



Hearing Systems – Part 2 of 2

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

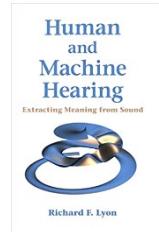
TU Ilmenau – Audio Systems Technology

(Online) | January 26, 2022

Dr.-Ing. Tamas Harczos

•• Reminder

- Useful links:
 - <https://hearingsystems.github.io/> (presentation slides and recordings),
 - <https://moodle2.tu-ilmenau.de/course/view.php?id=1373>.
- 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)
 - [MATLAB](#) 2018b+ (free student version) or [GNU Octave](#) 6.4+ (free)
 - [Wavosaur 1.7+](#) or [Audacity 3.1.3+](#) audio editor (both free)



•• Recap: Hearing aids – Modern form factors



Behind the ear (BTE)



Receiver in canal (RIC)



In the canal (ITC)



Completely in canal (CIC)



- + least earwax impact
- definitely visible



- + least feedback



- + glasses-friendly
- ear occlusion



- + glasses-friendly
- ear occlusion
- usability

•• Recap: Hearing aids – Features

General:

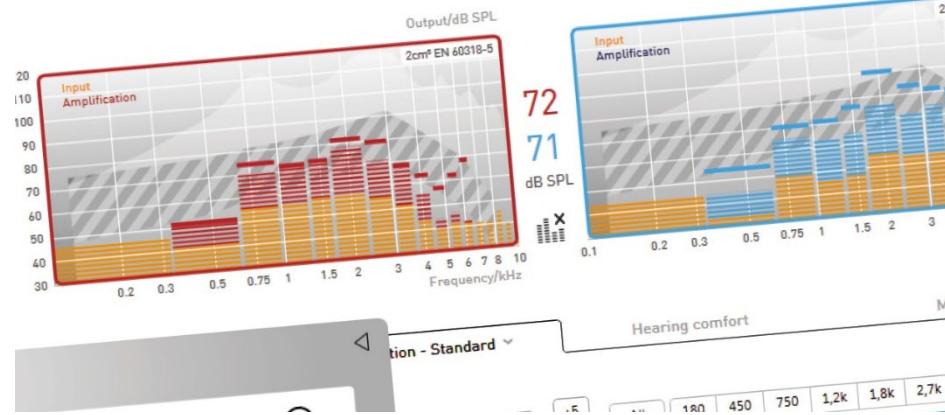
- Small, lightweight, intuitive, discrete.
- Remote control, smartphone app.
- Wireless streaming (TV, remote microphone).
- Quickly rechargeable, long lasting battery.

Audiological features:

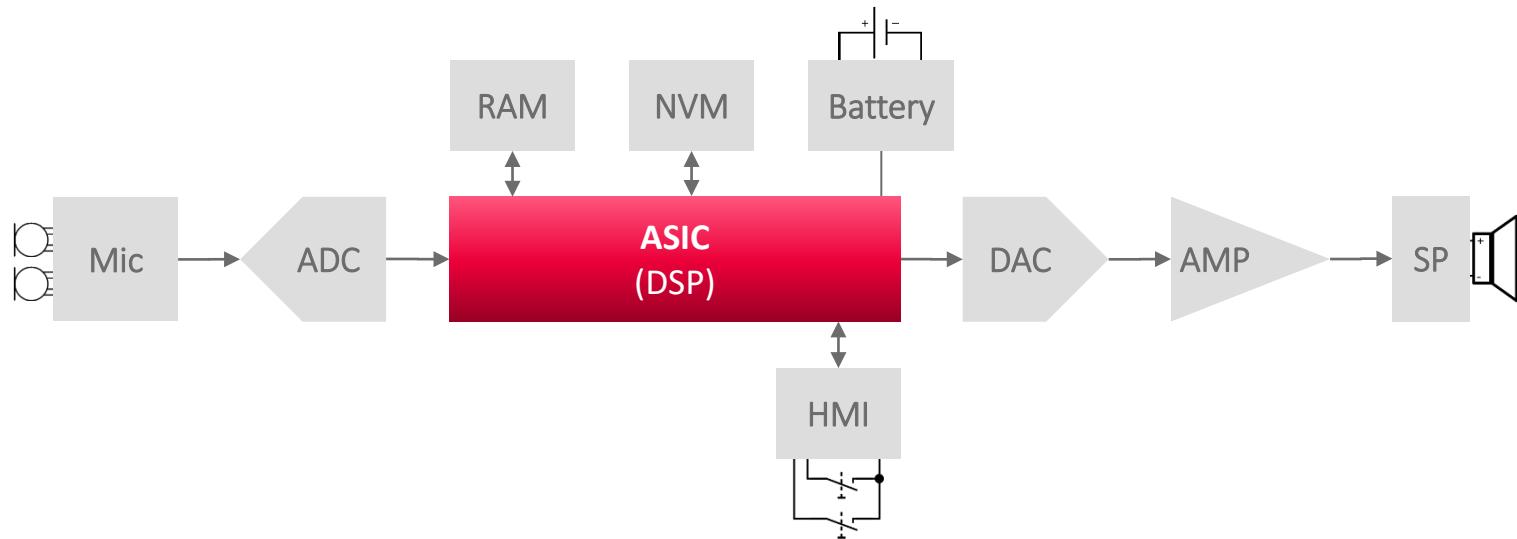
- Low noise, high bandwidth (10 kHz+).
- 16+ frequency channels for DRC.
- Adaptive microphone directionality.
- Noise reduction: ambient, wind, impulse.
- Environmental classification.
- Advanced feedback cancellation.
- Frequency shifting.
- Low latency (<< 10 ms), binaural algorithms.

Fitness and medical features:

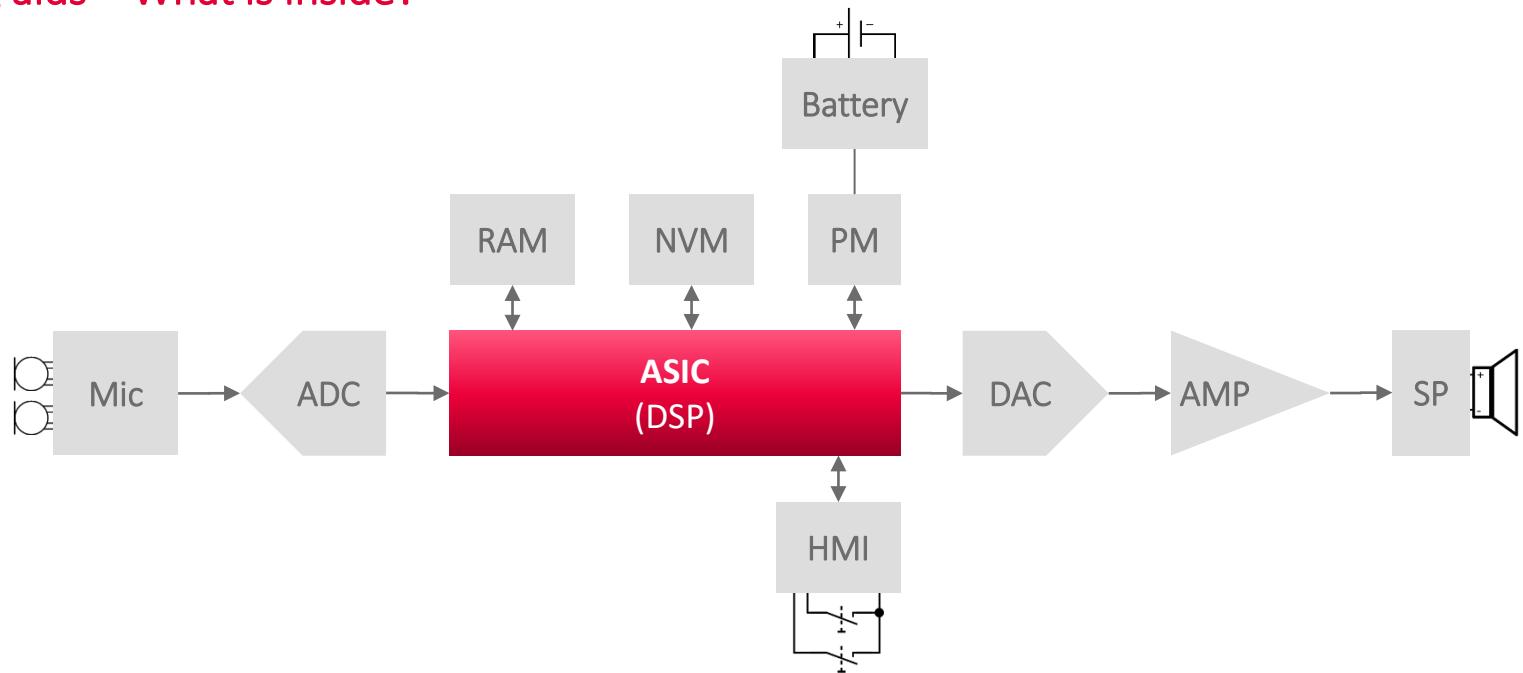
- Fitness tracking (step counter, pulse rate etc.).
- Blood pressure monitoring ([Sonion BiometRIC](#)).
- On-demand activity log.
- Fall detection.



