitch cues
  Better stimulation strategies (SAM project, Dissertation, Fraunhofer IDMT)

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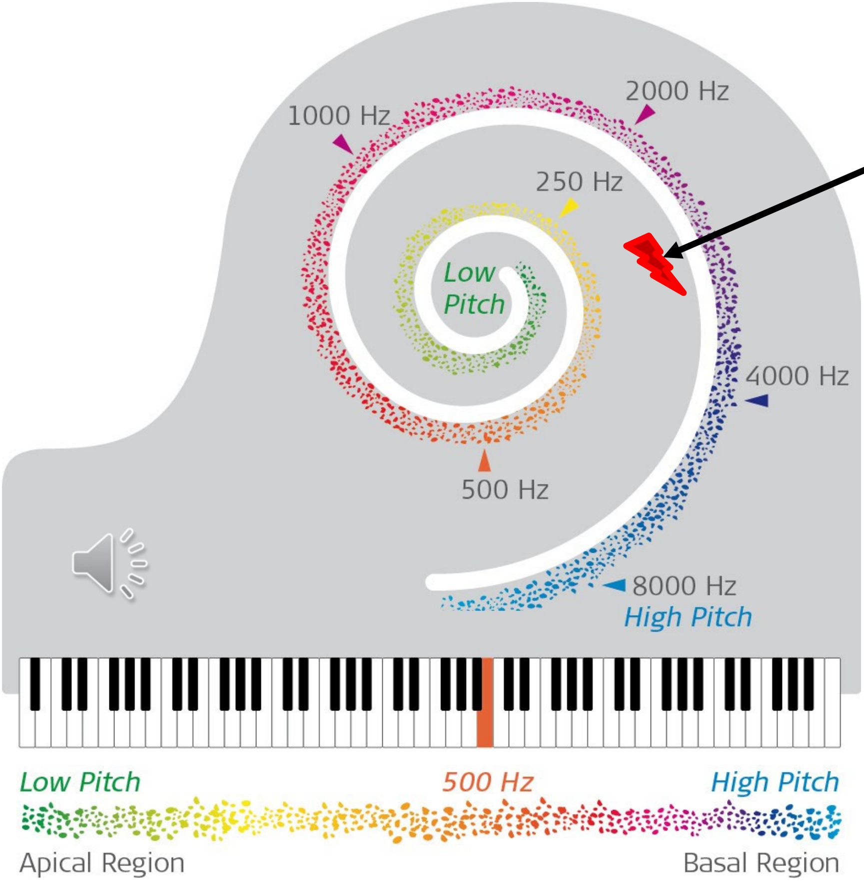
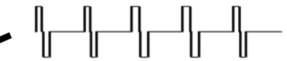
•• Pitch perception



Source: medel.com, 2021



20 Hz

80 Hz

160 Hz

•• Cochlear implants – Ways to improve pitch sensitivity

- Train cochlear implant users
  Use the brain's plasticity. Needed anyway in CI therapy, but has its limits.

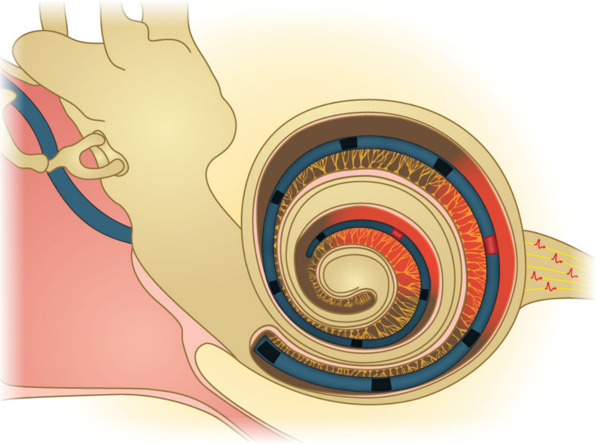
- Enhance pitch changes
  Smart preprocessing can increase speech melody changes in real-time (PREX project, Fraunhofer IDMT).

