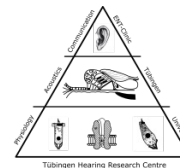


Hearing & Audiometry

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ENT Clinic Tuebingen

Biomedical Technologies in Diagnostic and Therapy



UNIVERSITÄTS
KLINIKUM
TÜBINGEN

Hearing

Frequency range: 16 Hz – 20 kHz

Intensity range: 120 dB

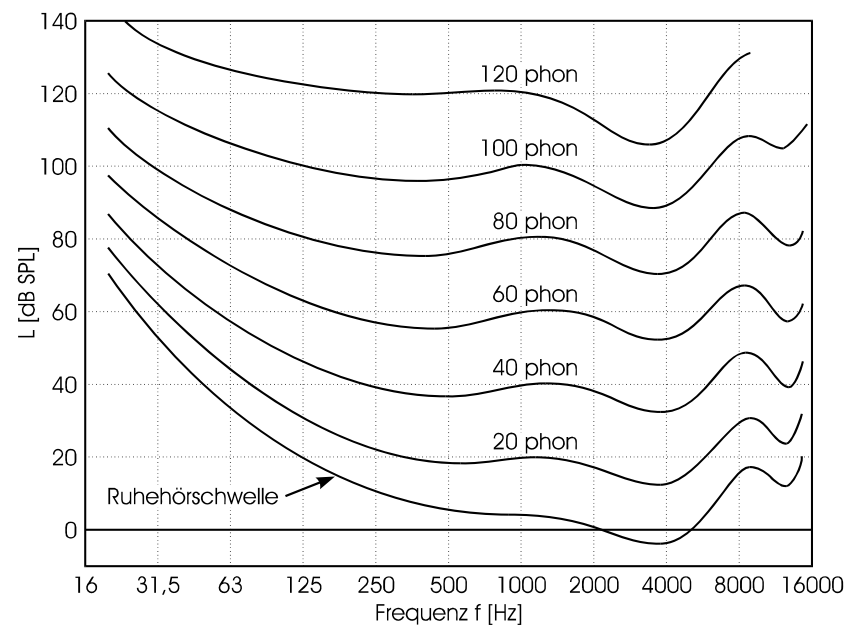
Hearing threshold: approx. 20 μPa (500 Hz – 5 kHz)

-> physical:

sound pressure dB SPL = dB re. 20 μPa

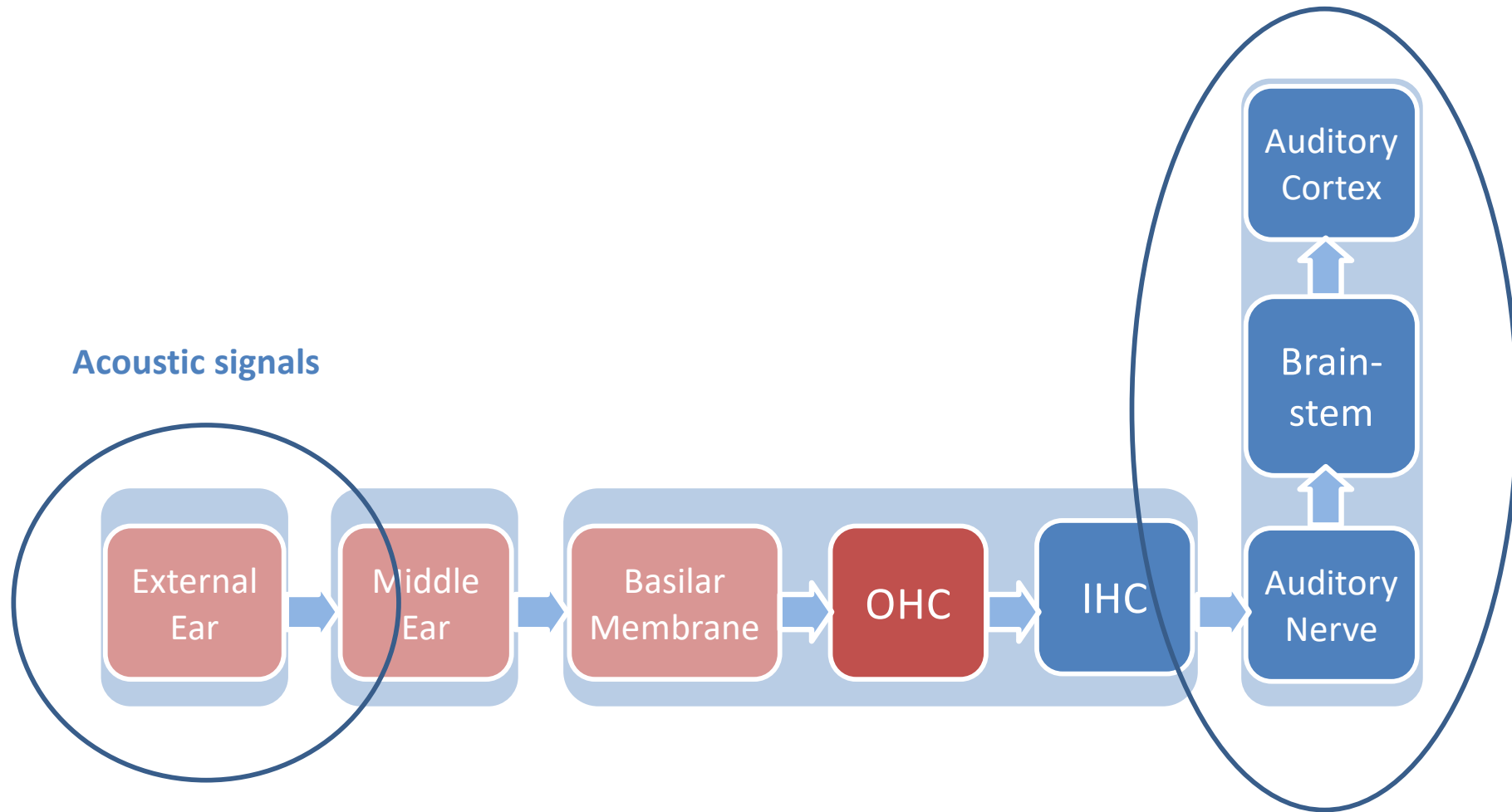
-> psychoacoustical/medical:

hearing level dB HL = dB re. normal threshold



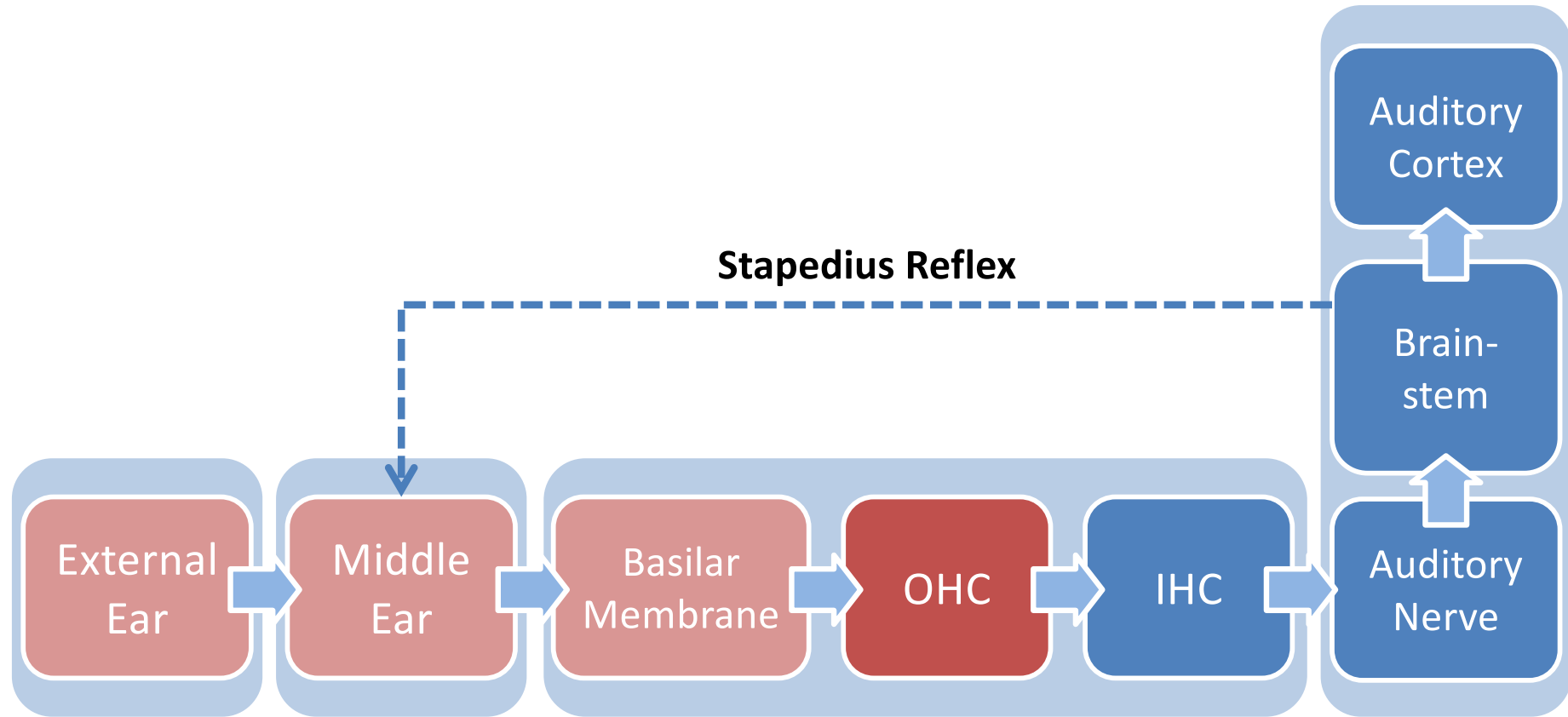
Hearing pathway

Auditory evoked electrical potentials



OHC – Outer Hair Cell
IHC – Inner Hair Cell

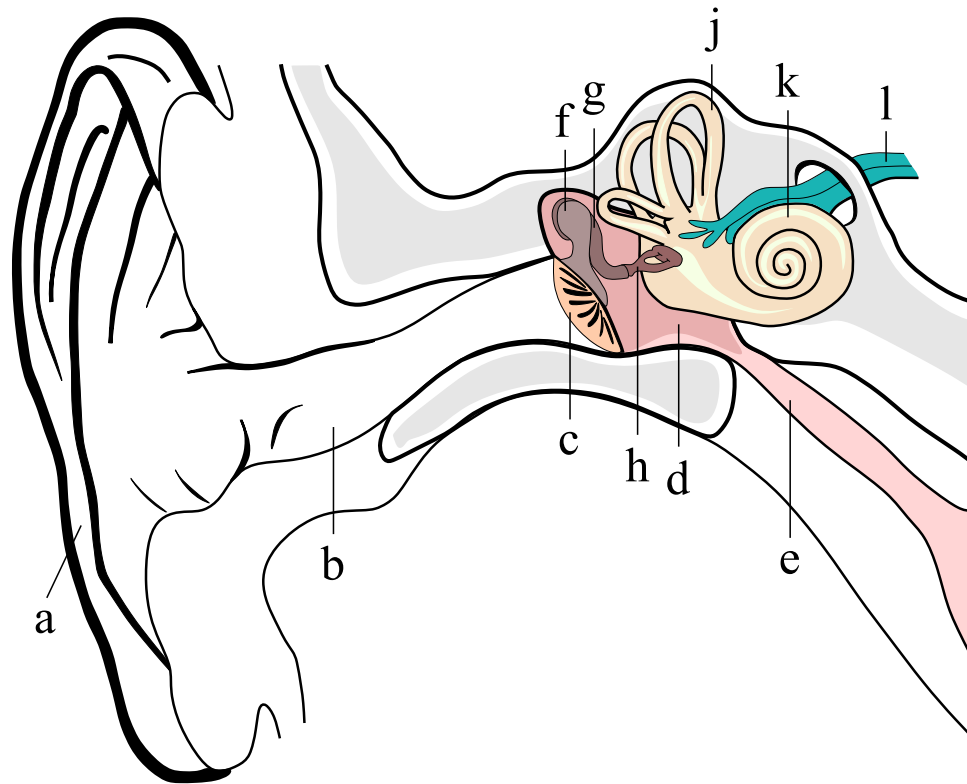
Hearing pathway



Cochlear Amplifier

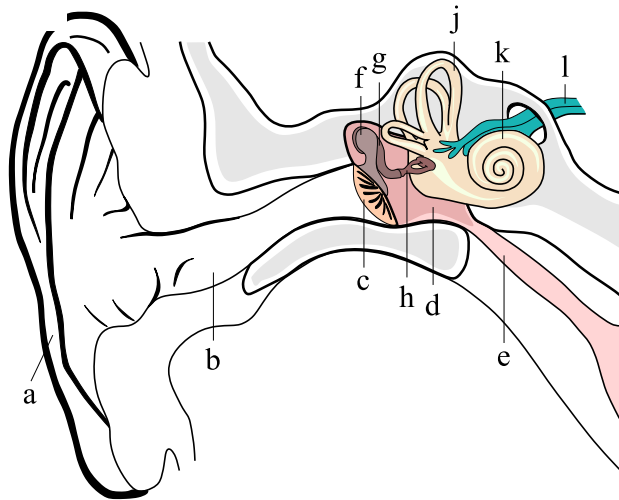
OHC – Outer Hair Cell
IHC – Inner Hair Cell

External and middle ear



- a auricle
- b ear canal
- c eardrum
- d tympanic cavity
- e Eustachian tube
- f malleus
- g incus
- h stapes
- j semicircular canal
- k cochlea
- l auditory nerve

External and middle ear



acoustic function and technical analogy:

auricle:	exponential horn
ear canal:	acoustic tube
ossicles:	mechanical lever
tympanic membrane/ stapes:	hydraulic lever (area ratio 1:20)

important concepts:

- impedance matching -> reduction of reflections
- transmission lines (dt.: Kettenleiter) -> distributed structures/smooth transitions