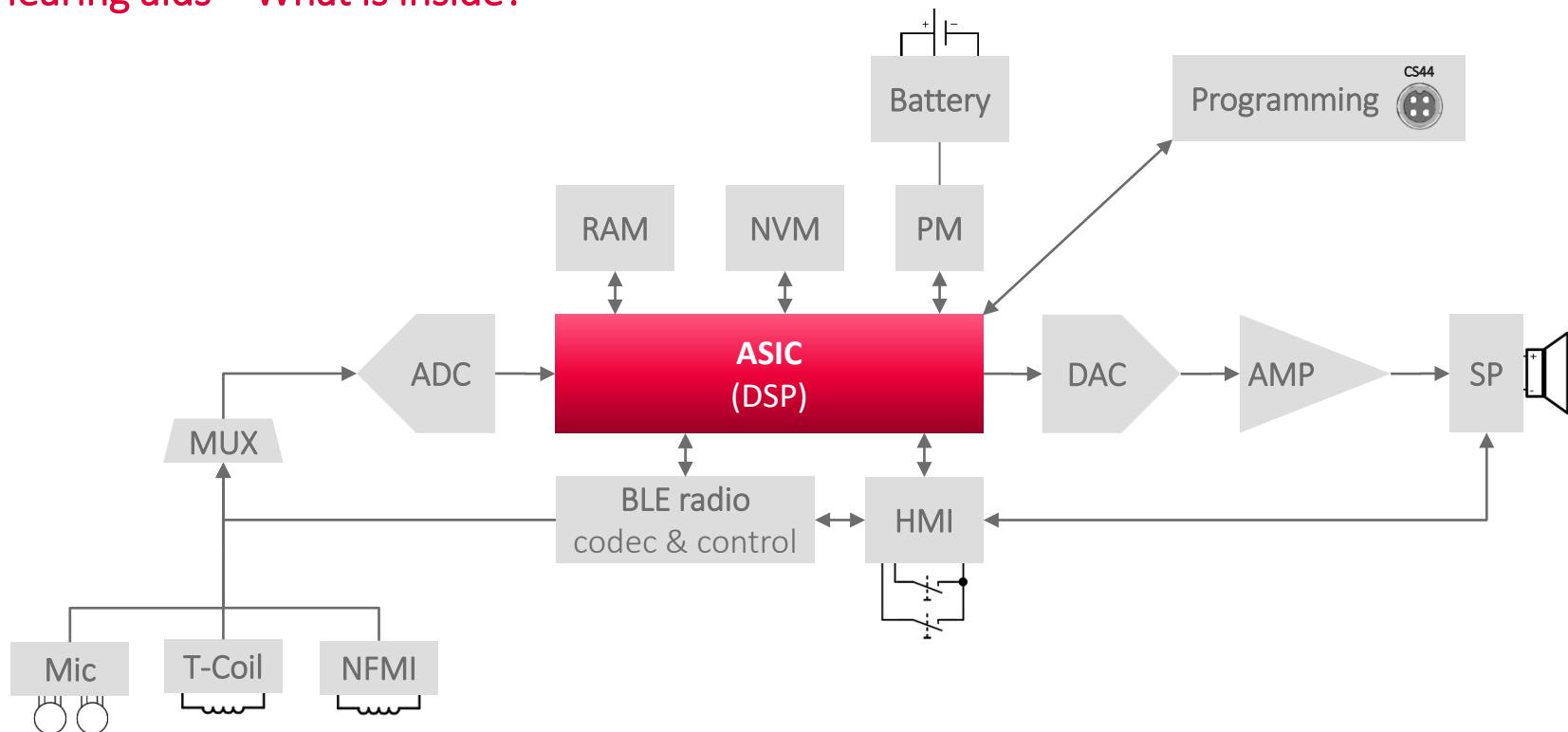
•• Hearing aids – What is inside?



•• Hearing aids – What is inside?

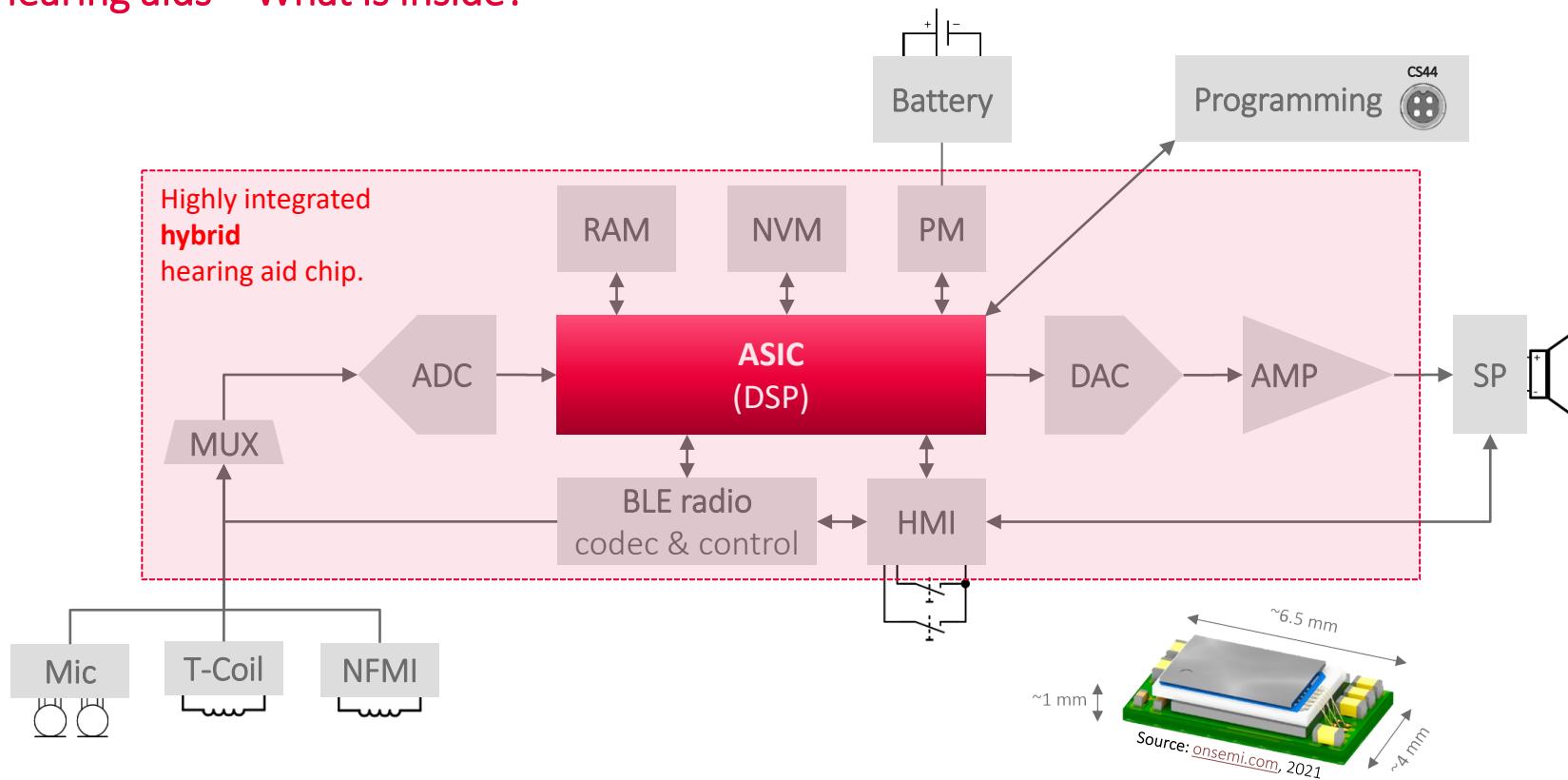


•• Hearing aids – What is inside?



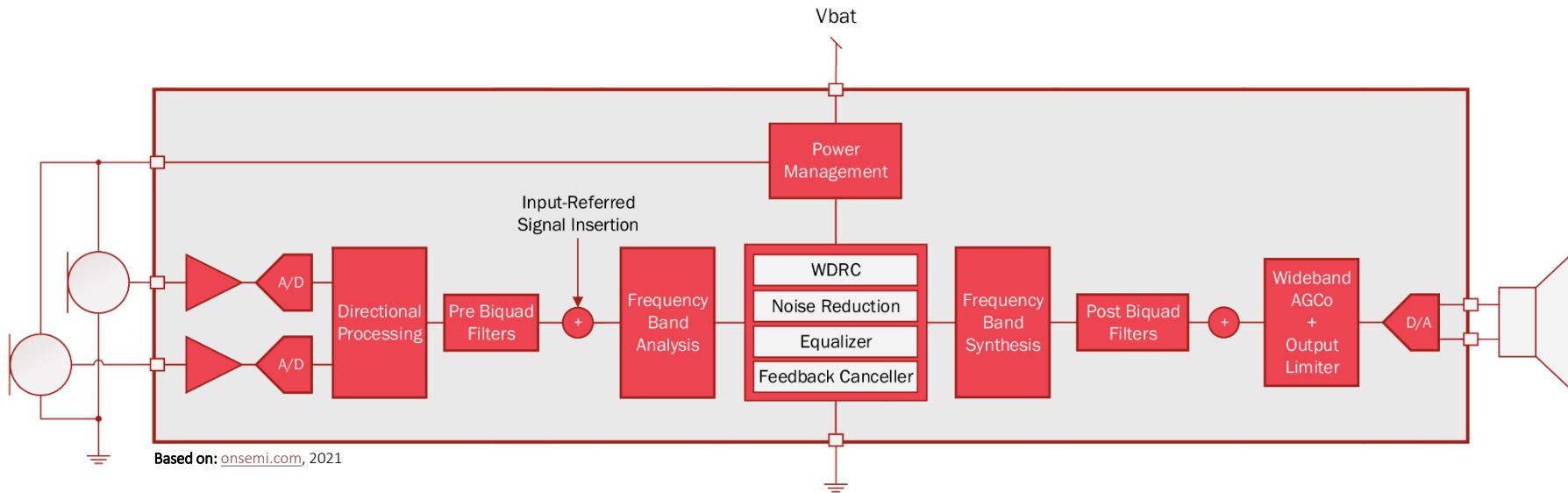
ASIC: application specific integrated circuit, **HMI:** human-machine interaction, **MUX:** multiplexer, **NFMI:** near-field magnetic induction, **NVM:** non-volatile memory, **PM:** power management, **T-Coil:** Telecoil (receiver for inductive loop), **WL:** (other) wireless technology

•• Hearing aids – What is inside?