- Improve temporal pitch cues
  Better stimulation strategies (SAM project, Dissertation, Fraunhofer IDMT)

- Improve place pitch cues (reducing current spread)
  - Better electrode design ("modiolus-hugging" or "adhering" electrodes),
  - Current steering (parallel stimulation over multiple electrode contact points)
  - Optogenetic stimulation (optical cochlear implants).

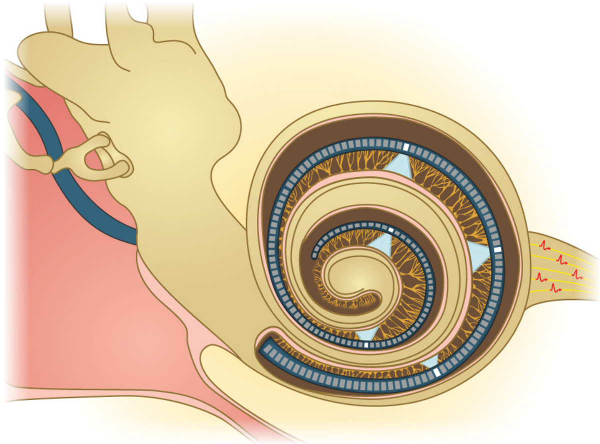
•• Optogenetic cochlear implants

Electrical stimulation

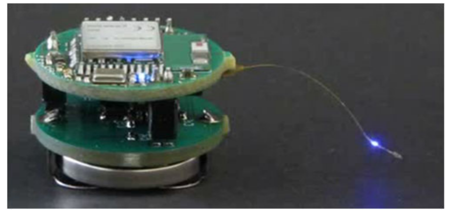


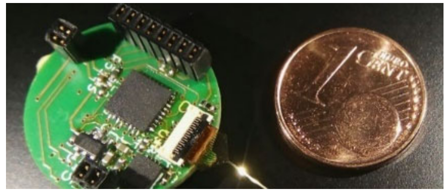
Source: Jeschke & Moser, 2015

Optical stimulation



Research hardware



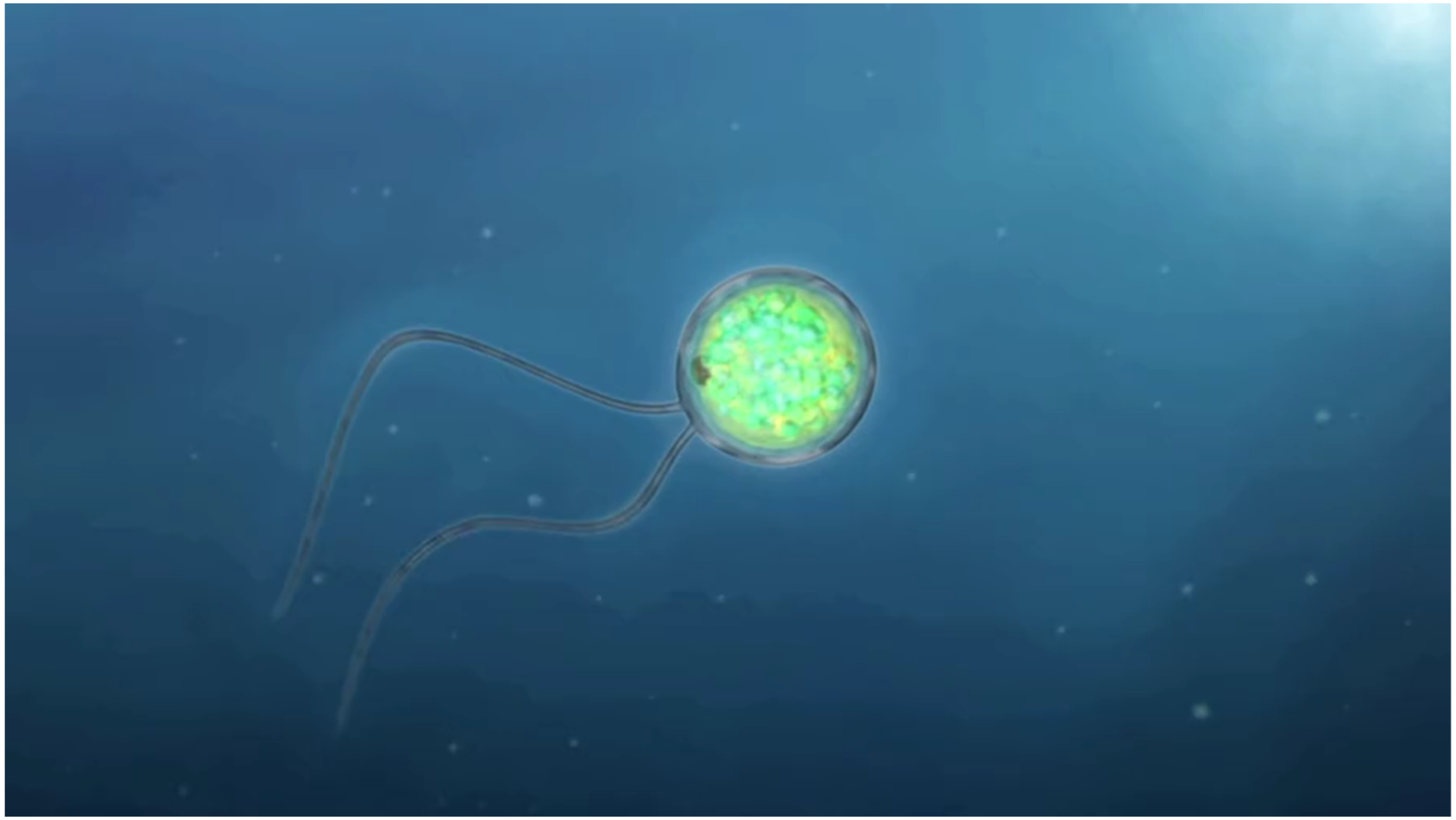


<u>Challenges of optogenetic cochlea stimulation:</u>

- Light-sensitive neurons: efficient, reliable and safe opsin* expression via *genetic manipulation* of the spiral ganglion neurons.
- Stimulation technology must be efficient, reliable and safe.

*opsin = light-gated ion channel

Optogenetics



Source: be.mit.edu, 2021

•• Optogenetics – Demo with the research hardware

Music: Josh Armistead - **Lazer Beams**

•• The Embedded Signal Processing (ESP) Team of audifon in Ilmenau

- Primary goals (among all) are:
  - monitoring hearing aid development trends;