Acoustical. Impedance / reflectance

$$Z(f) = \frac{p}{u} \quad \text{impedance} \quad u \text{ [m}^3\text{/s] : volume velocity}$$

$$Y(f) = \frac{u}{p} \quad \text{immittance / admittance}$$

ear canal: tube of ~8 mm diam: supports only one mode -> 1D-acoustical field

$$p(t, x) = p^+(t, x) + p^-(t, x), \text{ where}$$

$$p^+(t, x) = P^+ \cos(\omega t - kx + \theta_P^+), \text{ and}$$

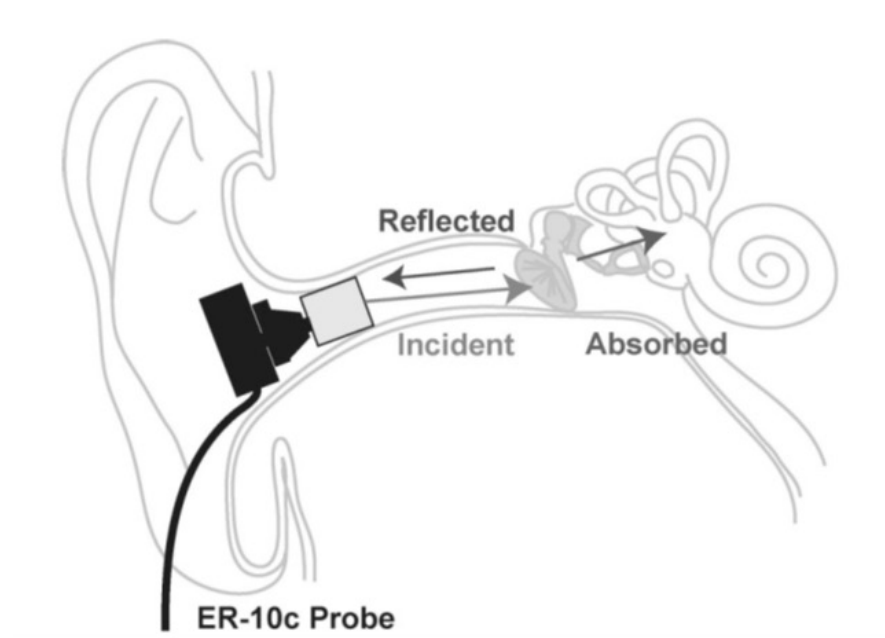
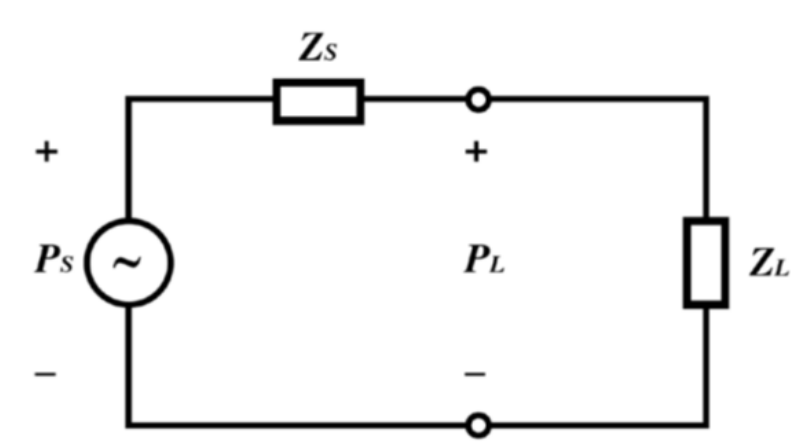
$$p^-(t, x) = P^- \cos(\omega t + kx + \theta_P^-)$$

$$\mathbf{Z} = -j \frac{\rho_0 c}{S} \cot\left(\frac{2\pi f}{c} l\right)$$

$$\mathbf{R}(f, 0) = \frac{\mathbf{Z}_T(f) - Z_0}{\mathbf{Z}_T(f) + Z_0}, \quad \text{pressure reflectance}$$

$$Z_0 = \rho_0 c / S$$

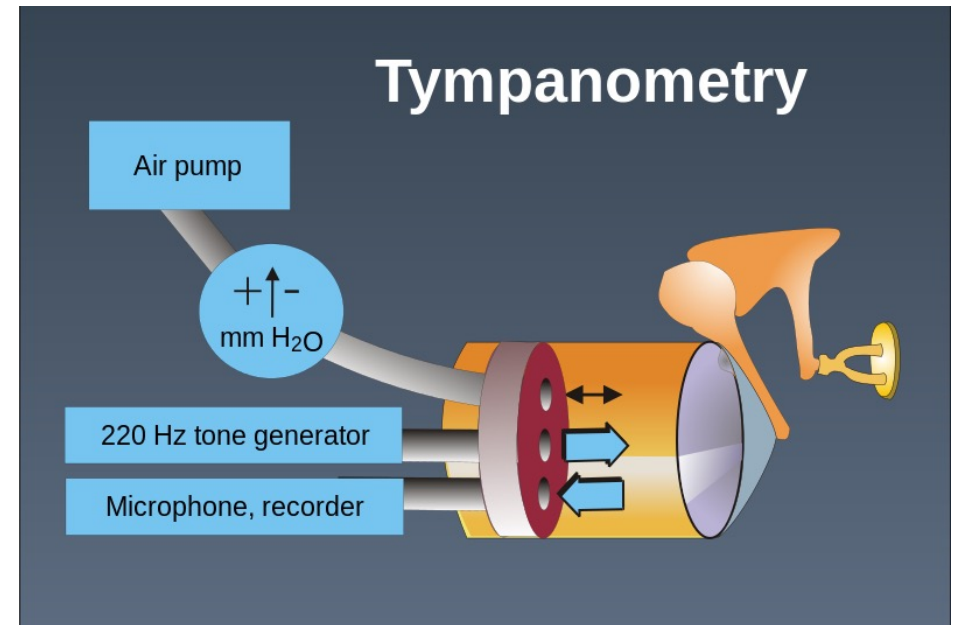
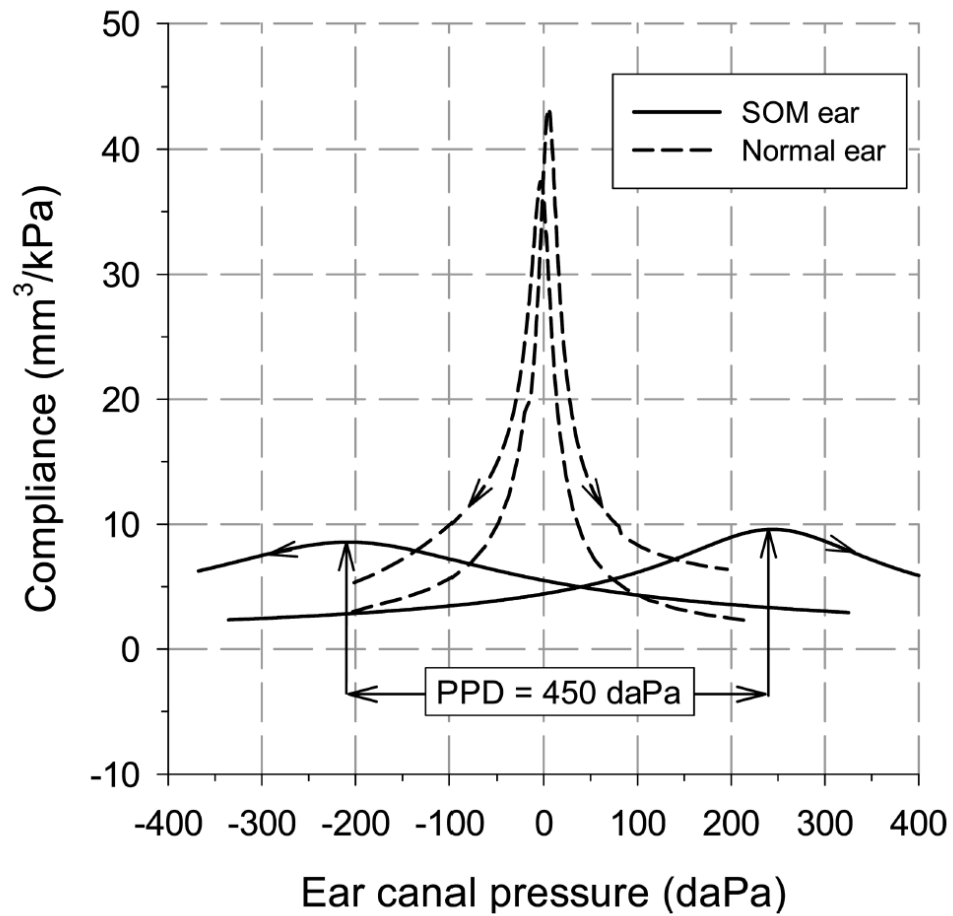
Impedance measurement



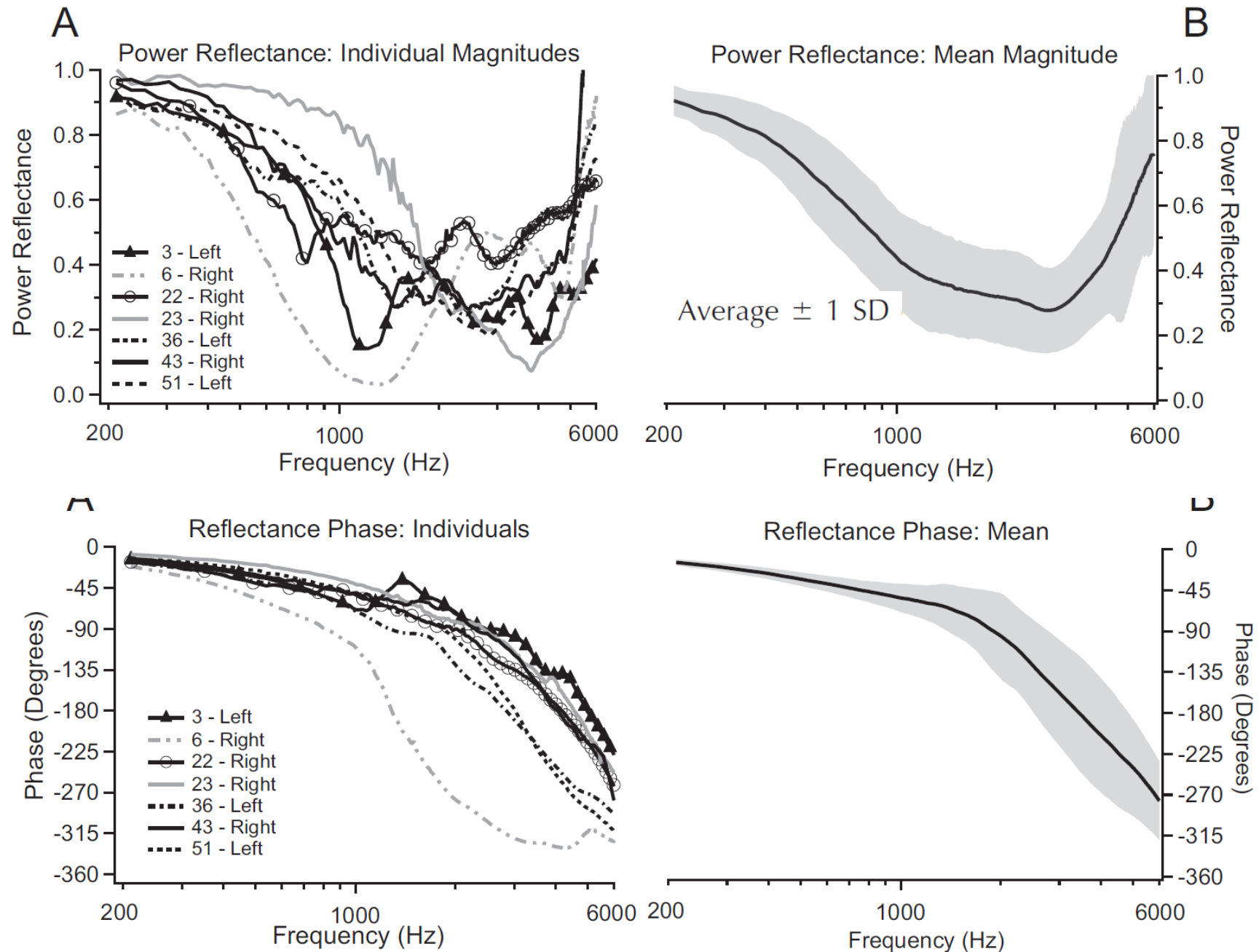
$$P_S = P_L \left(\frac{Z_S}{Z_L} + 1 \right)$$

Probe: contains a speaker and a microphone

Acoustical. Tympanometry



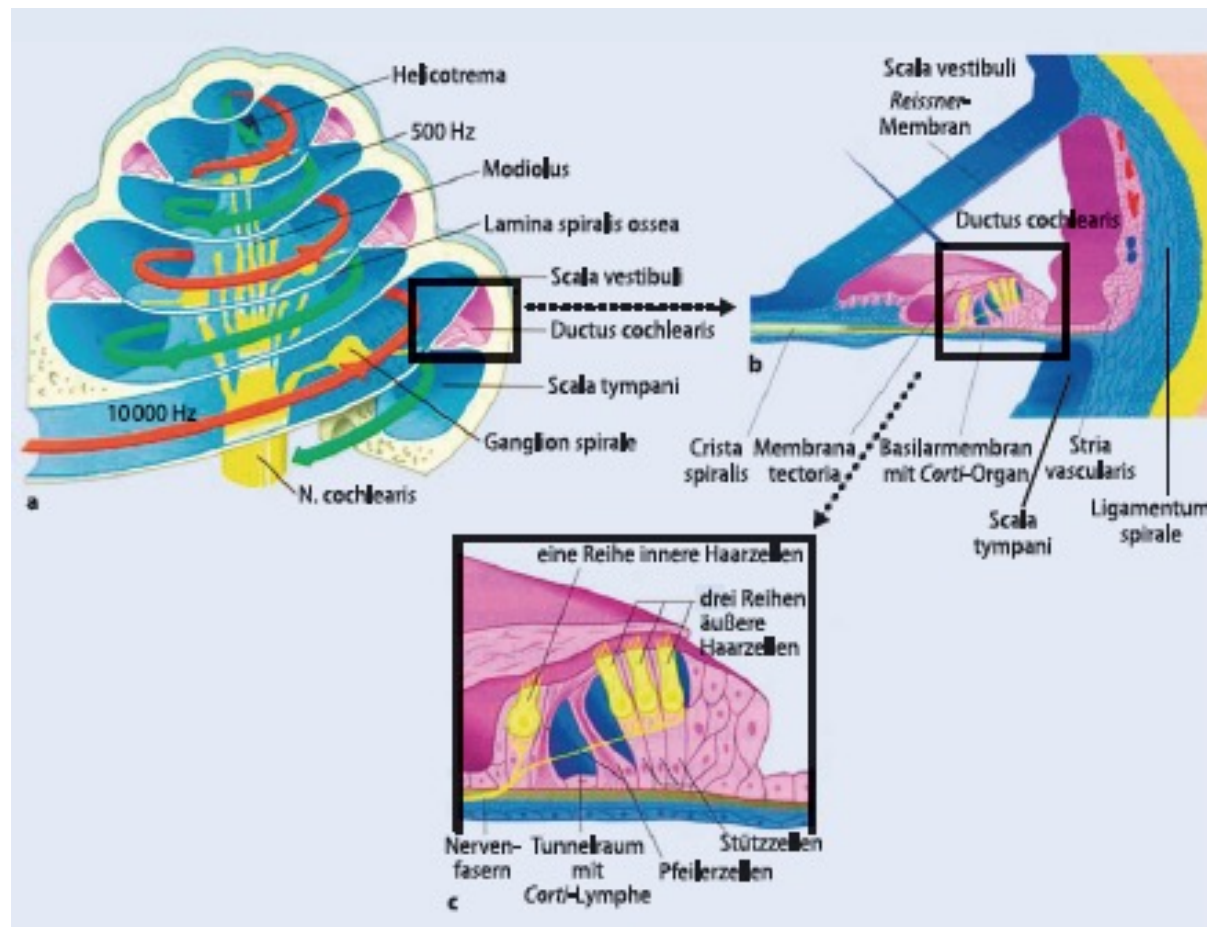
Acoustical. Impedance / reflectance



Middle ear:

- Essentially treated as linear system (for fixed ME-pressure)

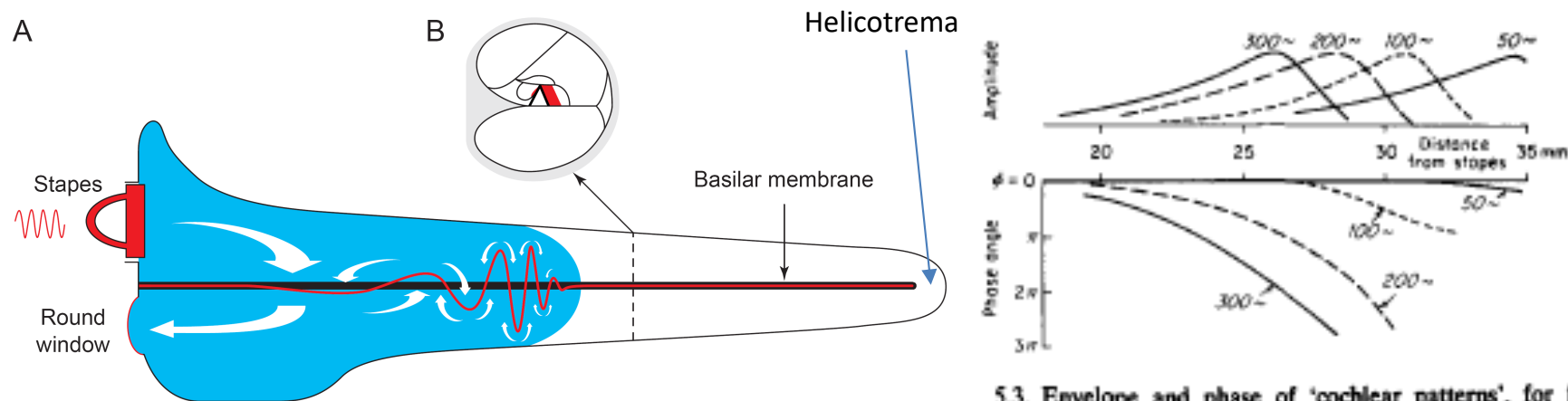
The inner ear



The passive inner ear*

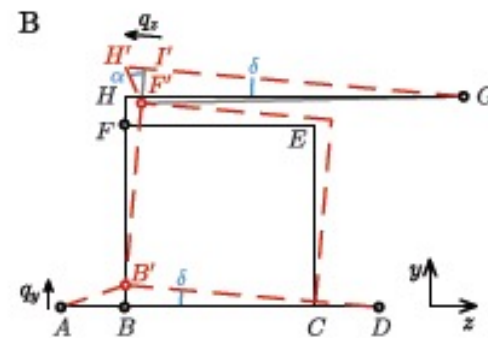
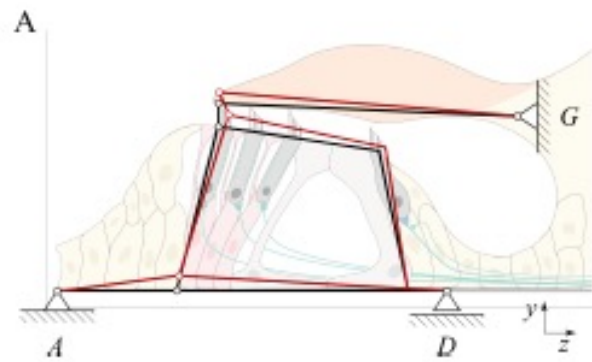
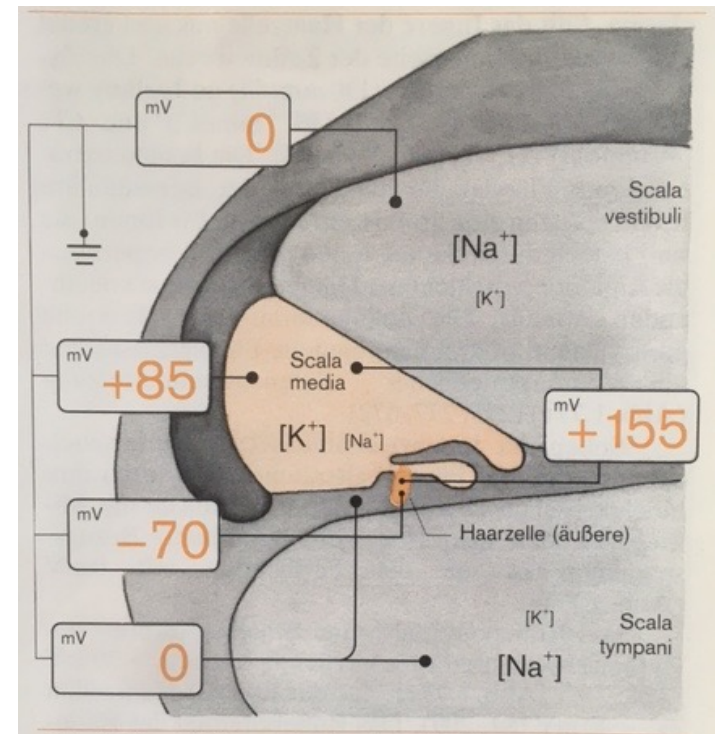
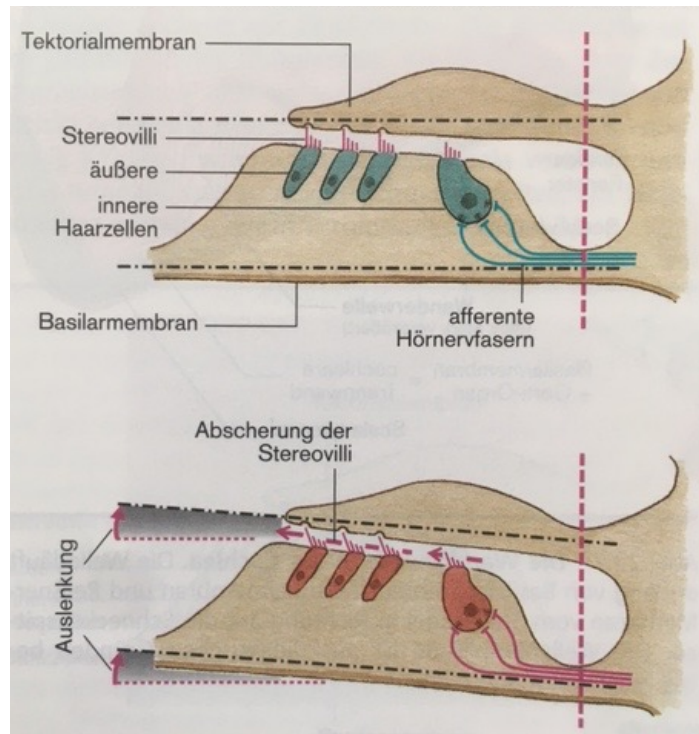
* (passive: without active amplification)

- radial BM section: treatable as independent vibrating structures
- inner-ear fluids: treatable as incompressible fluid
- Drive for basilar membrane (BM): Pressure difference between scala vestibuli/tympani
- Helicotrema: shunts static pressure
- Mechanical gradients: BM mass rising towards helicot., stiffness decreasing -> piano strings
- fluid coupling leads to development of traveling wave
- yields high-frequency tones at base and low-freq. at apex
- place of max. amplitude: „characteristic place“ for stimulating frequency
- „tonotopicity“ -> inner ear as Fourier-Analyser / Spectrum Analyser



5.3. Envelope and phase of 'cochlear patterns', for four low frequencies. After Békésy [2], by permission from Experiments in hearing by G. von Békésy, Copyright 1960, McGraw-Hill Book Company (p. 462, fig. 11-58).

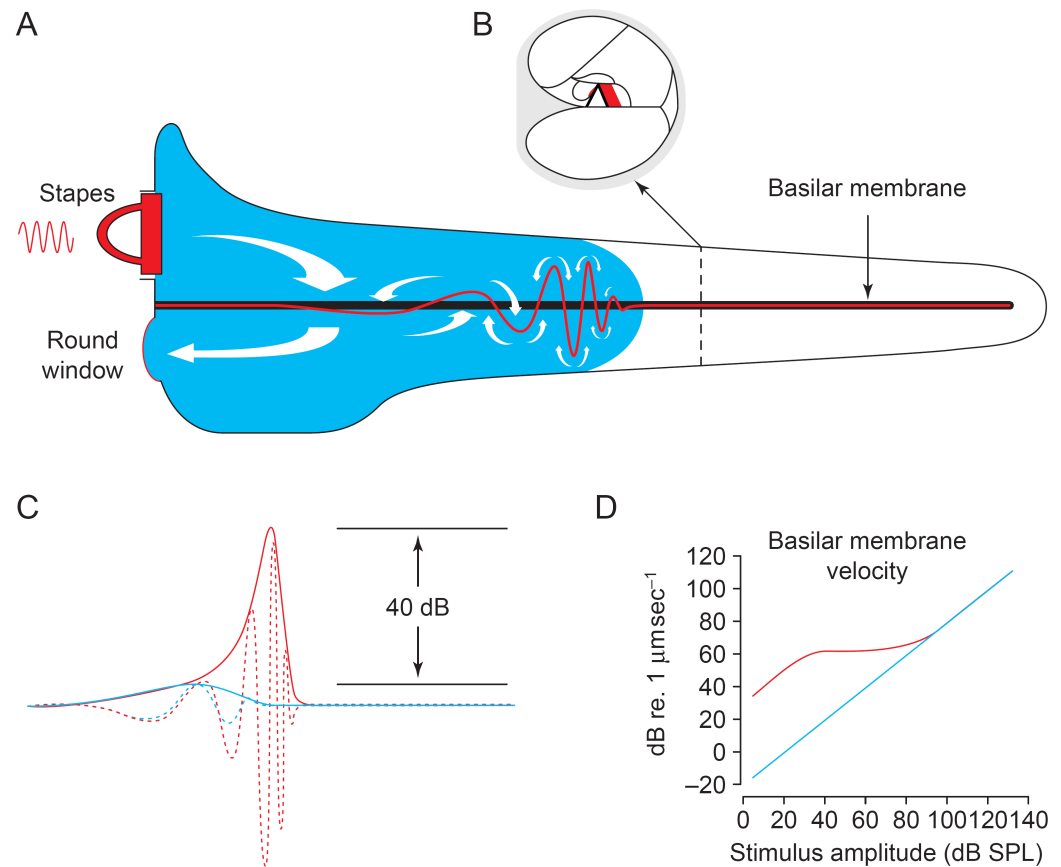
The passive cochlea



The passive cochlea

- Shearing between tectorial membrane (TM) and organ of Corti -> stimulus for stereocilia
- Stereocilia of inner hair cells (IHC) stand free -> stimulus by radial fluid flow
- IHC convey signal to the brain (afferent innervation)
- Stereocilia of outer hair cells (OHC) embedded in TM
- OHC obtain efferent innervation by the brainstem, but send no information to the brain

The active cochlea



- @low stimulus levels: 40-60 dB gain
- higher frequency discrimination/freq. tuning
- gain & tuning vanish *reversibly* with interruption of blood supply to the cochlea

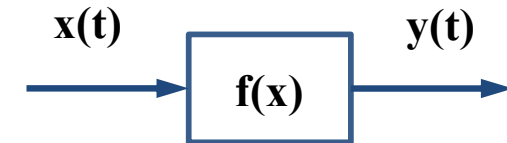
The active cochlea

- Stimulation of OHC stereocilia leads to AC-potential variation intracellularly (receptor p.)
- (Called mechano-electrical transduction: MET)
- Prestin molecules undergo potential-dependent conformation changes
- -> inject mechanical force -> cell elongation/shortening (electro-mechanical transd.: EMT)
- MET & EMT form a feedback loop
- one-tone stimulation: limited region basal to tonotopic place shows positive feedback!
- -> the „locally-active“ cochlea
- Active cochlea depends on metabolic supply of the cochlea (blood...)

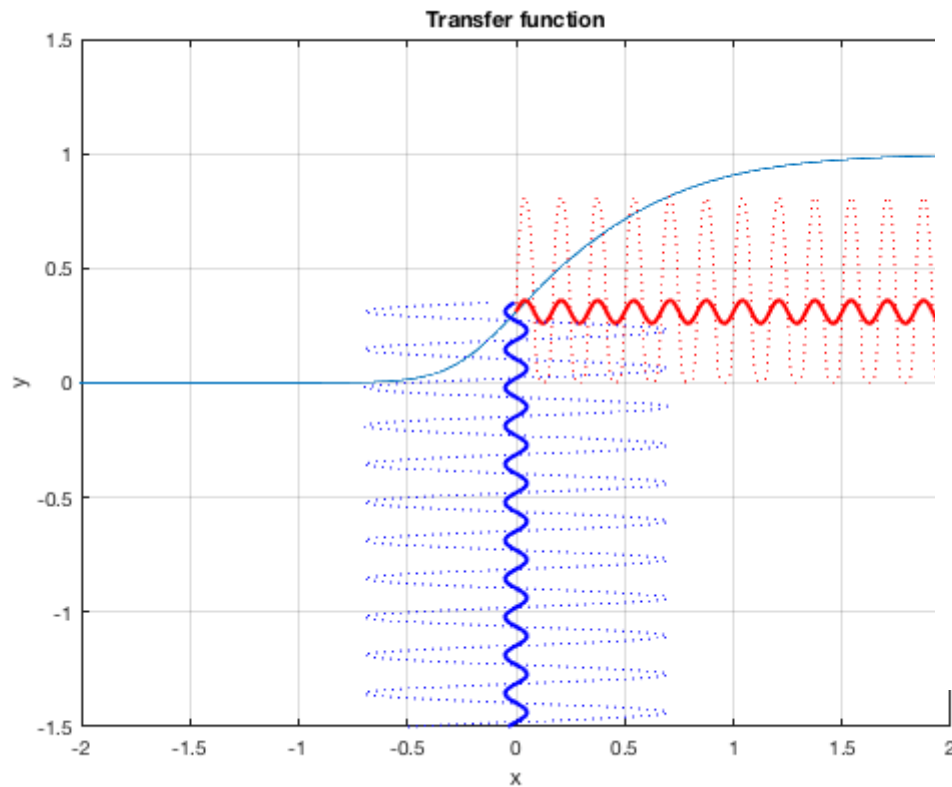
MET: nonlinear signal-processing stage

linear system:

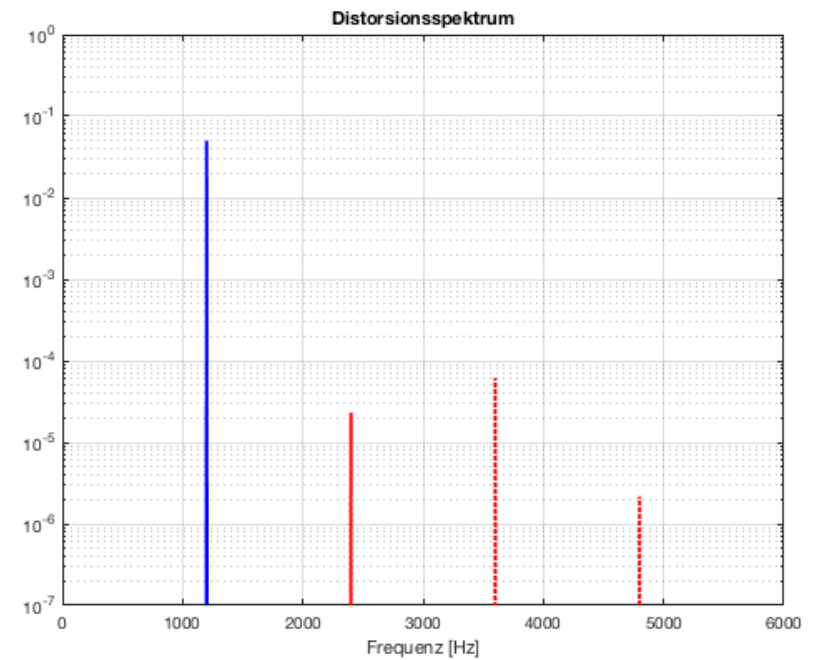
$$f(a x_1(t)) + f(b x_2(t)) \leftrightarrow a X_1(f) + b X_2(f)$$



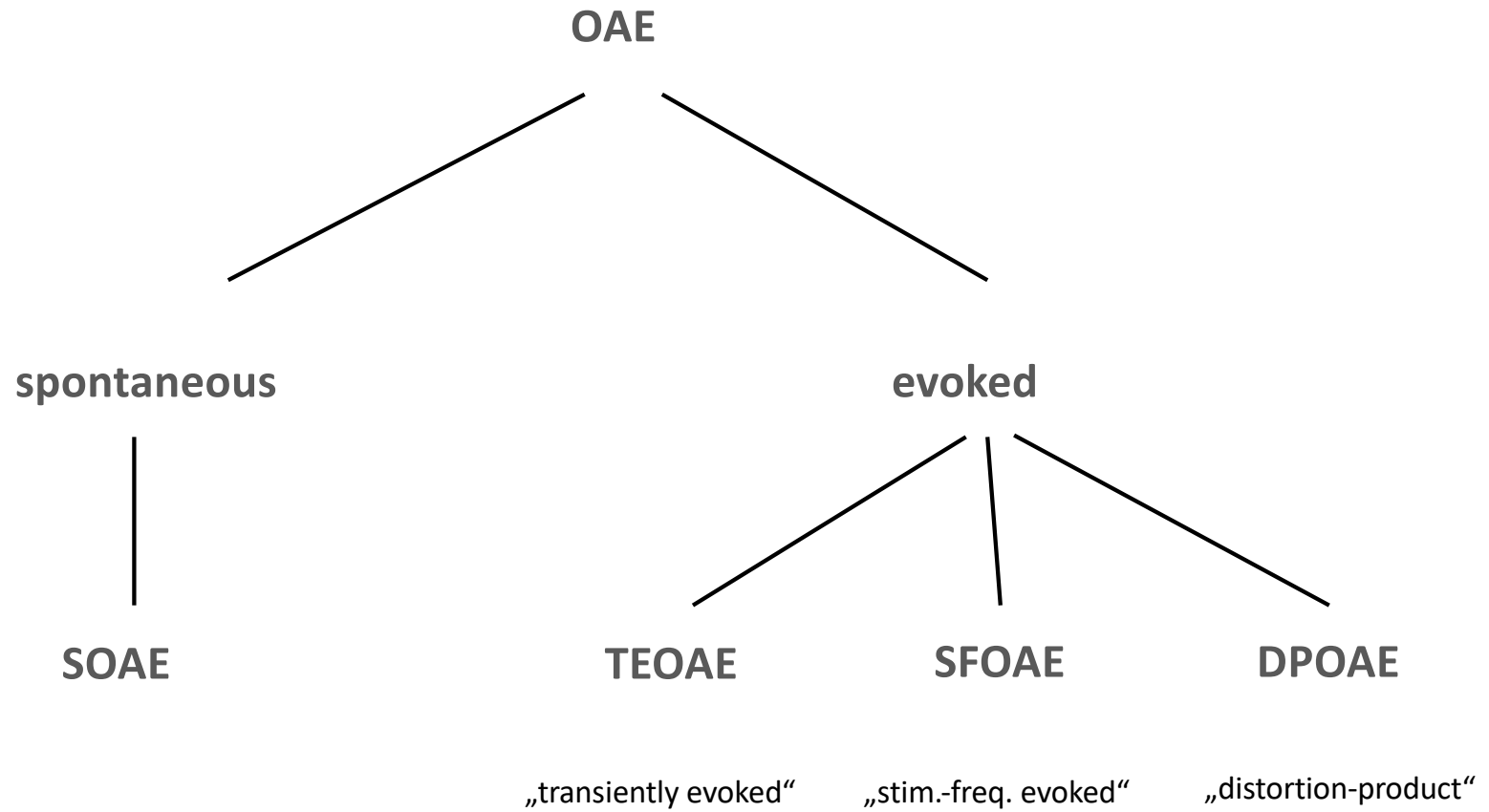
Time domain



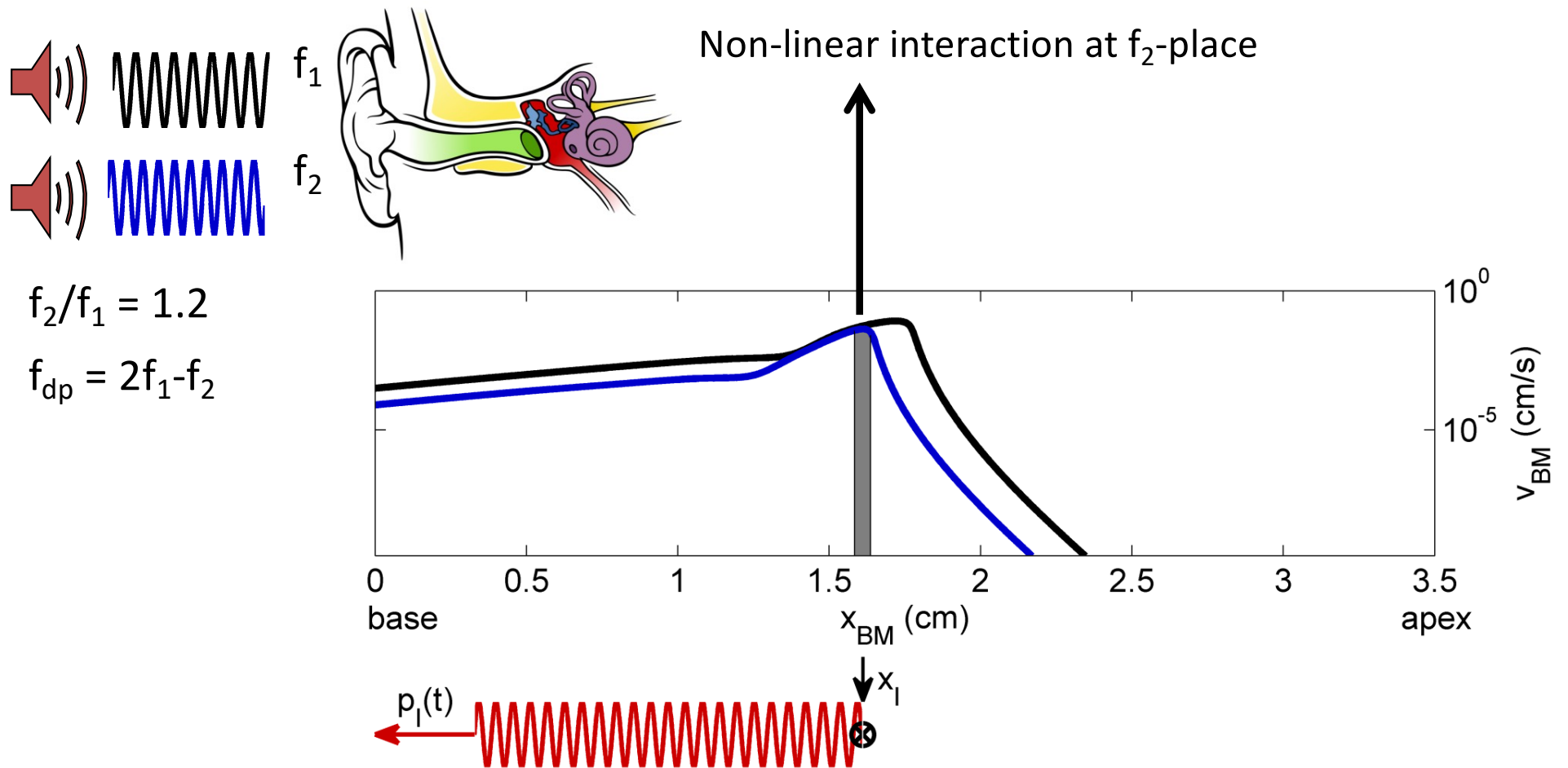
Frequency domain



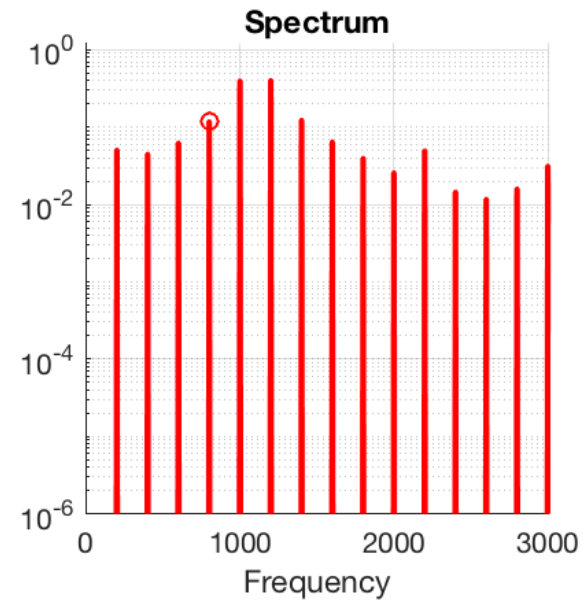
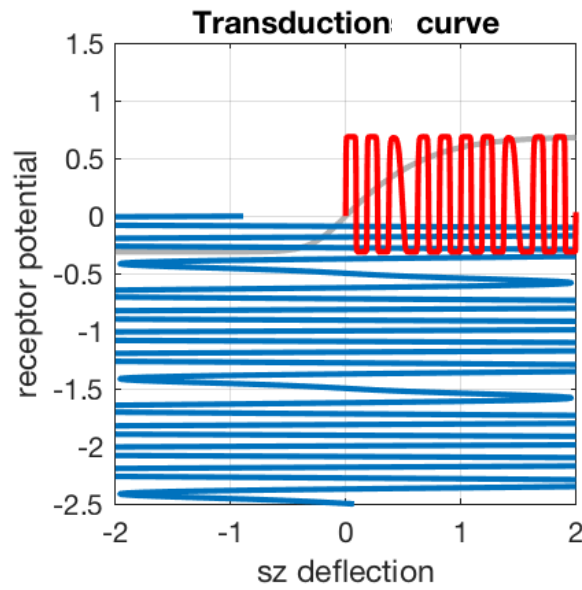
Otoacoustic emission (OAE) systematic



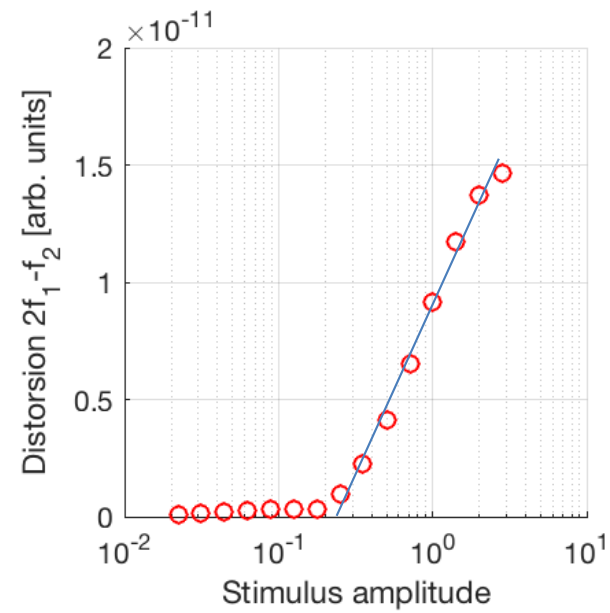
DPOAE generation



DPOAE: Generation principles



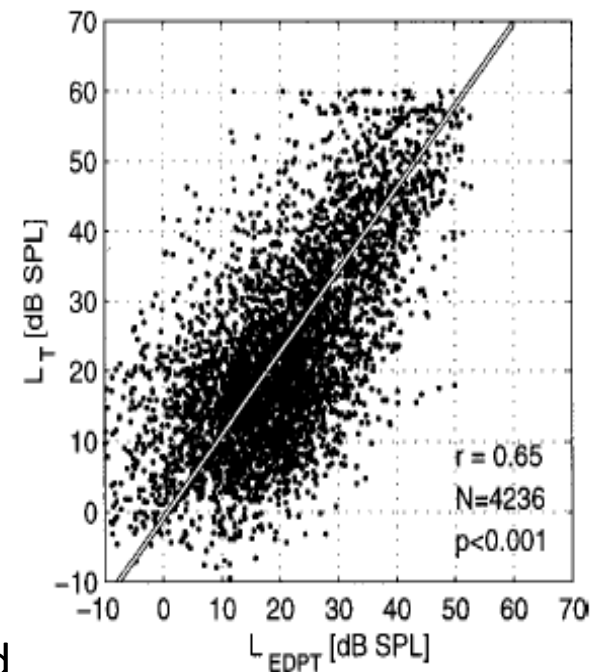
$$f_{dp} = 2f_1 - f_2$$



DPOAE

- DPOAE growth functions rise strongly when MET reaches saturation
- -> „Distortion-product threshold“ (DPT)
- DPT correlates with subjective pure-tone threshold*