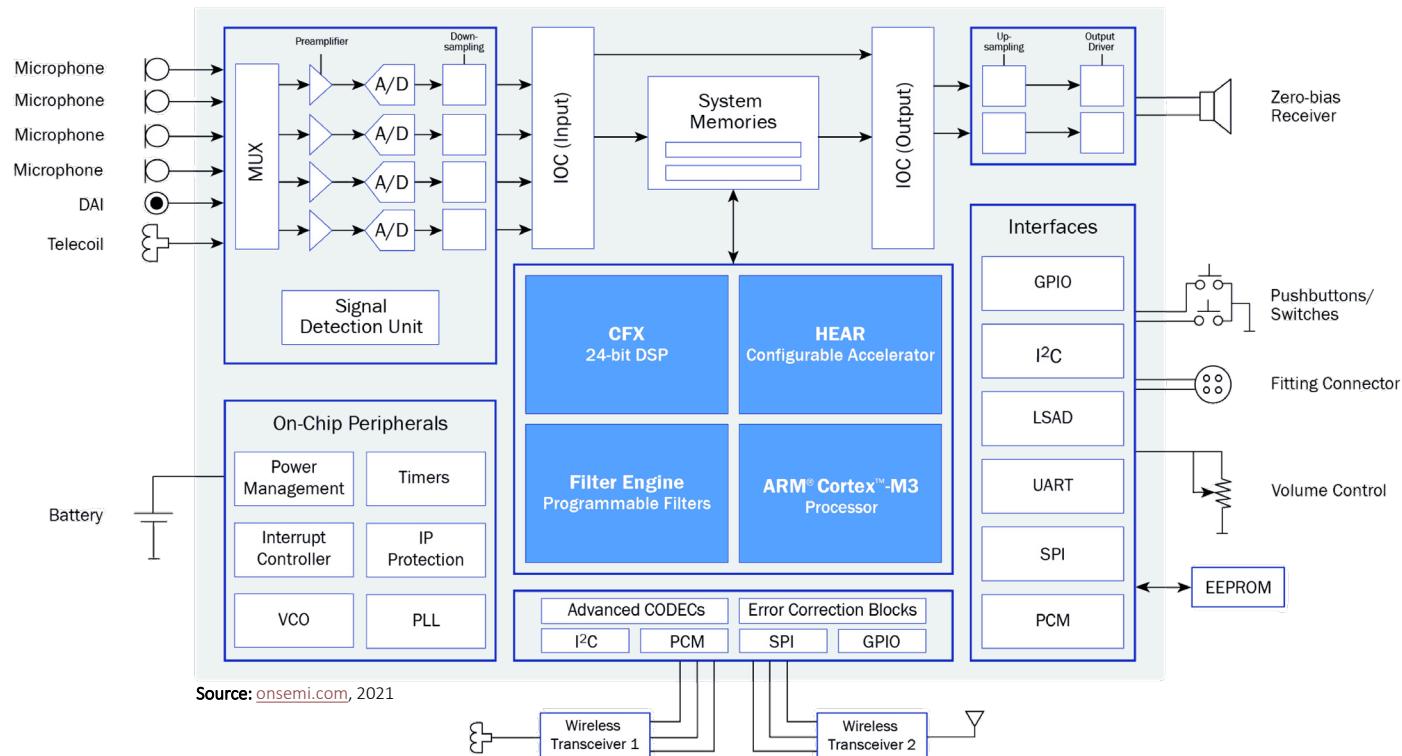


ASIC: application specific integrated circuit, **HMI:** human-machine interaction, **MUX:** multiplexer, **NFMI:** near-field magnetic induction, **NVM:** non-volatile memory, **PM:** power management, **T-Coil:** Telecoil (receiver for inductive loop), **WL:** (other) wireless technology

•• Hearing aids – Basic signal flow



•• Hearing aids – Architecture of an ASIC



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

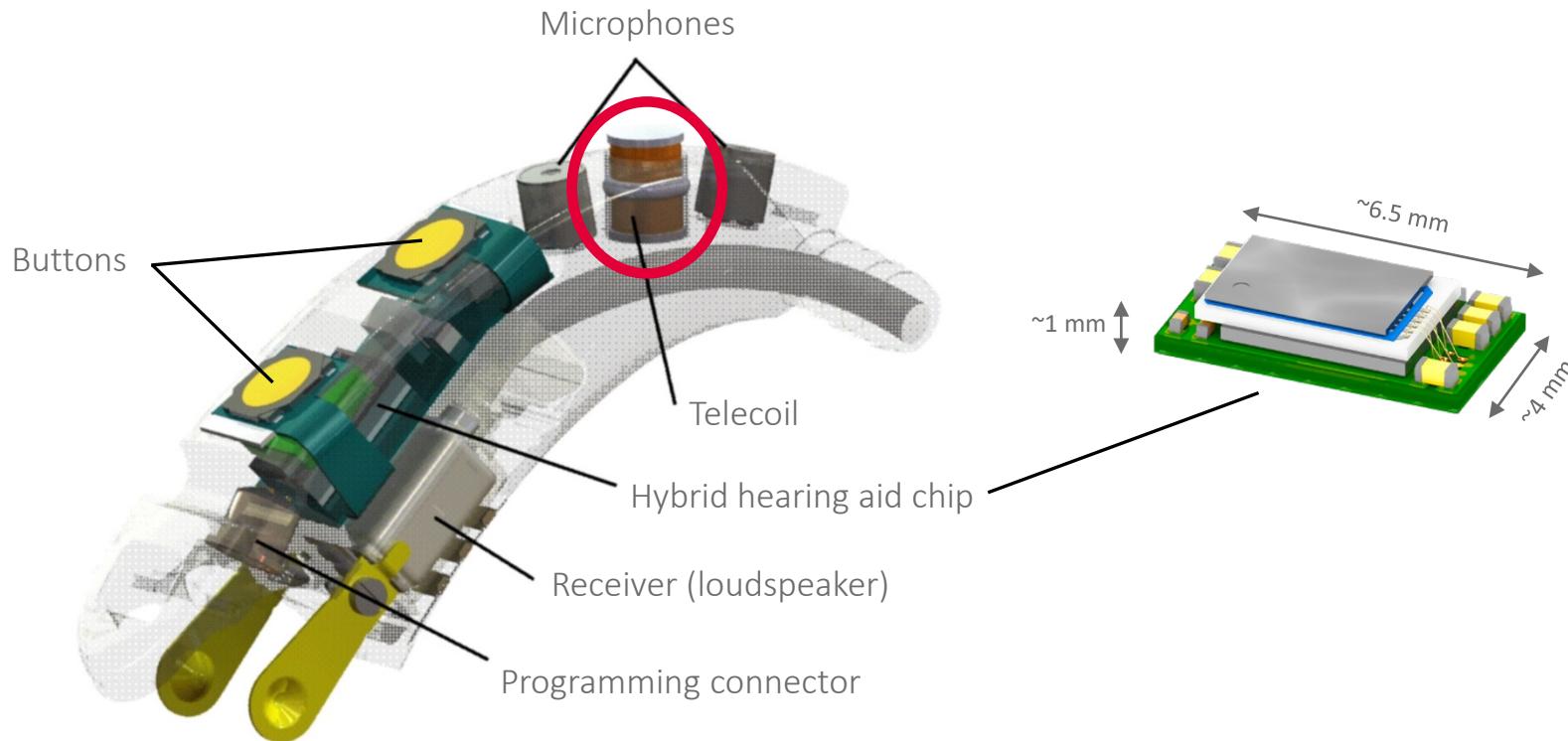
	Hearing aid ASIC	Hearable ASIC	PC CPU
Typical power consumption (algorithms on, wireless off)	~ 1-2 mW	~ 15-50 mW	~ 35-125 W
Typical power consumption (algorithms on, BLE in use)	+ 3-8 mW	+ 15-50 mW	
Clock speed	~ 10-60 MHz	~ 20-200 MHz	~ 3000-4000 MHz
MIPS @ max. clock speed	~ 500 MIPS	~ 2 000 MIPS	~ 500 000 MIPS
Typical dimensions	~ 4 x 7 x 1 mm = 28 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