  - preparation for future hearing aid HW platforms;
  - developing algorithms that may become part of the firmware of future hearing aids.
- Status quo:
  - Three full members, still missing an embedded C programmer.
  - Our first success: the *PrimeHA* project.
- PrimeHA:
  - Diploma work of Amelie Hintermaier entitled *“Entwurf einer kompakten, energieeffizienten, frei programmierbaren Hörgeräteplattform zur praxisnahen Erprobung audiologischer Algorithmen“*.
  - Got very good grade with distinction.

Tamas Harczos Amelie Hintermaier Iko Pieper

•• PrimeHA: a platform to develop and test hearing aid algorithms

Main features:

- ARM Cortex M4f @ 64 MHz, 256 kB RAM, 1 MB NVM.
- Current consumption ~3-10 mA with BLE 5.1 radio.
- Audio input: 2x PDM MEMS microphones.
- Extras: motion sensor and µSD-card slot on board.
- Made of commercial off-the-shelf components.
- Fully C-programmable under free-for-all license.

Current use:

- Firmware framework development.
- Testing and optimizing audio signal processing algorithms like feedback canceller, multi-band compressor, noise reduction.
- Learning lessons on acoustically engineered mechanical design.

Thank you very much!
Questions?

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

audifon GmbH & Co. KG