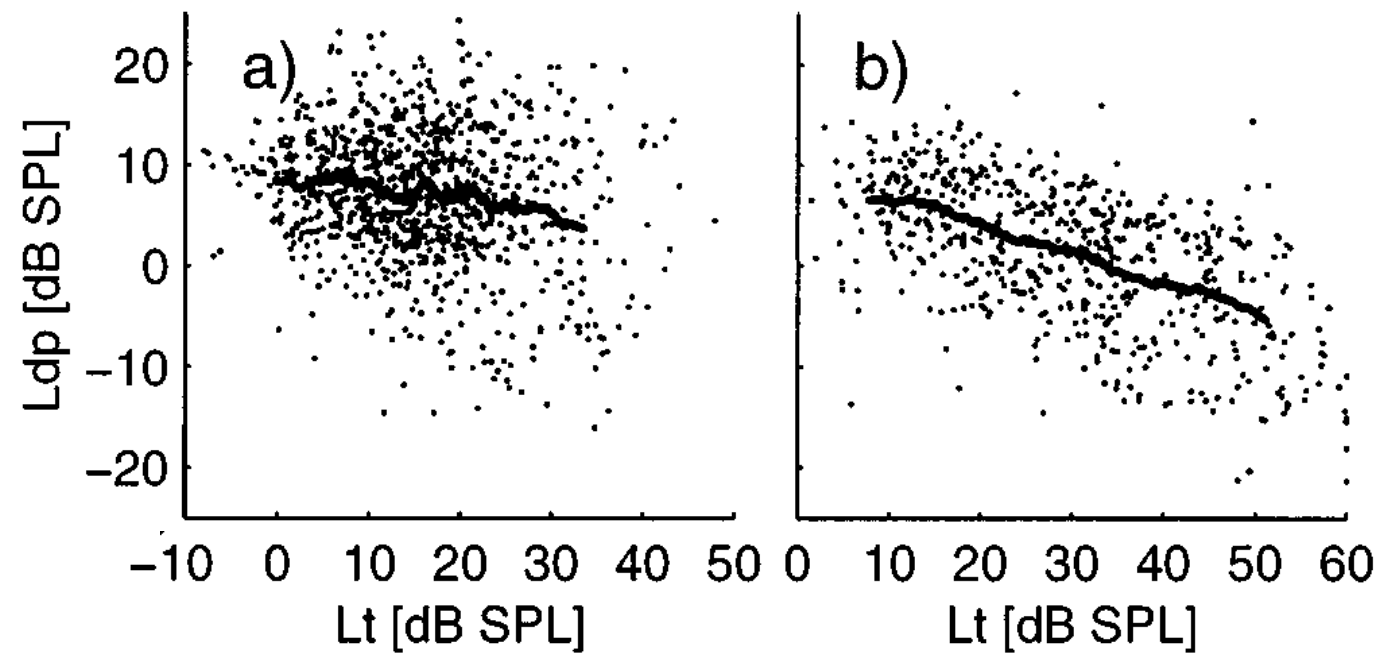
*under assumption of normal neural transmission



L_T : behav. threshold

L_{EDPT} : DPT

DPOAE – clinical use



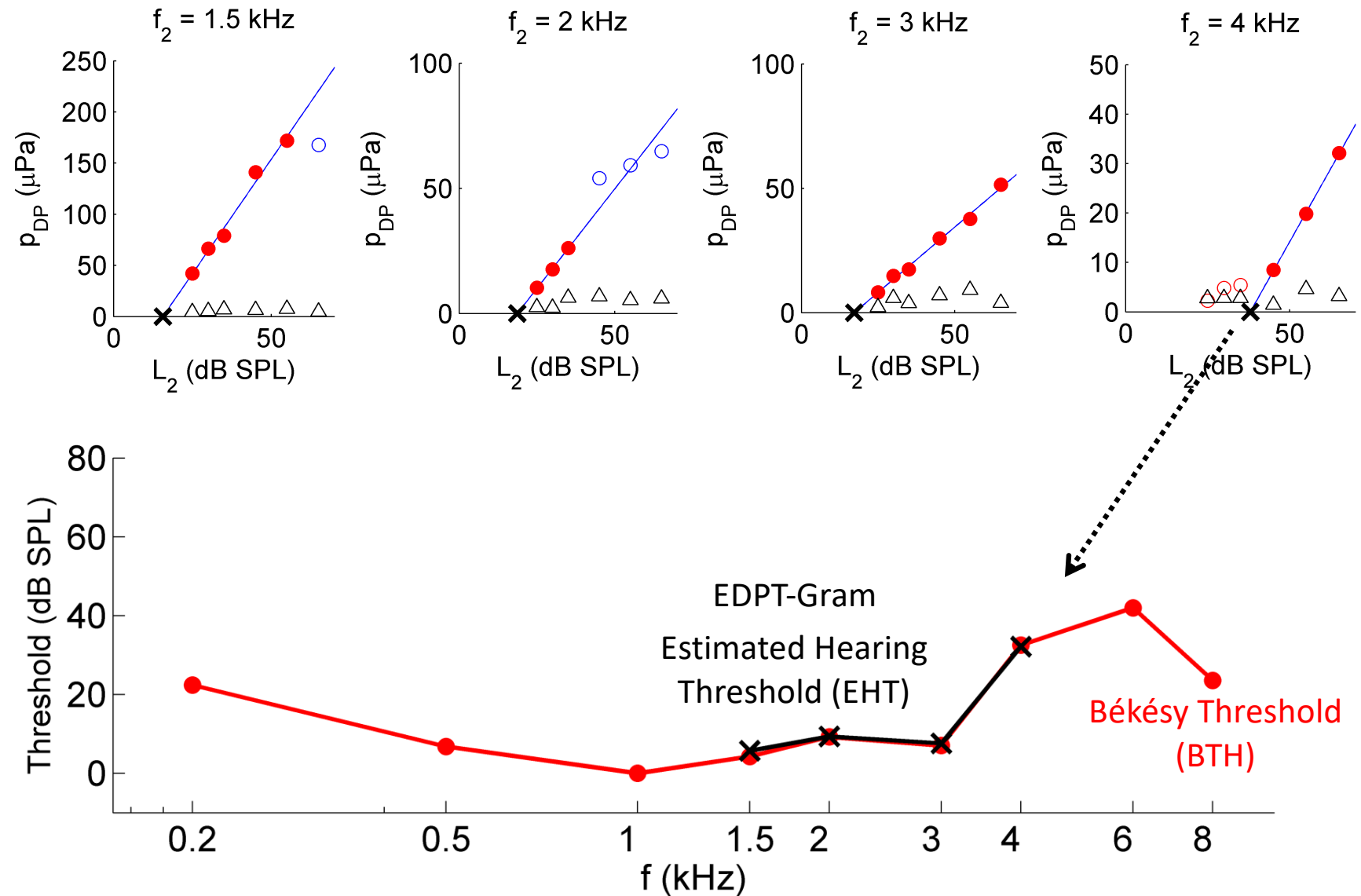
Normal hearing

Hearing impaired

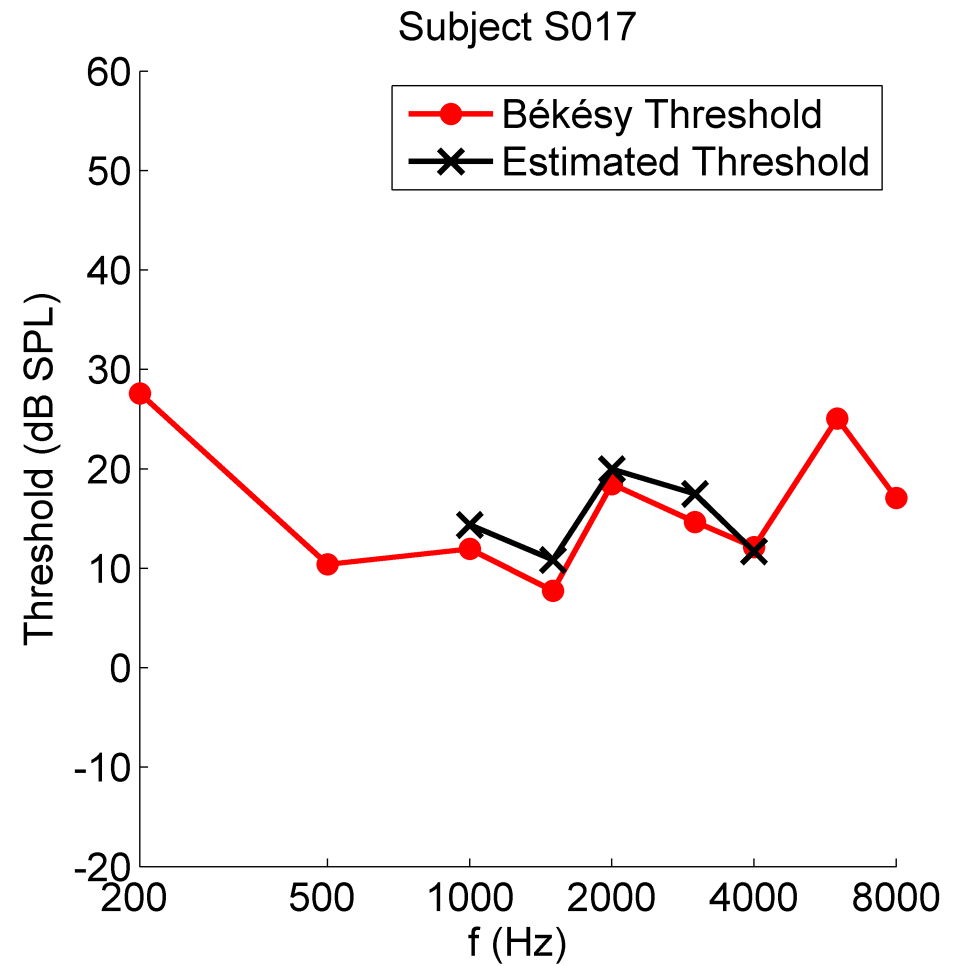
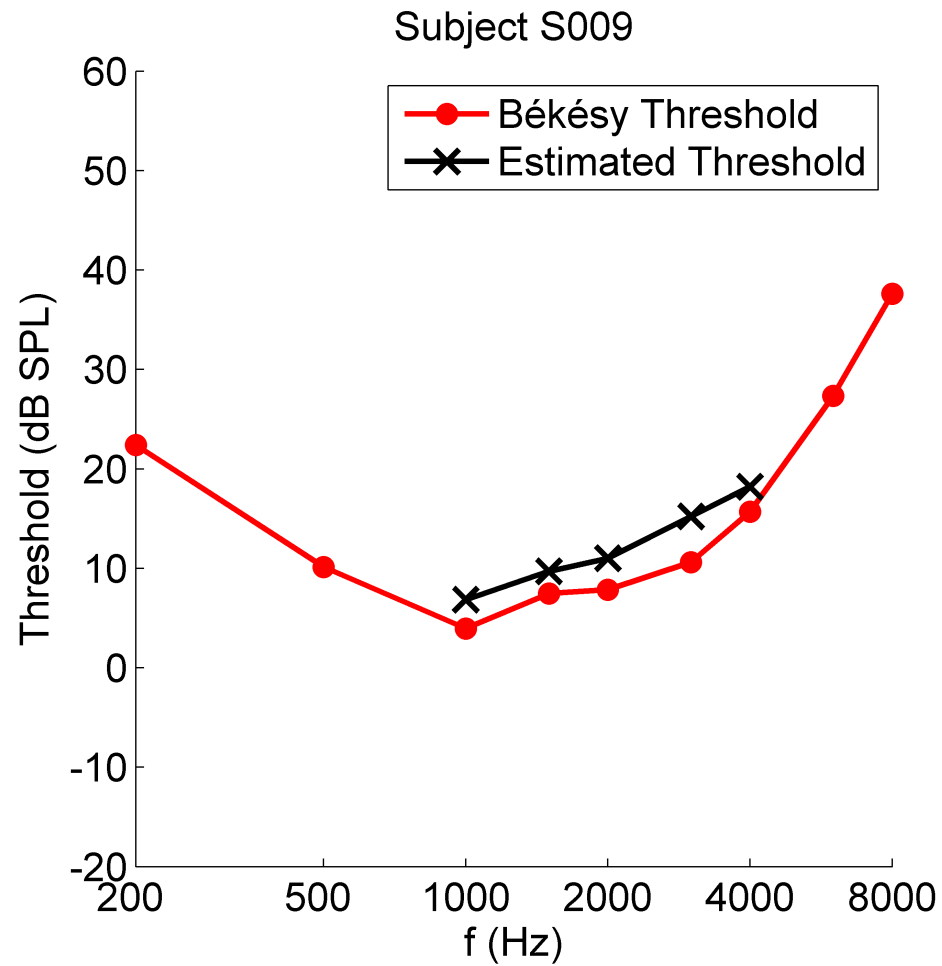
$L_2=65$ dB SPL; $L_1=65$ dB SPL

Kummer et al., 1998

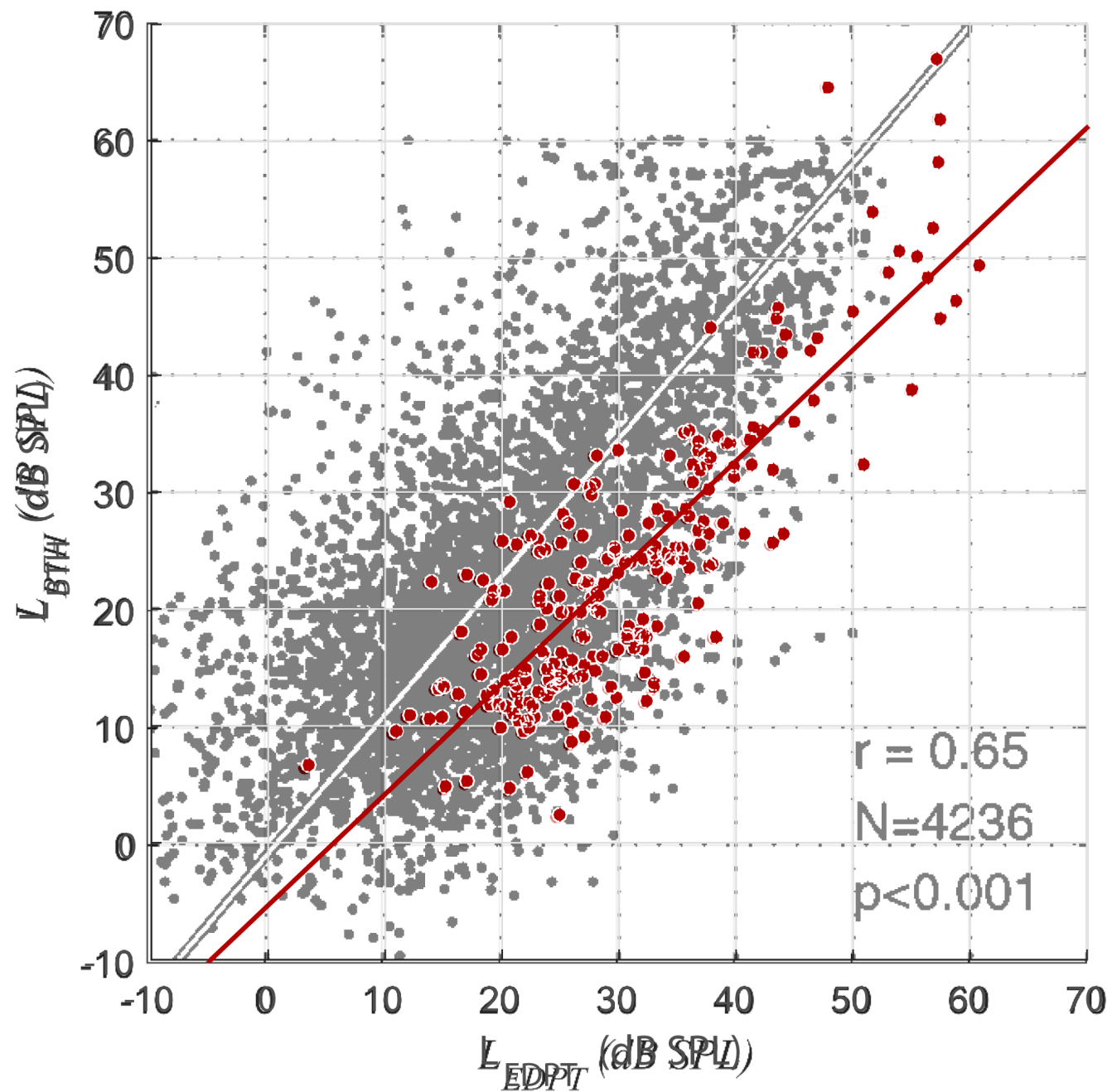
Auditory Threshold Estimation Using I/O-Functions