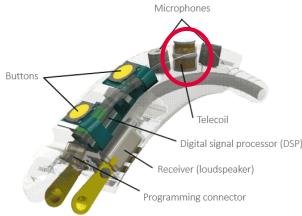
Source: [kind.com](#), 2021

•• Hearing aids – Construction of a hearing aid

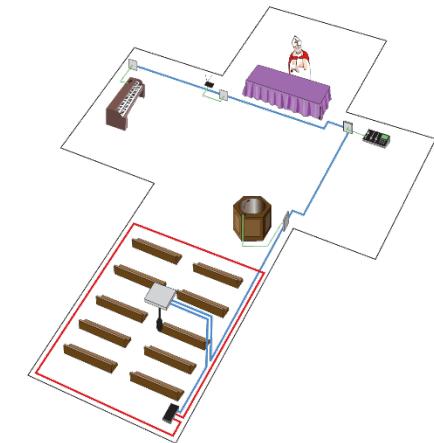


Source: kind.com, 2021

•• Excursion: Telecoil

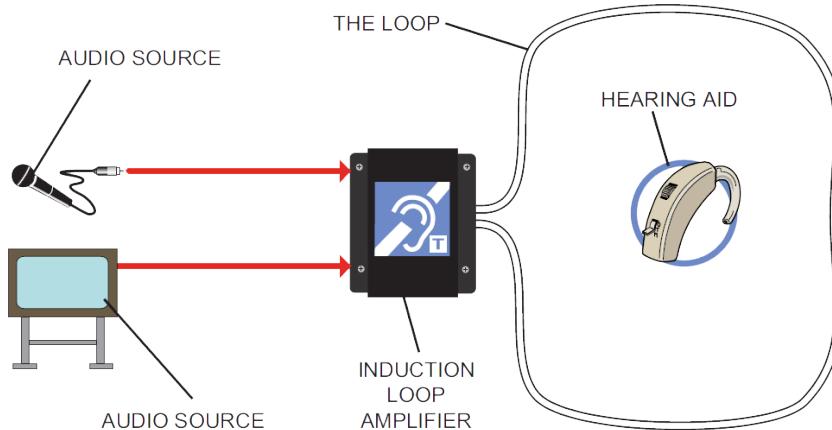


Source: signet-ac.co.uk, 2021

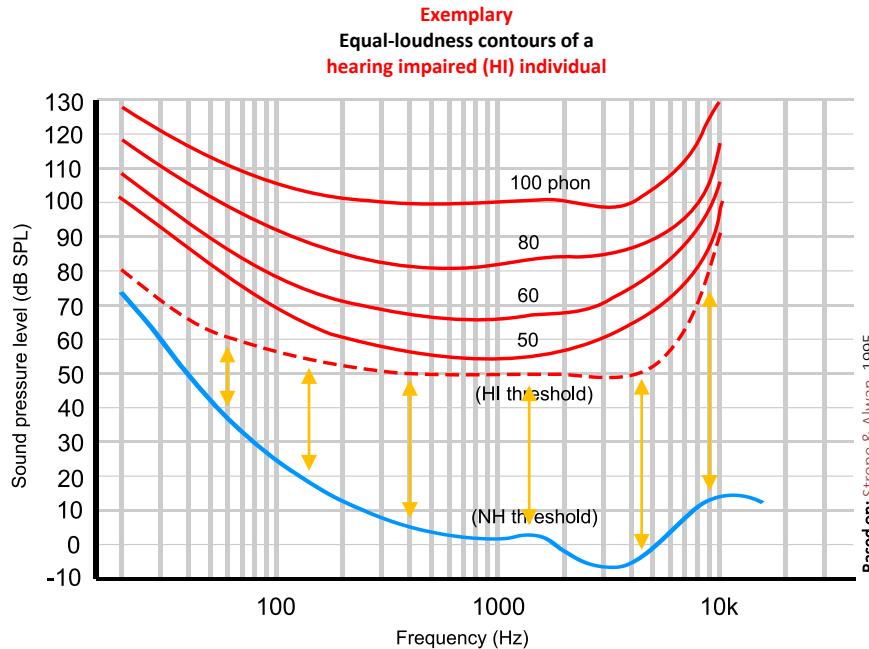
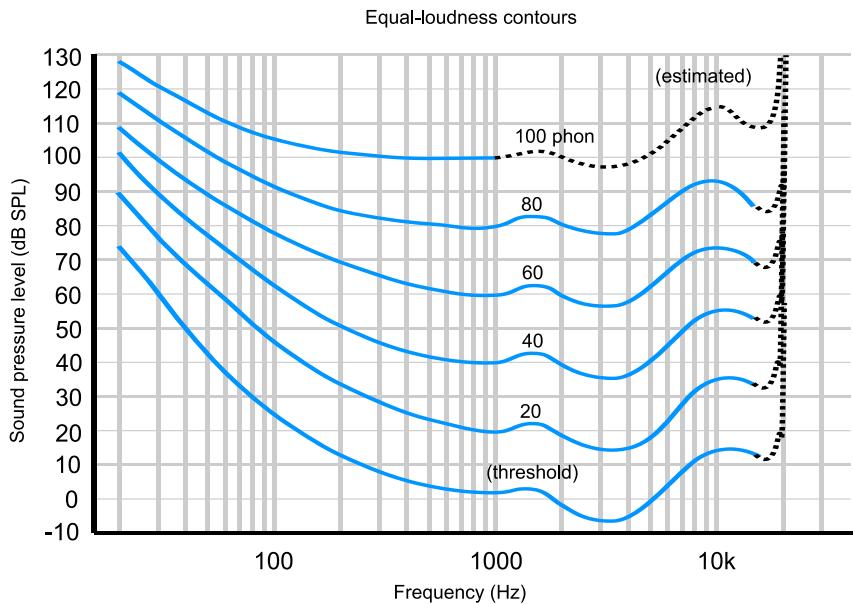


T-coil or induction loop receiver:

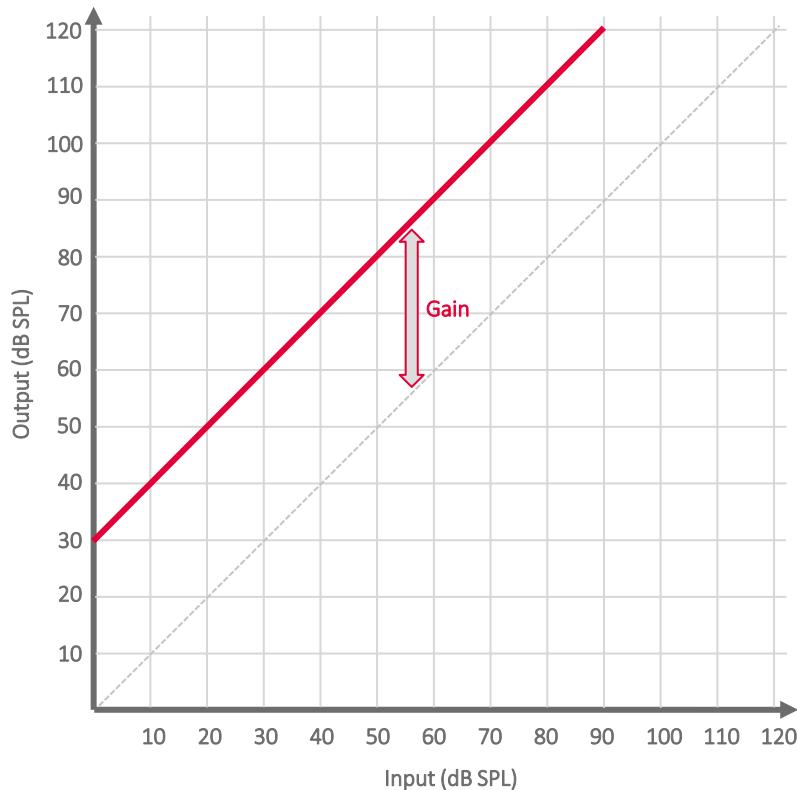
- Operating at audio frequencies, no RF.
- Induction loop parts:
 - constant current amplifier,
 - closed loop cable.
- Attention (privacy):
 - EM-field bleeding.
 - Always broadcast.



•• Recap: Equal-loudness contours



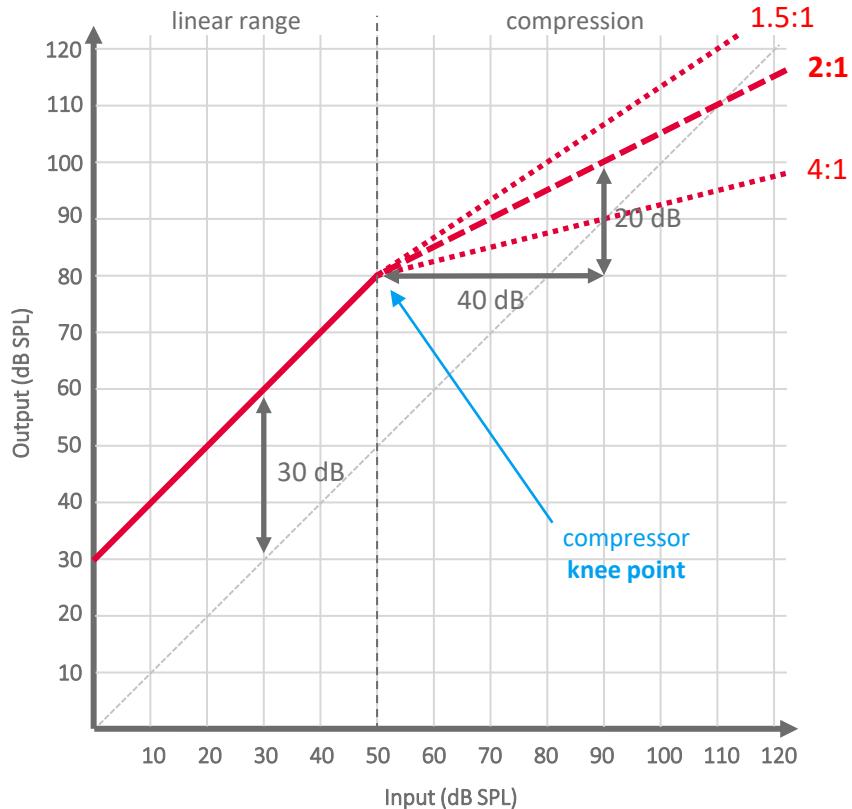
•• Hearing aids – Wide dynamic range compression



Linear amplification alone:

- 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.

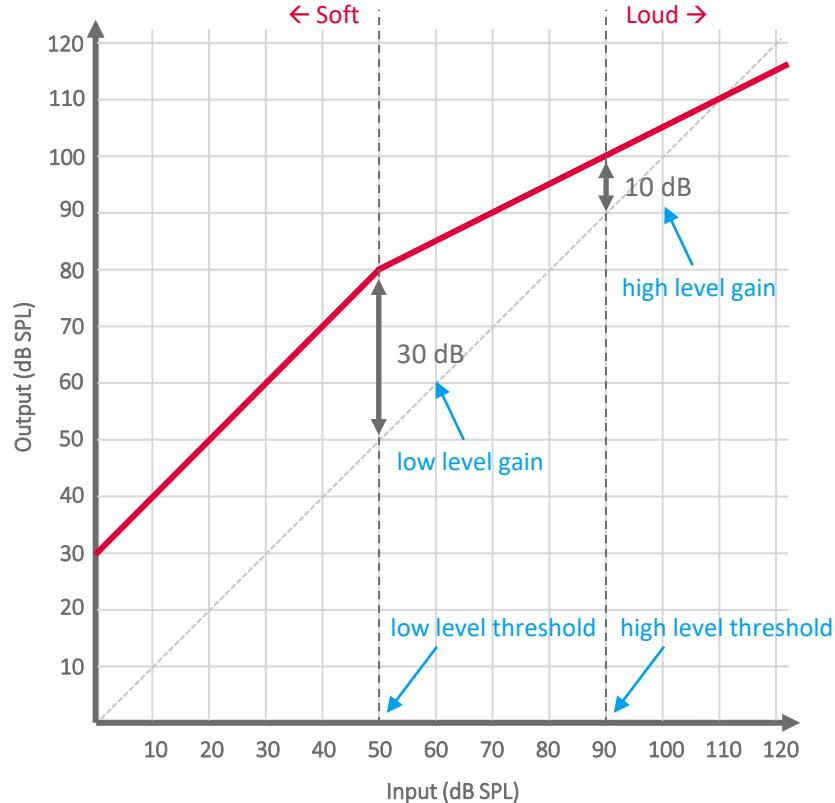
•• Hearing aids – Wide dynamic range compression



Compression:

- Example:
40 dB increase in the input leads to
20 dB increase in the output, i.e.,
→ **compression ratio: $40 \text{ dB} : 20 \text{ dB} = 2:1$**
- Compression ratio can vary, but usually does
not exceed 4:1 in the hearing aid field.

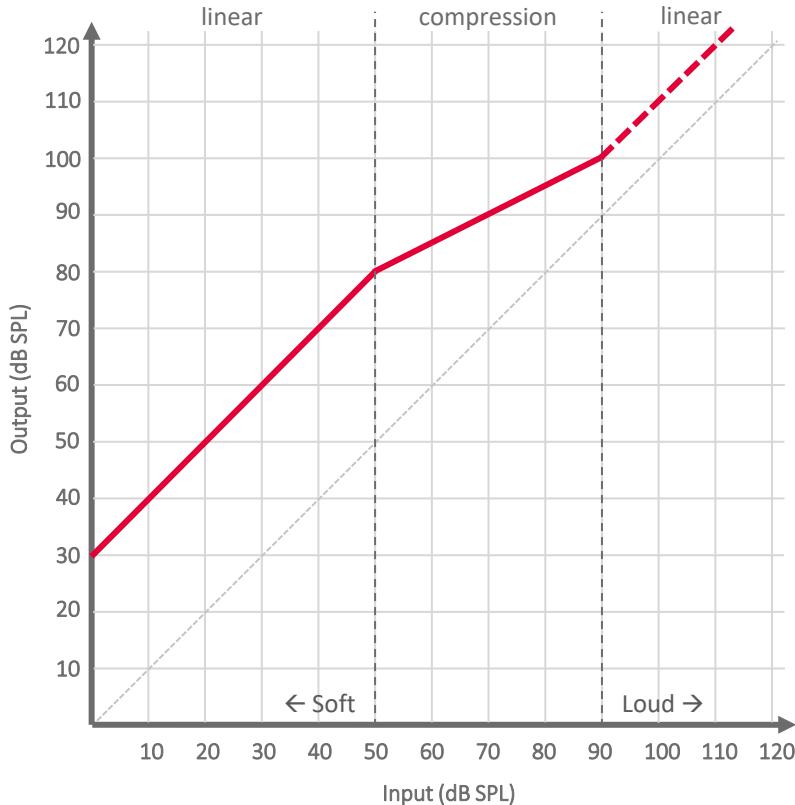
•• Hearing aids – Wide dynamic range compression



Compression:

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

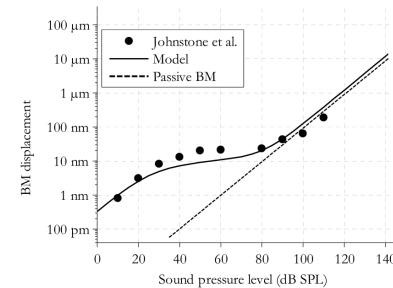
•• Hearing aids – Wide dynamic range compression



Second linear range:

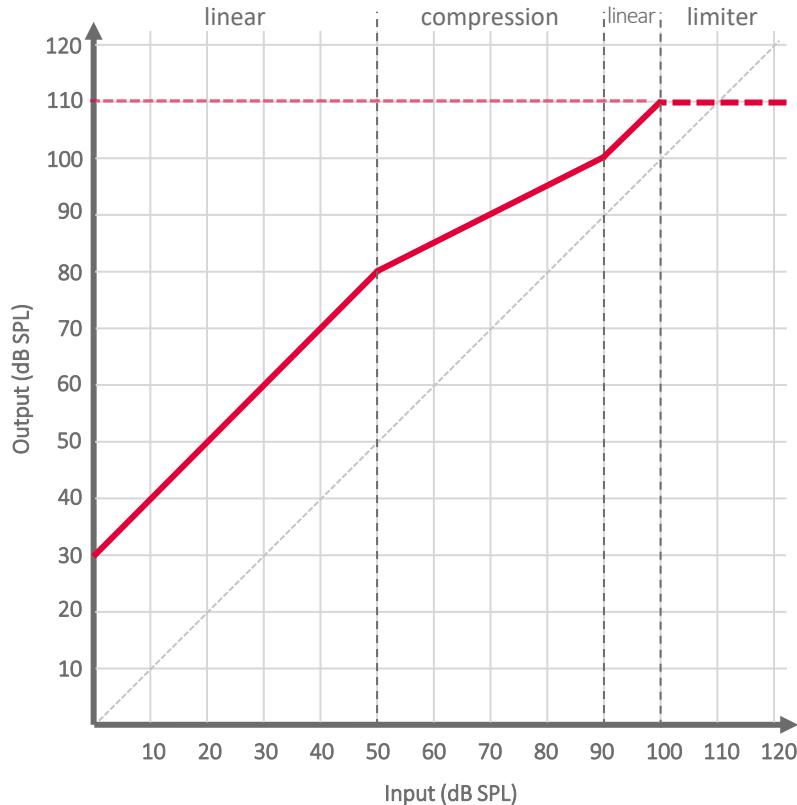
- Can be useful to allow the listener to realize that the input is very loud.
- Should be verified to not extend into the threshold of pain. (See “limiter” on next slide.)
- Remember the normal hearing ear handles loud noises very similarly! Basilar membrane nonlinearity:

Reminder



Adapted from: Johnstone et al., 1986

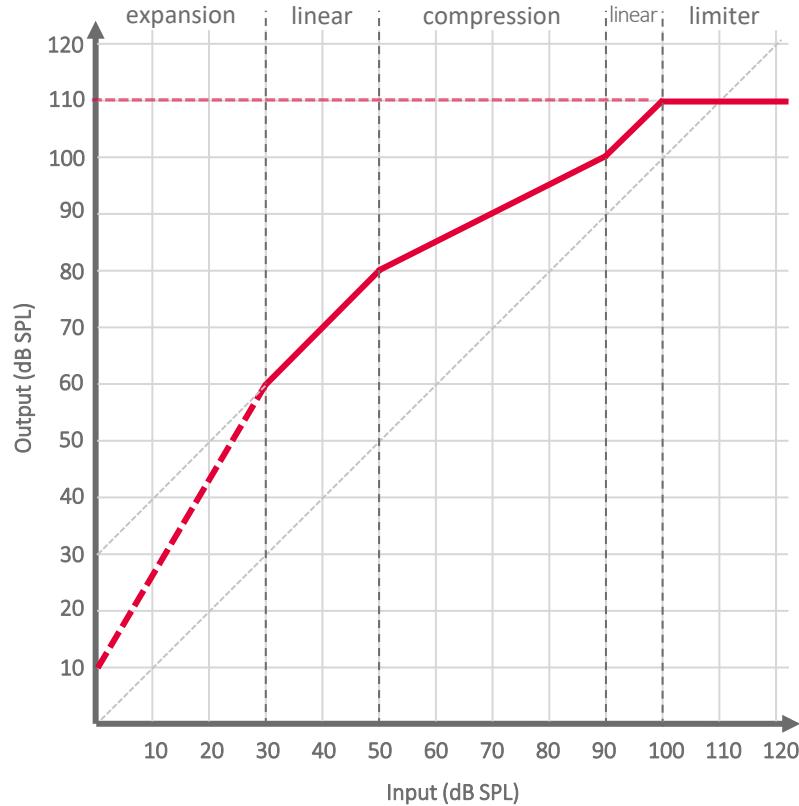
•• Hearing aids – Wide dynamic range compression



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 $\infty:1$ compression rate.