Results

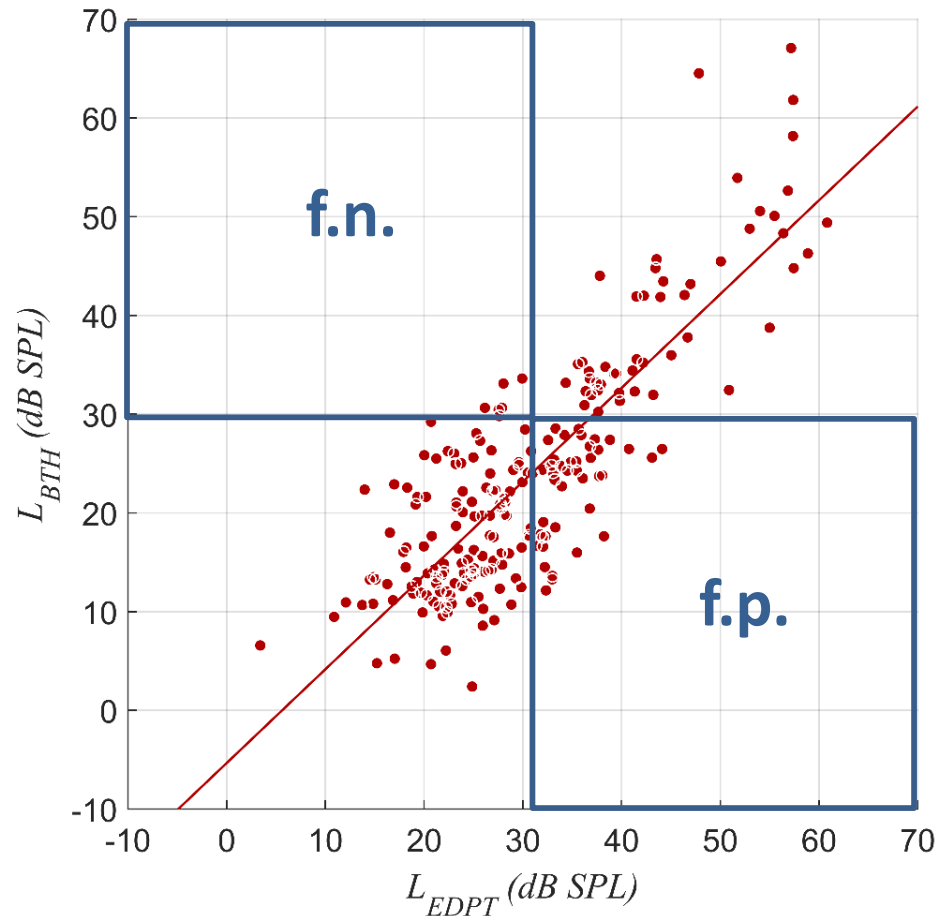


threshold estimation accuracy



Threshold Estimation ($f_2 = 1 \dots 8$ kHz)

Békésy threshold vs. estimated distortion product threshold (pulsed DPOAE):



EDPT acceptance criteria

$$r^2 \geq 0.8$$

$$\sigma_{EDPT} \leq 10 \text{ dB}$$

$$\sigma_{\Delta L} = 6.0 \text{ dB (6.5 dB)*}$$

$$r^2 = 0.7$$

$$(1 \text{ kHz} \leq f_2 \leq 8 \text{ kHz})$$

Accepted EDPTs: 82% (222/272)

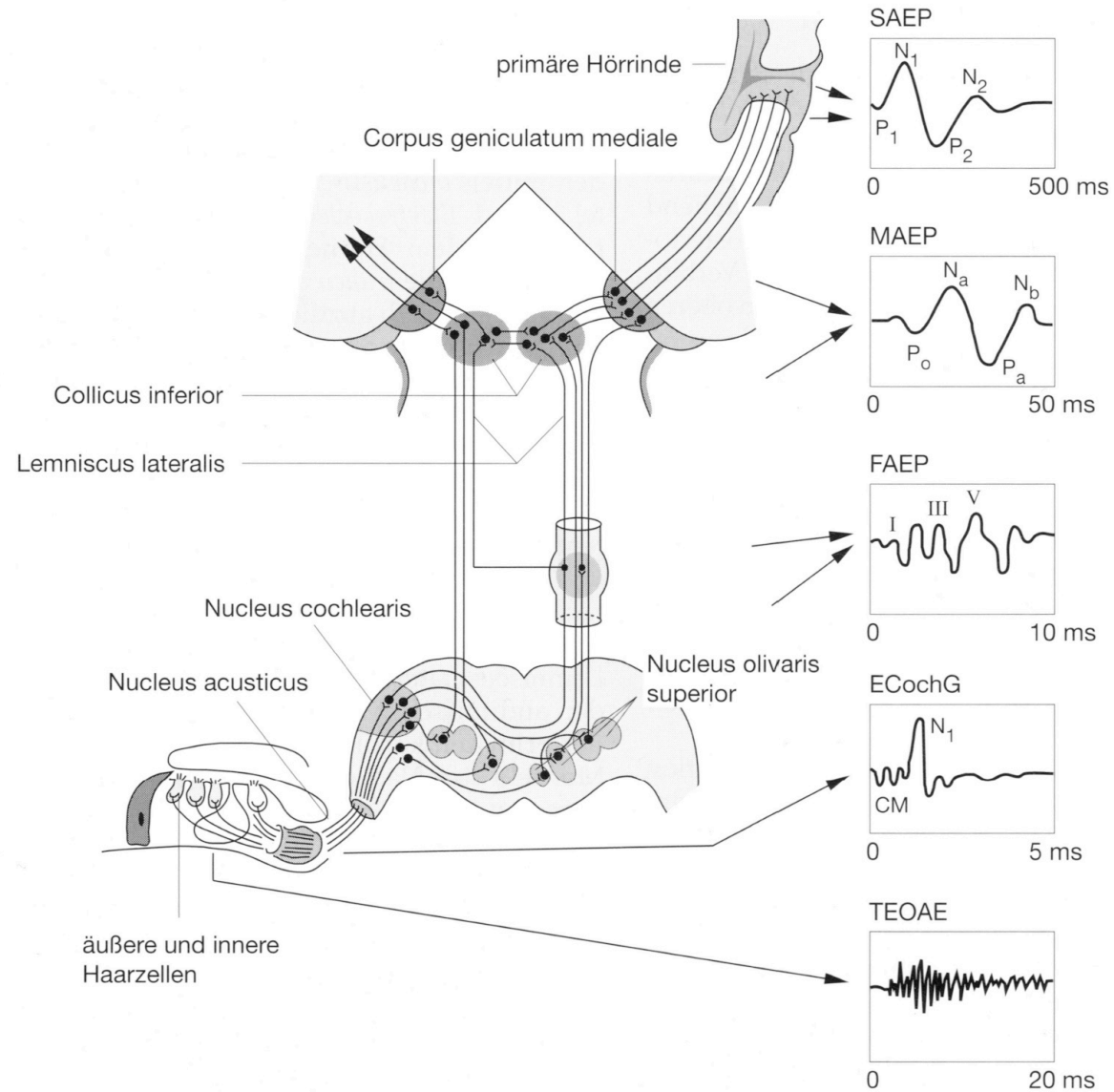
$$L_{BTH} = 0.95L_{EDPT} - 5.34 \text{ dB SPL}$$

N = 34 (19 NH, 15 HI)

* - corrected for σ_{BTH} , $s = 1$ dB/dB

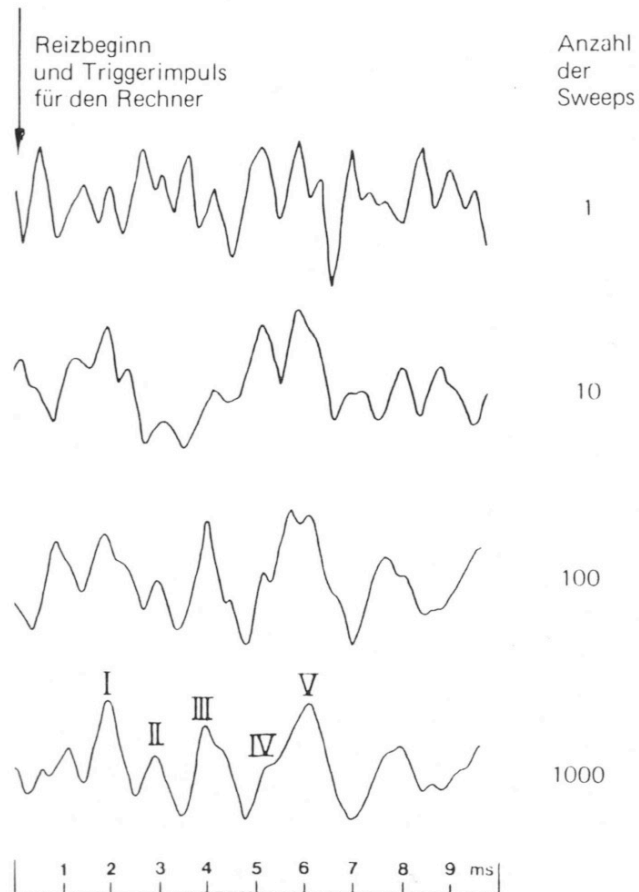
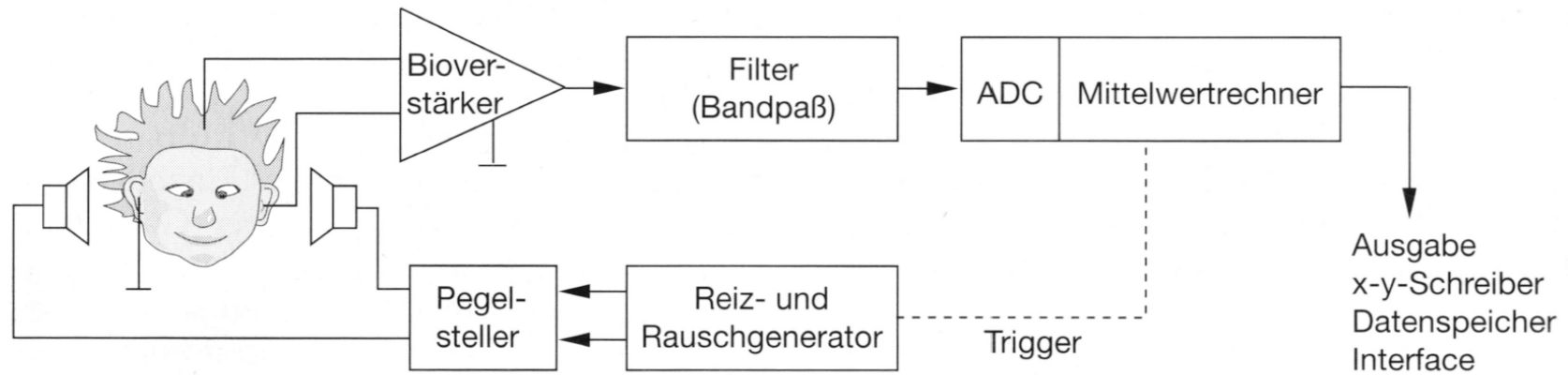
- dichotomous decision:
TEOAE measurable: HL < 30 dB
DPOAE measurable: HL < 50 dB
- however: validity depends on parameters/instrumentation (avg time...)
- decision have low accuracy
- Advantage: measurement time approx. 5-10 min.