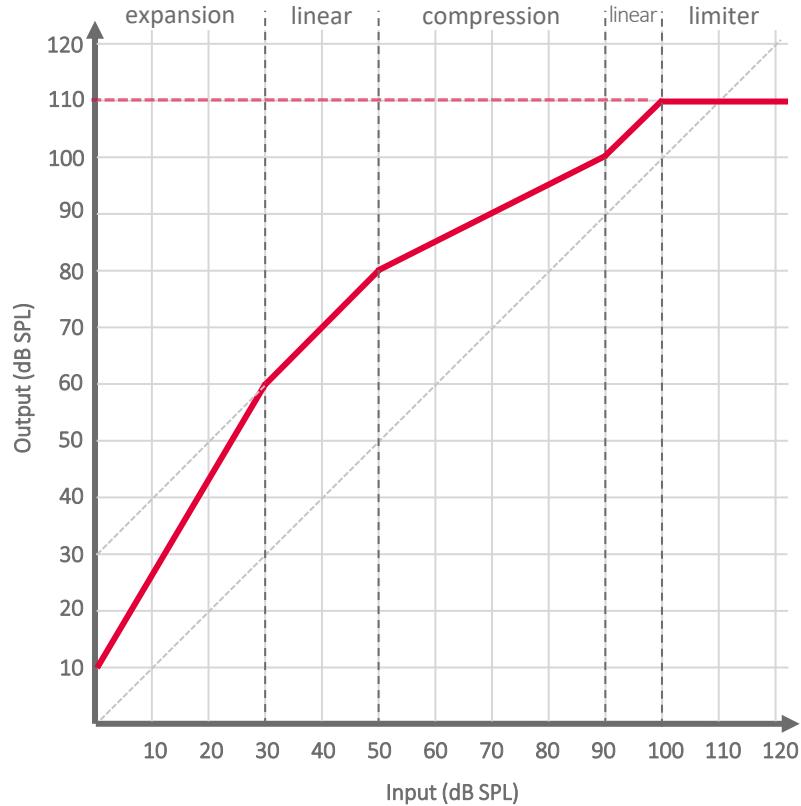
•• Hearing aids – Wide dynamic range compression



Expansion:

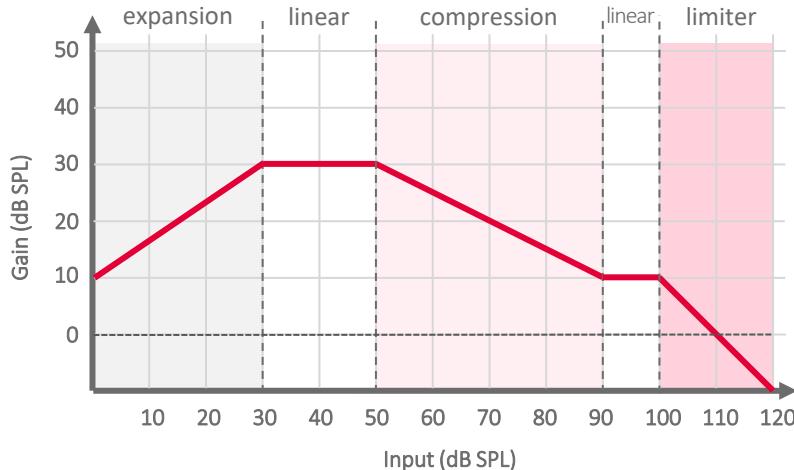
- Usually employed in the low SPL range.
→ Less gain added to soft noises.
- Reduces inherent noise of the system (e.g. that of microphones or preamps).
- Reduces irrelevant background noise.
→ Increases overall SNR.
- Typical expansion rate: 1:1.5 - 1:3.
(1:1.66 in the graph on the left.)

•• Hearing aids – Wide dynamic range compression

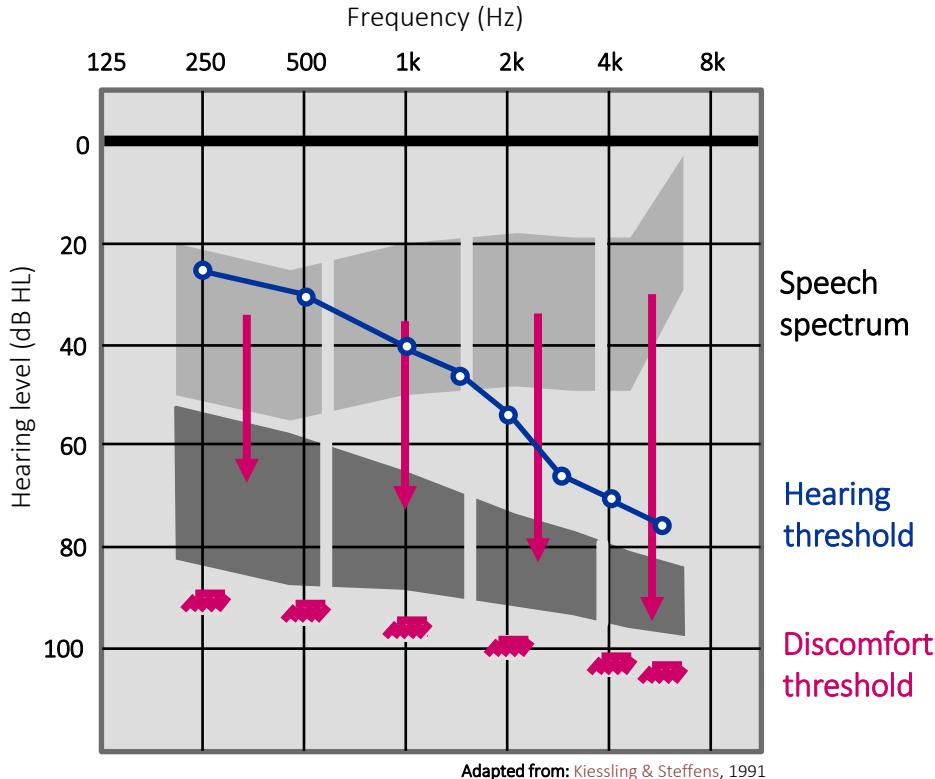


Gain plot:

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

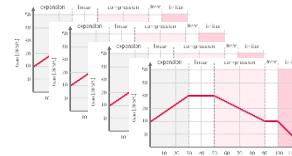


•• Hearing aids – Multi-channel WDRC



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.

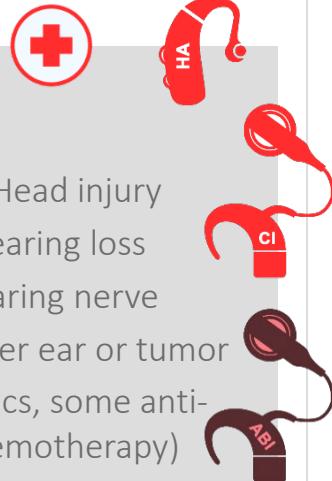
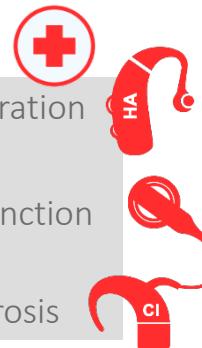
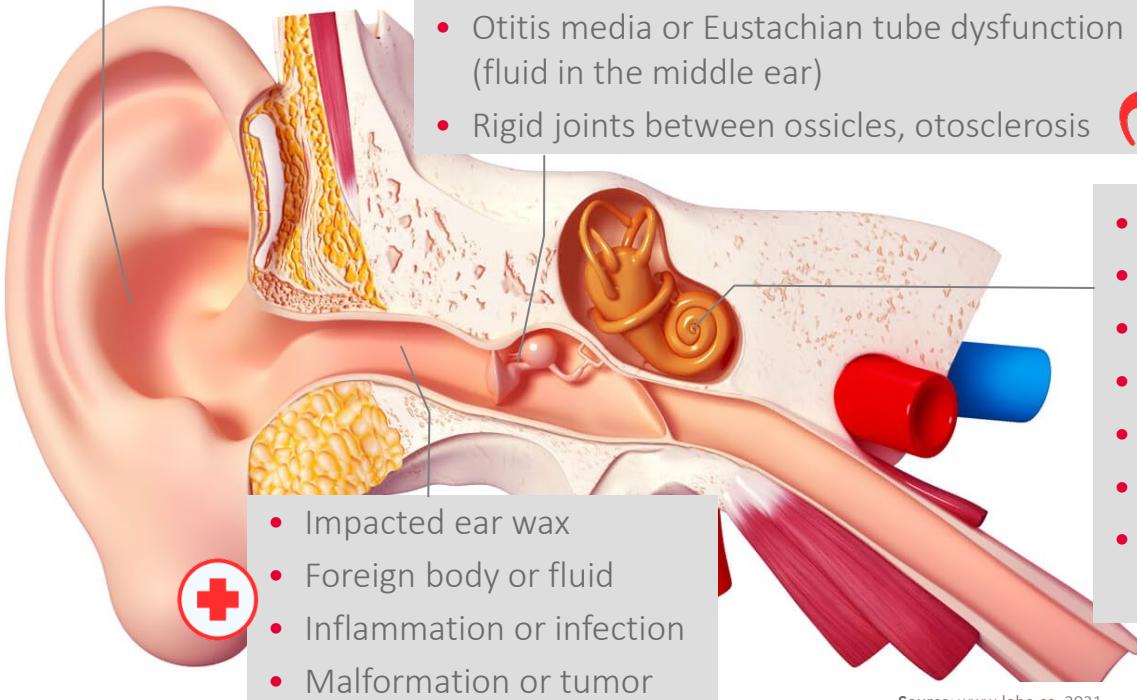


- A computationally cheap, but high quality filter-bank with almost perfect reconstruction is needed.
- (Keywords for searching further information: FFT-based WOLA filter-banks and warped filters.)

•• Recap: Causes of hearing impairment

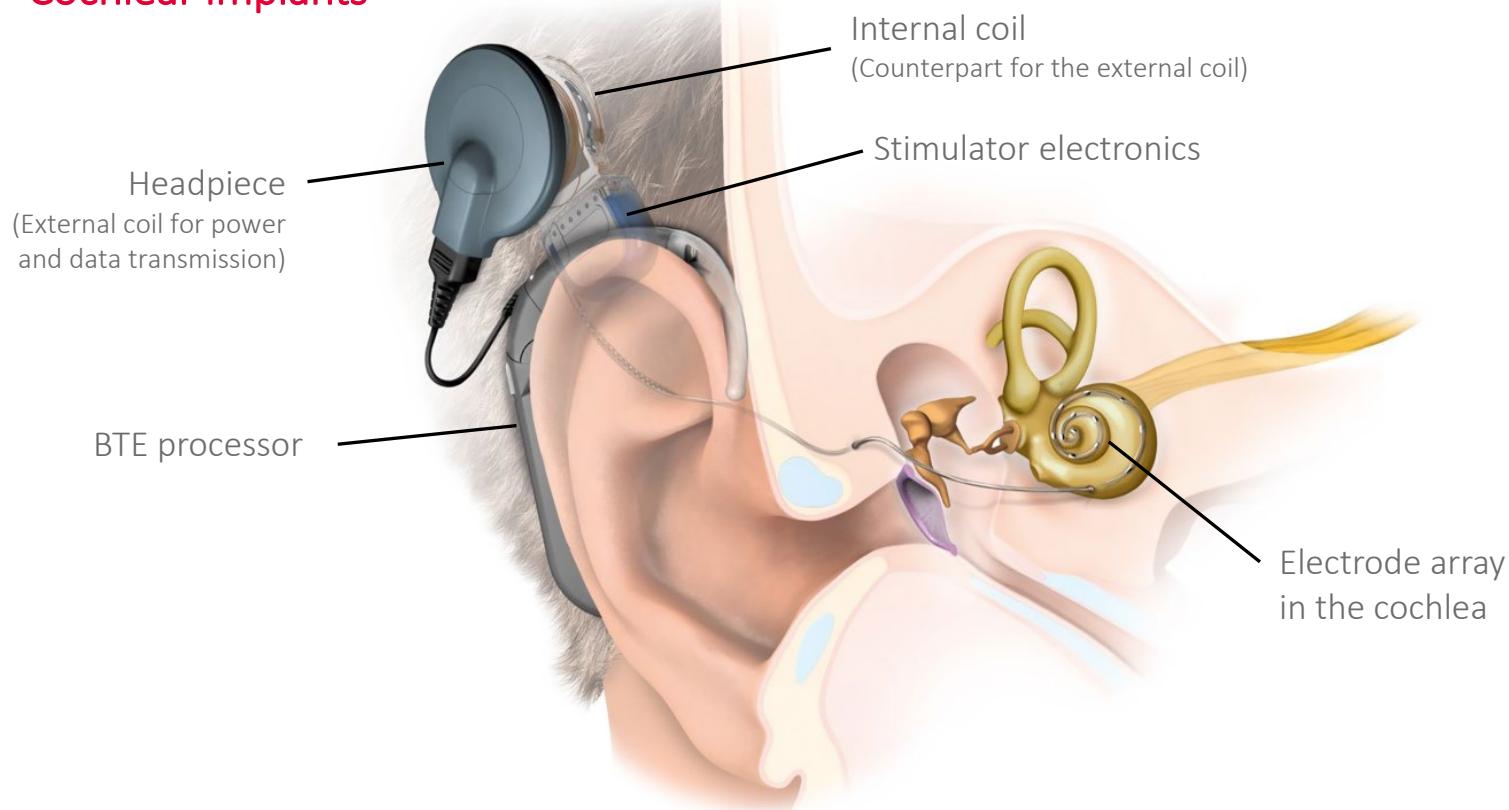


- Malformation
- Foreign body



Source: www.lobe.ca, 2021.

•• Cochlear implants

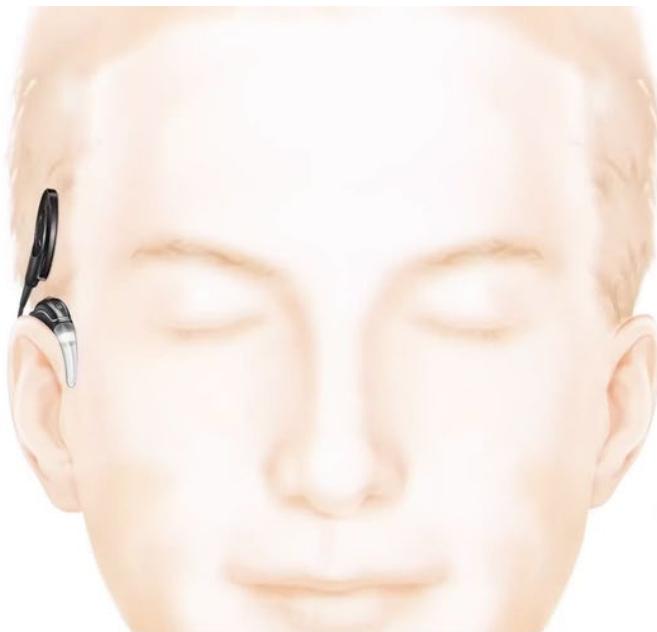


•• Cochlear implants



Source: cochlear.com, 2021

•• Cochlear implants



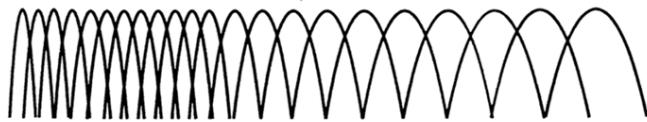
Source: cochlear.com, 2021 (unprocessed sound)

•• Cochlear implants – Signal processing strategy

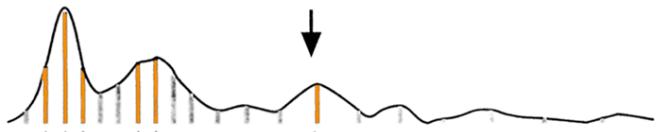
Input waveform



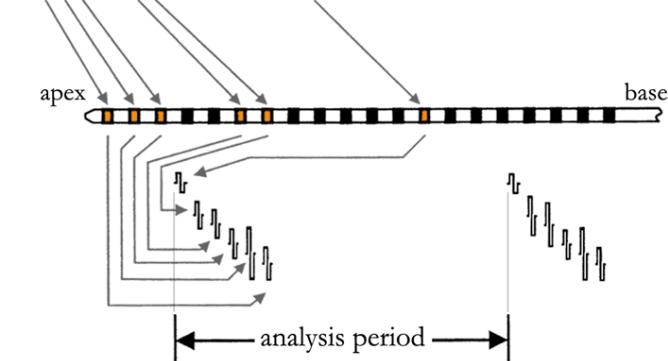
22-channel band-pass filter bank



Instantaneous spectrum



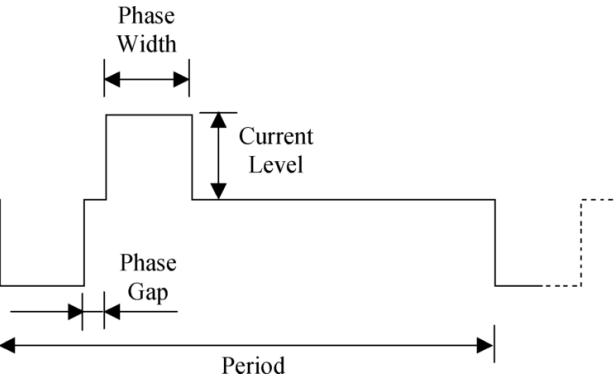
Electrode array



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

ACE signal processing strategy
(advanced combination encoder)