Hearing pathway & acoustically-evoked potentials (AEP)



Lehnhardt, Praxis der Audiometrie, 1996

AEP - measurement setup

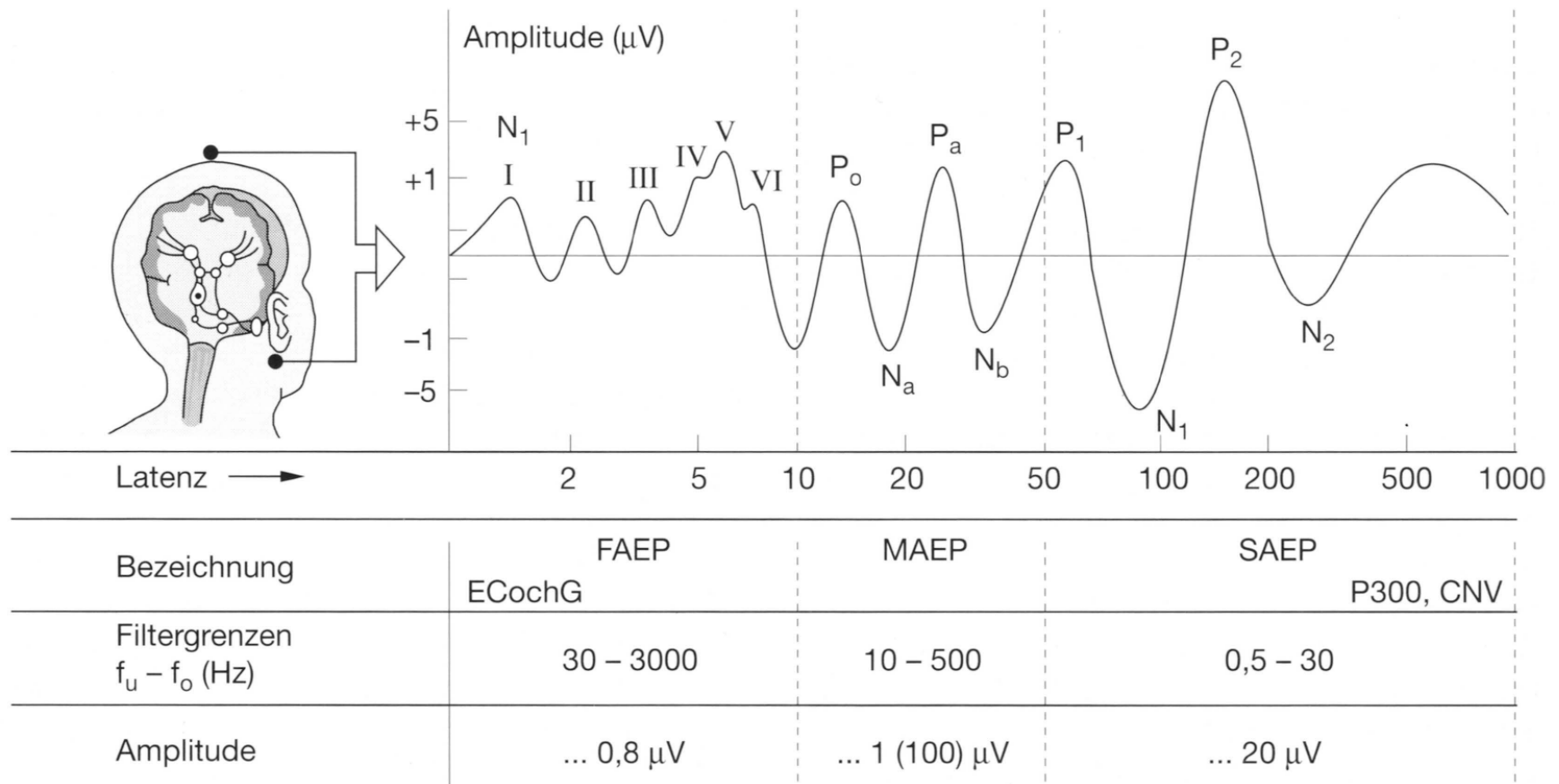


scalp recordings

Click-ABR

Lehnhardt, 1996

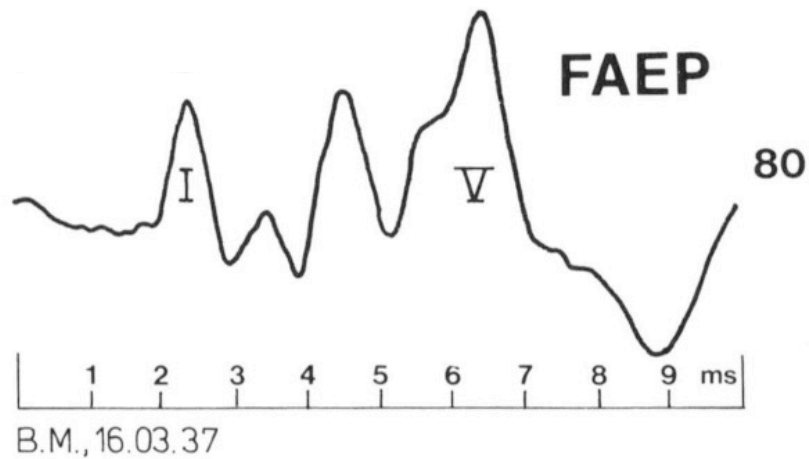
Measurement setup ABR (Auditory brainstem response)



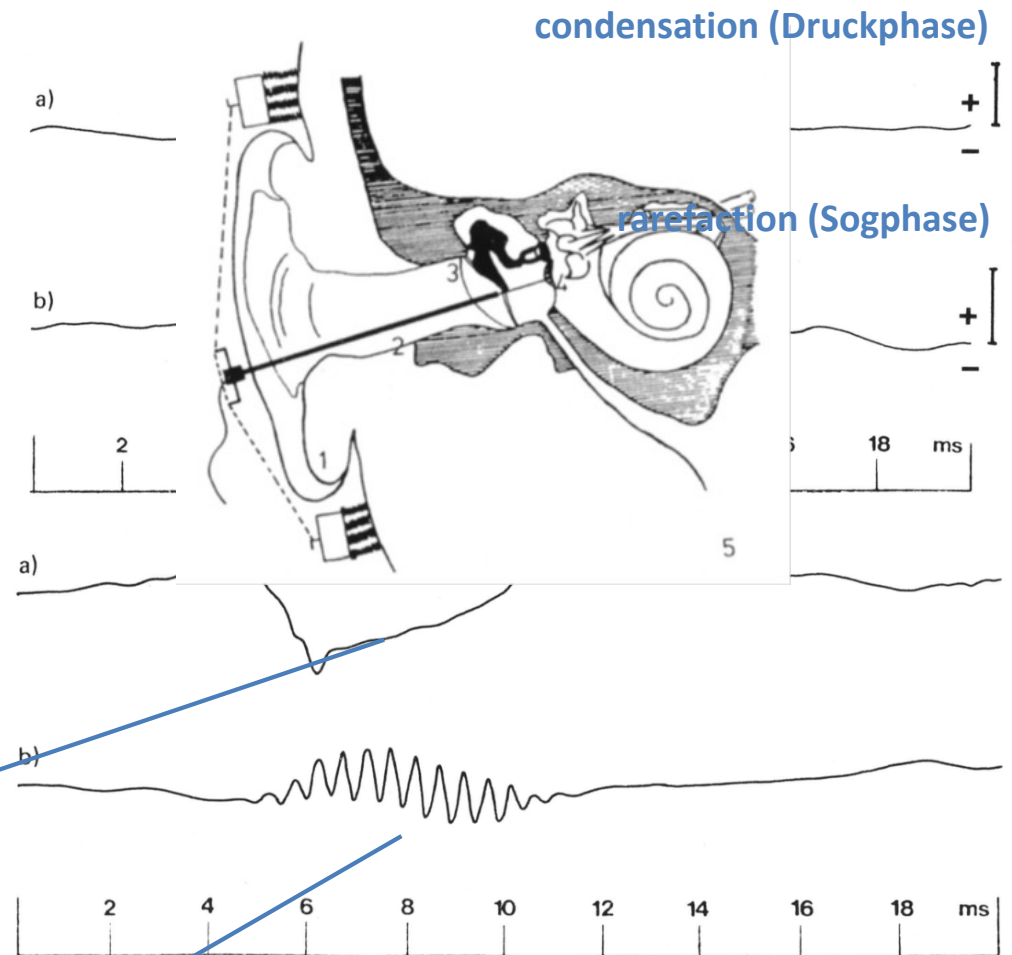
Lehnhardt, 1996

Measurement setup Electrocochleography (ECoG)

2 kHz tone-burst



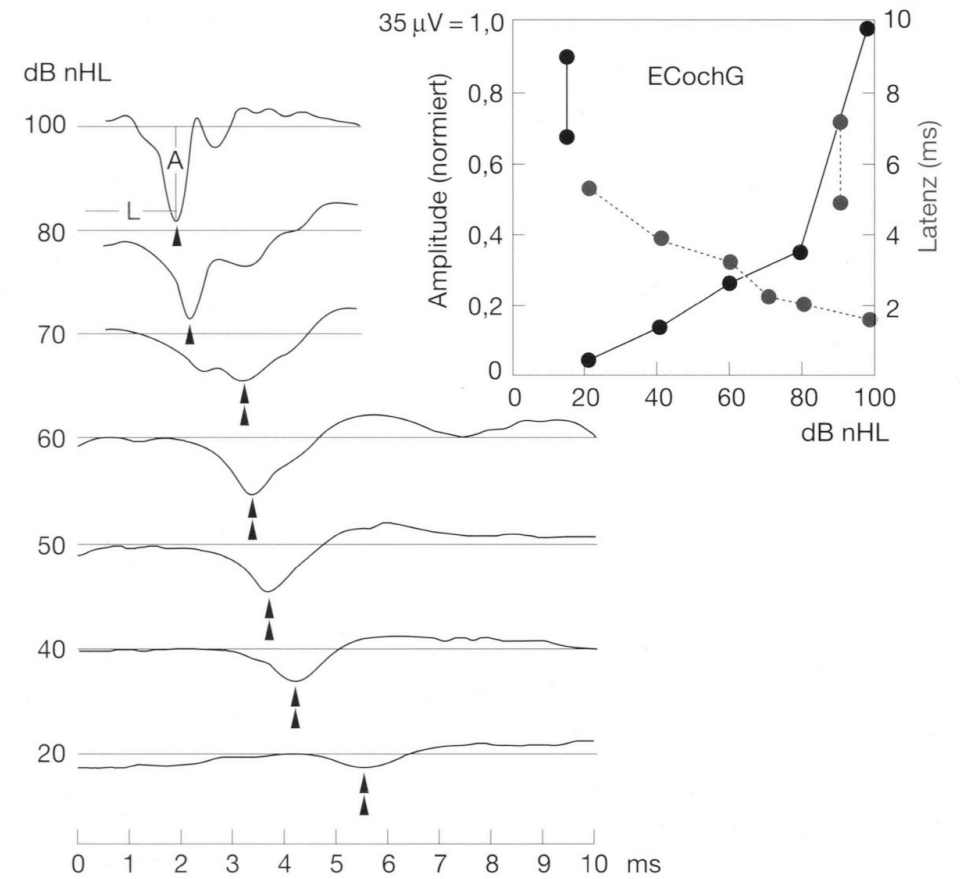
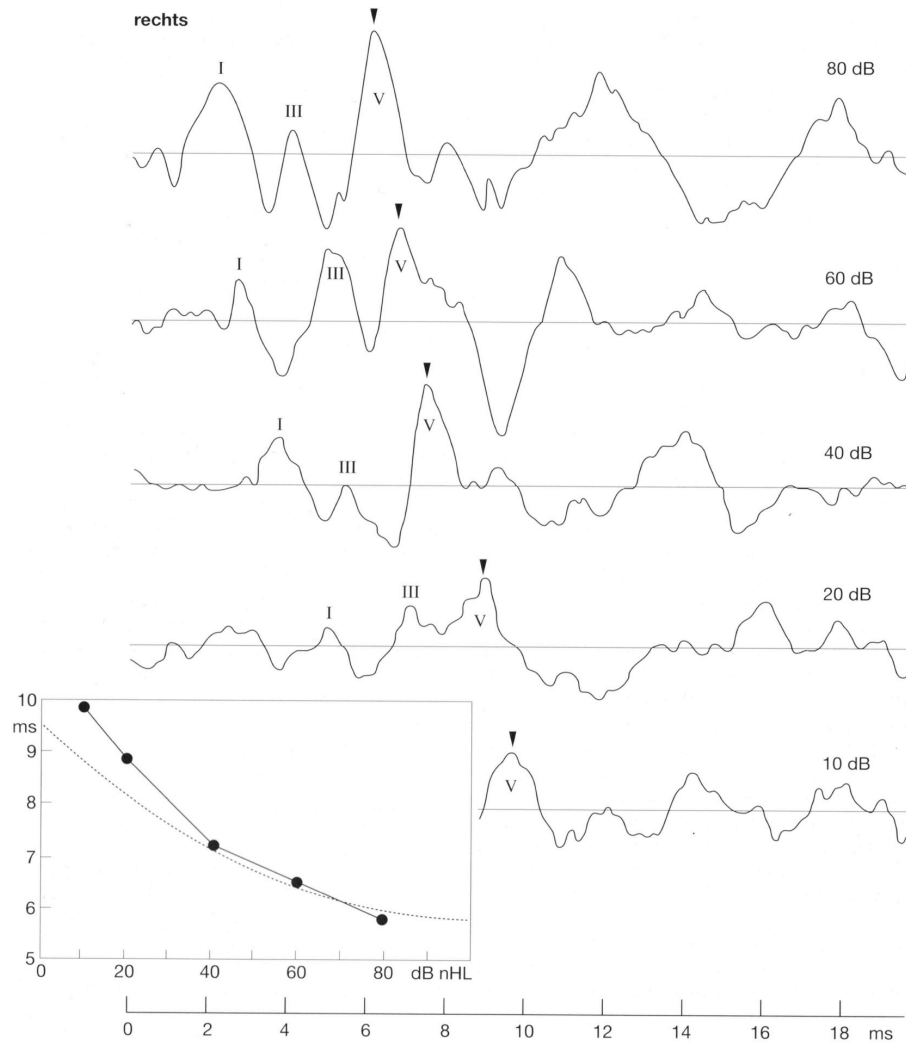
SP: summing potential



CM: cochlear microphonic

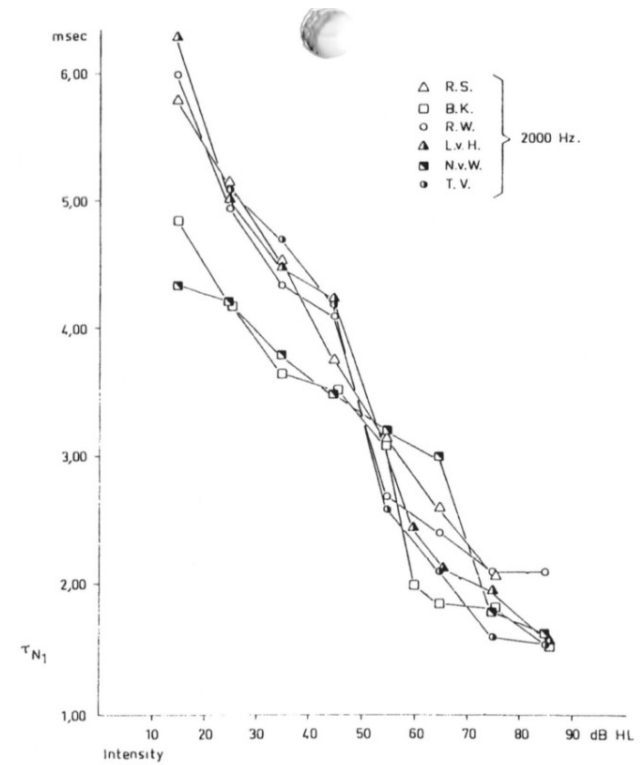
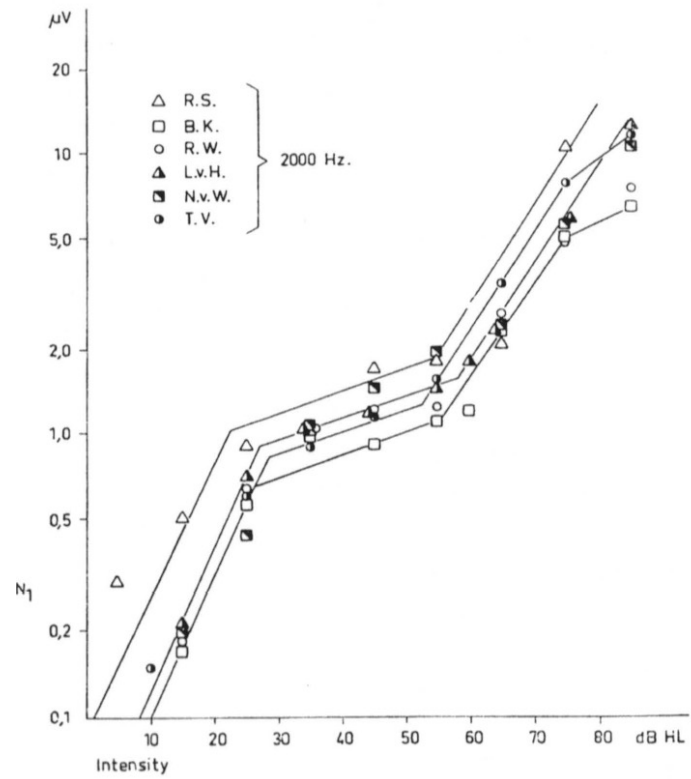
Lehnhardt, 1996