Biphasic, charge balanced pulses



Source: Tognola et al., 2005

•• Cochlear implants – Early history

Source: hearinghealthmatters.org, 2021

Alessandro Volta

50V DC ear-to-ear



1790s

1868

1950-57

1961

1982

1985

1996

2001

Source: abebooks.com, 2021



Rudolf Brenner's
AC stimulation

Source: [Eisenberg](https://eisenberg.com), 2005



William F. House's
single-channel CI

Source: [Clark](https://clark.com), 2013



House's first clinical
multi-channel CI

Clarion implant

Advanced Bionics
(USA)



Source: cochlear.com, 2021

Nucleus implant
Cochlear Ltd. (AU)

Commercialization →

Combi40+ implant
MED-EL GmbH (AT)

•• 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

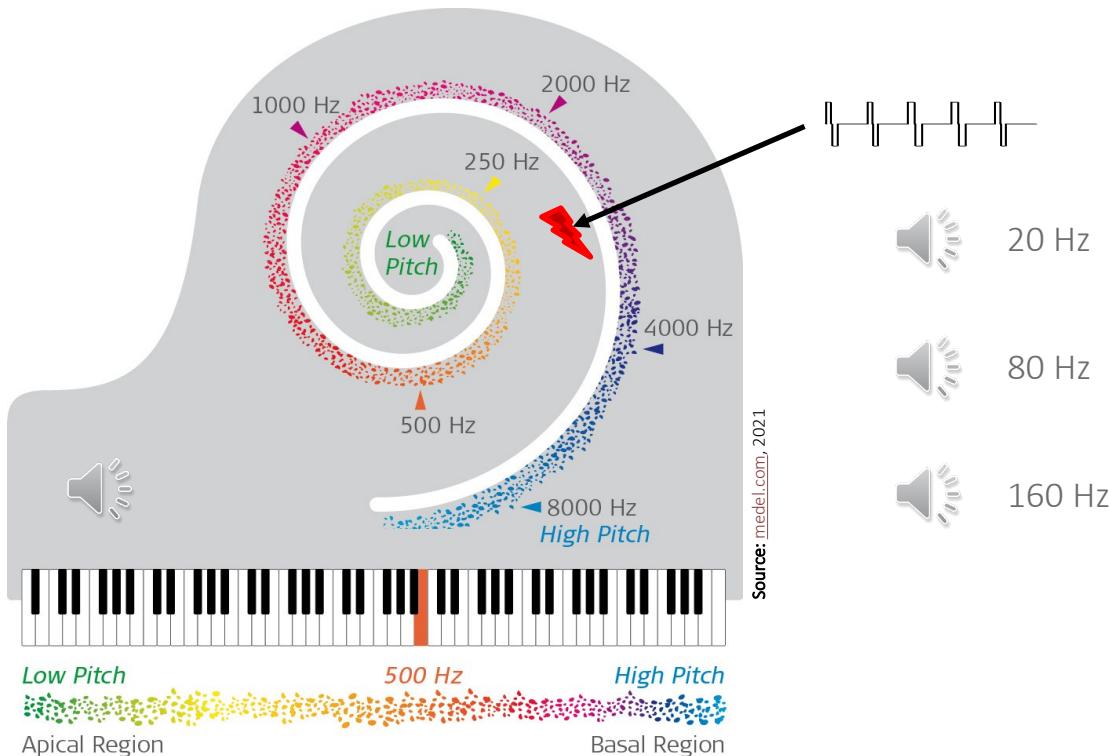
Smart preprocessing can increase speech melody changes in real-time (PREX project, Fraunhofer IDMT).



- Improve temporal pitch cues

Better stimulation strategies (SAM project, Dissertation, Fraunhofer IDMT)

•• Pitch perception



•• Cochlear implants – Ways to improve pitch sensitivity

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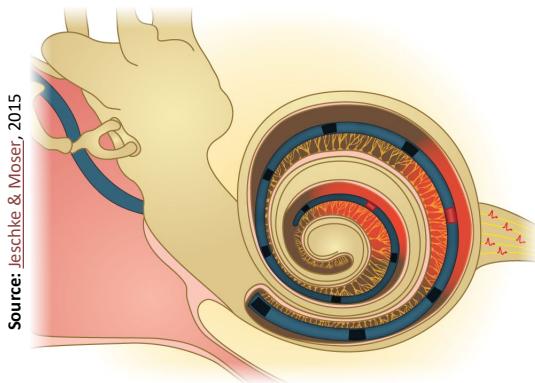


- Improve place pitch cues (reducing current spread)

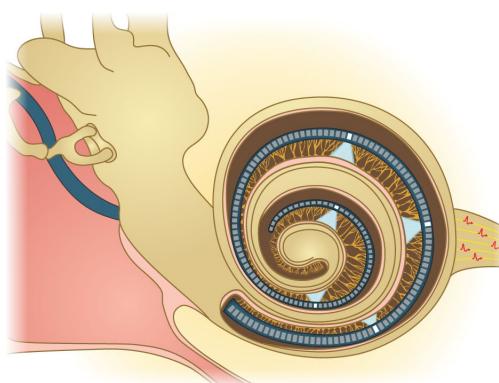
- Better electrode design (“modiolus-hugging” or “adhering” electrodes),
- Current steering (parallel stimulation over multiple electrode contact points)
- Optogenetic stimulation (optical cochlear implants).

•• Optogenetic cochlear implants

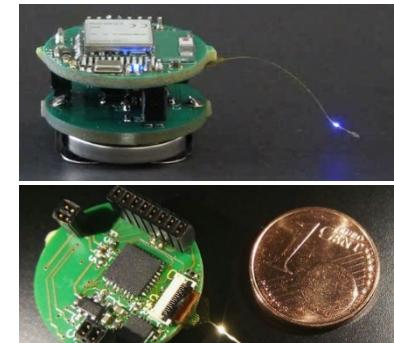
Electrical stimulation



Optical stimulation



Research hardware

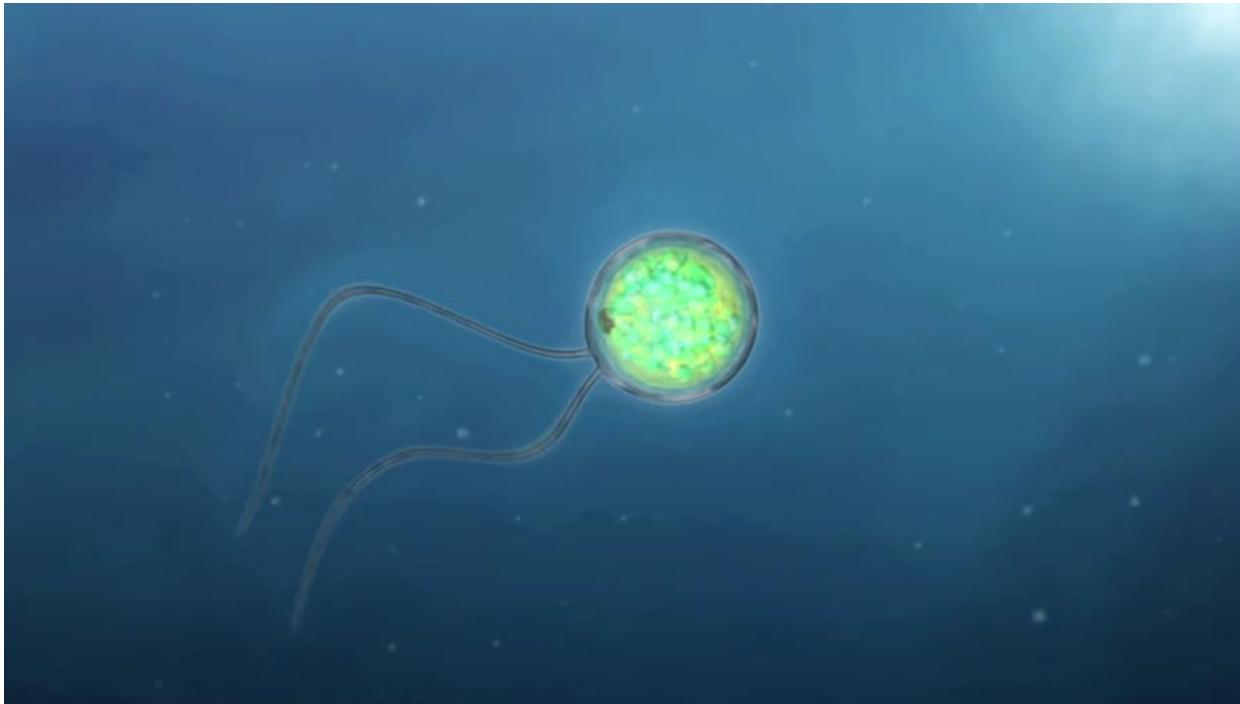


Challenges of optogenetic cochlea stimulation:

- **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](#)

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Thank you very much!
Questions?

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

audifon GmbH & Co. KG