ABR vs. ECoG



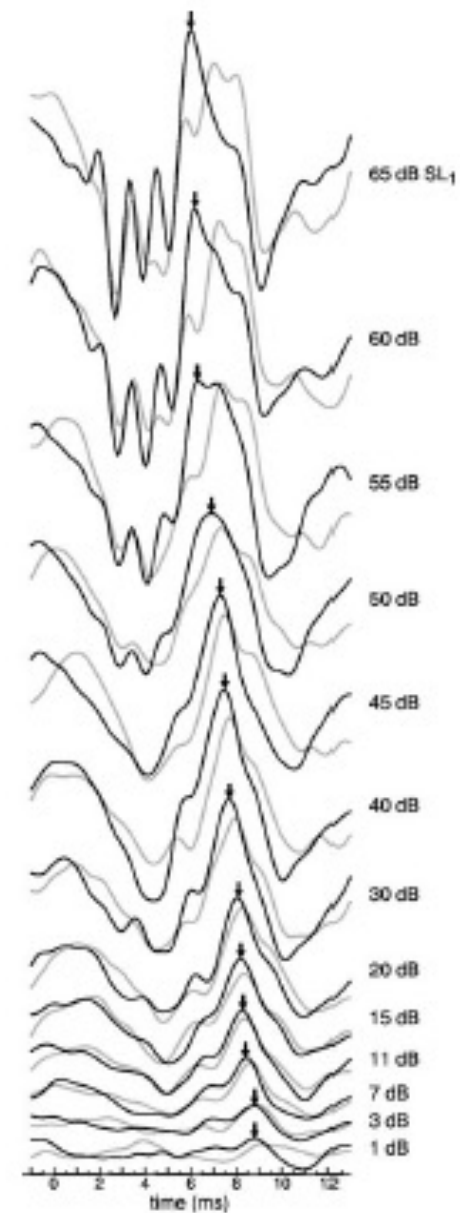
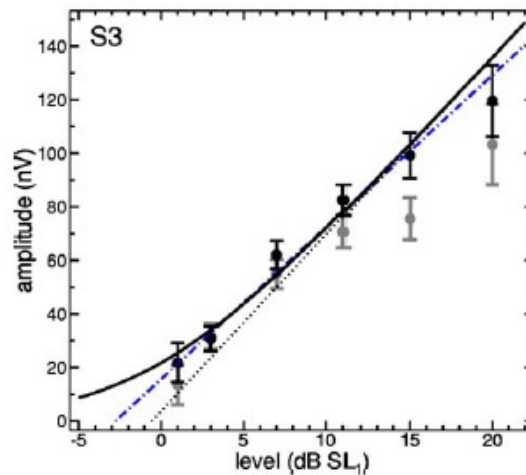
higher latency $\leftrightarrow$ sharper filter!

ECoG: growth functions & latencies



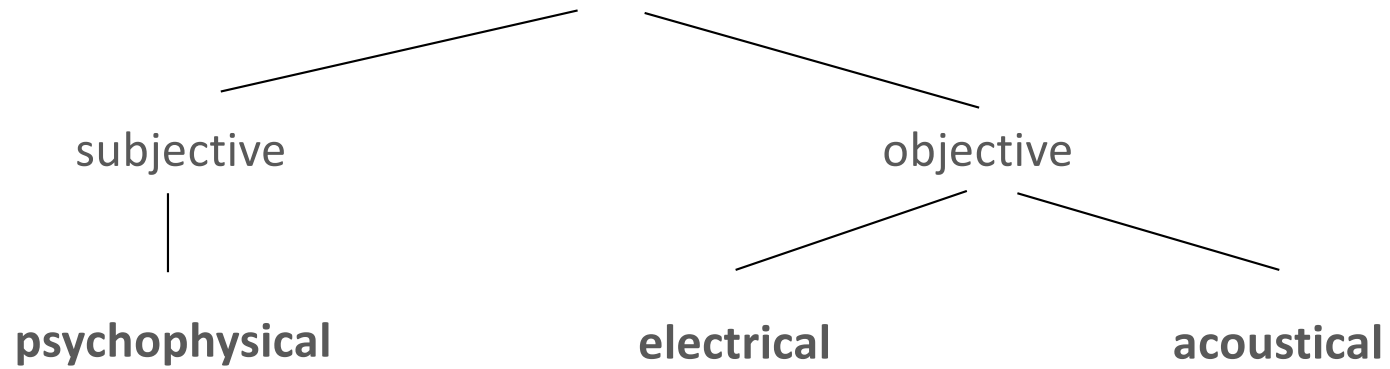
ABR: growth functions

- ABR threshold measurable at/even below subj. threshold
- Here: 4 kHz tone pulses
- but only in research: 1 Mio. averages per level!



- In clinical practise: 2000 avg per stimulus condition
- Often restricted to click stimuli -> broadband testing
- Depending on required frequency specificity and levels high measurement time
- In research: 1-2h, in clinical practise typ. $\frac{1}{2}$ - 1 h

Audiometry



- **Pure-tone threshold**
- **Speech audiometry**
- **Masking / TEN-test**

- **ABR**
- **ASSR**
- **ECoC / CAP**

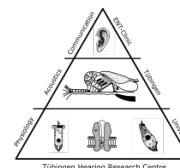
- **OAE**
- **Tympanometry**
- **Reflectance / Impedance**

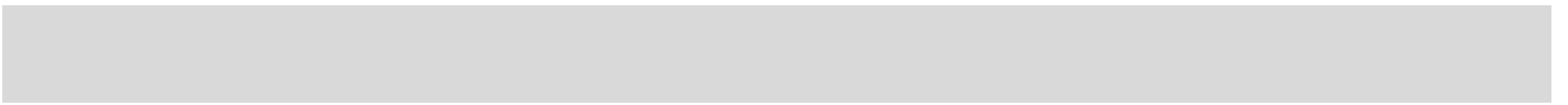
Audiometry

Ernst Dalhoff

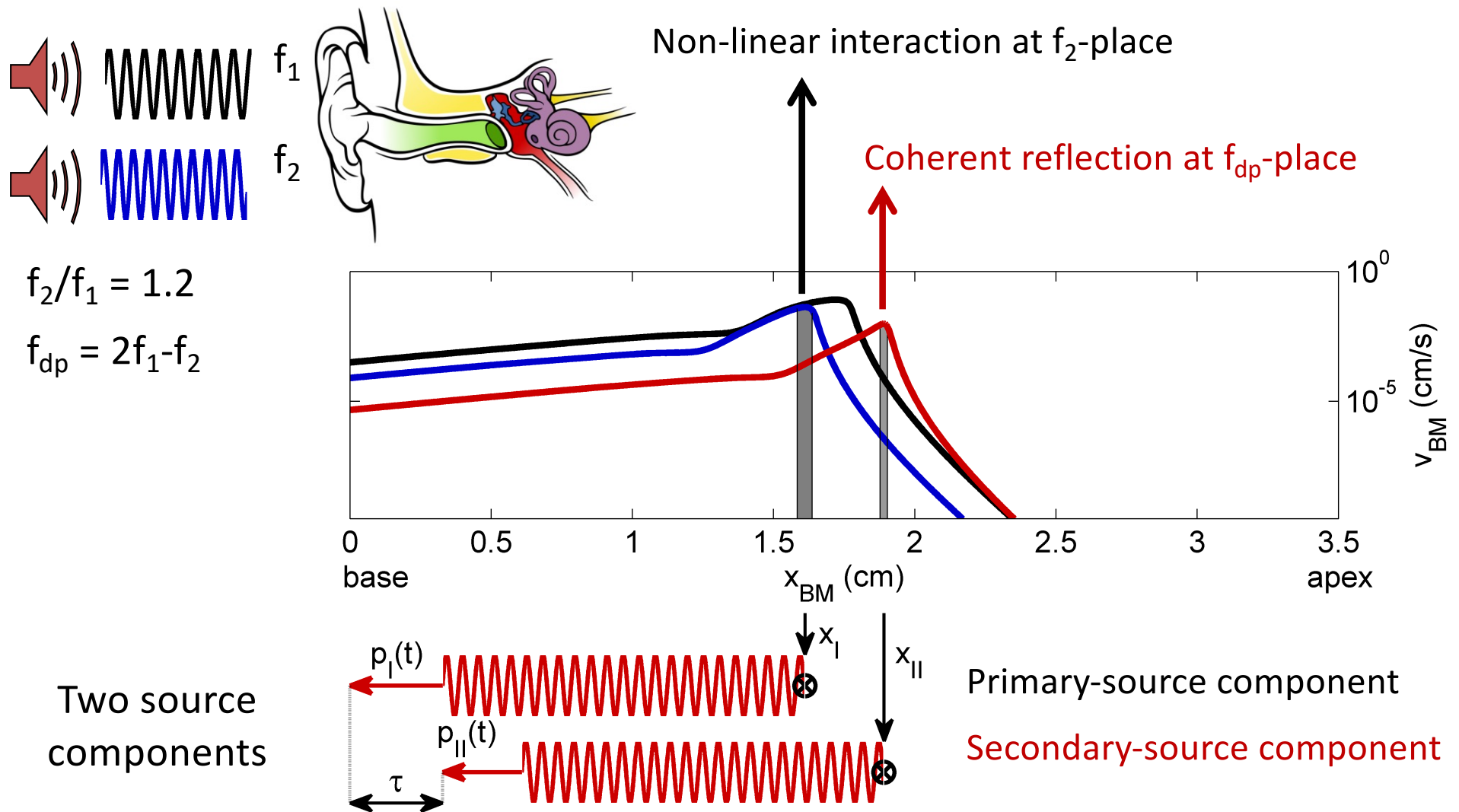
Section of Physiological Acoustics and Communication
ENT Clinic Tuebingen

Biomedical Technologies in Diagnostic and Therapy

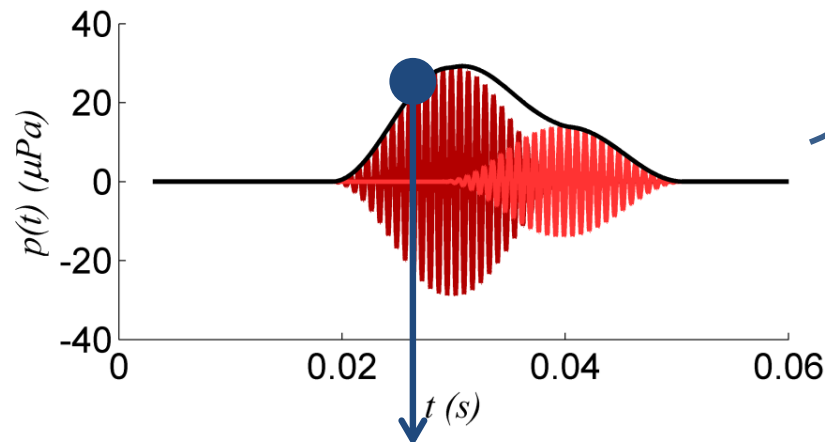
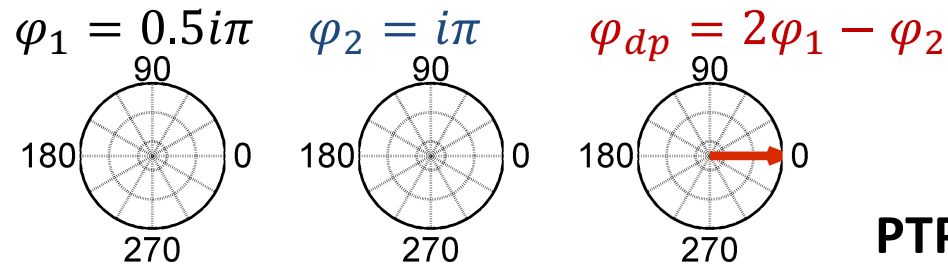
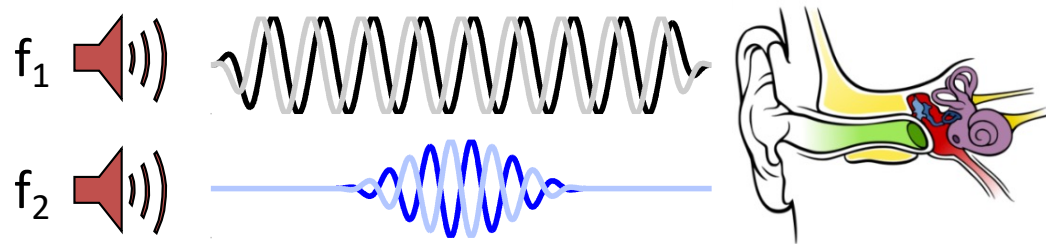




Acoustical. Improvements in research: DPOAE source separation.



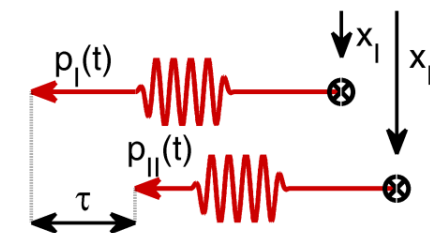
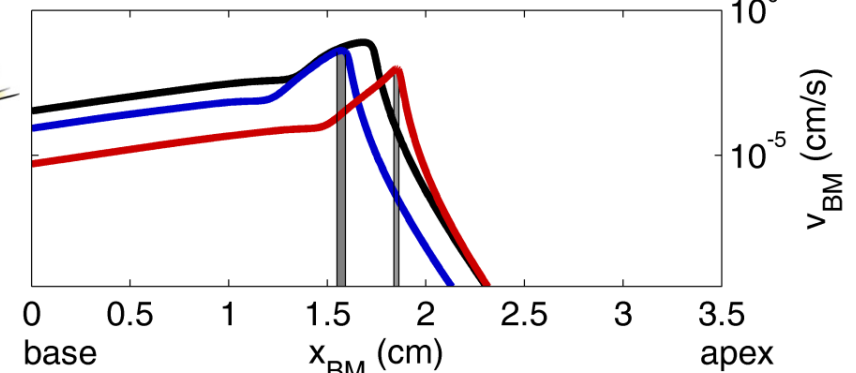
Short-Pulse DPOAE Acquisition



Nonlinear-generation component extracted by sampling

(Vetesník et al., 2009)

(Whitehead et al., 1996; Talmadge et al., 1999)



$$f_{dp} = 2f_1 - f_2$$

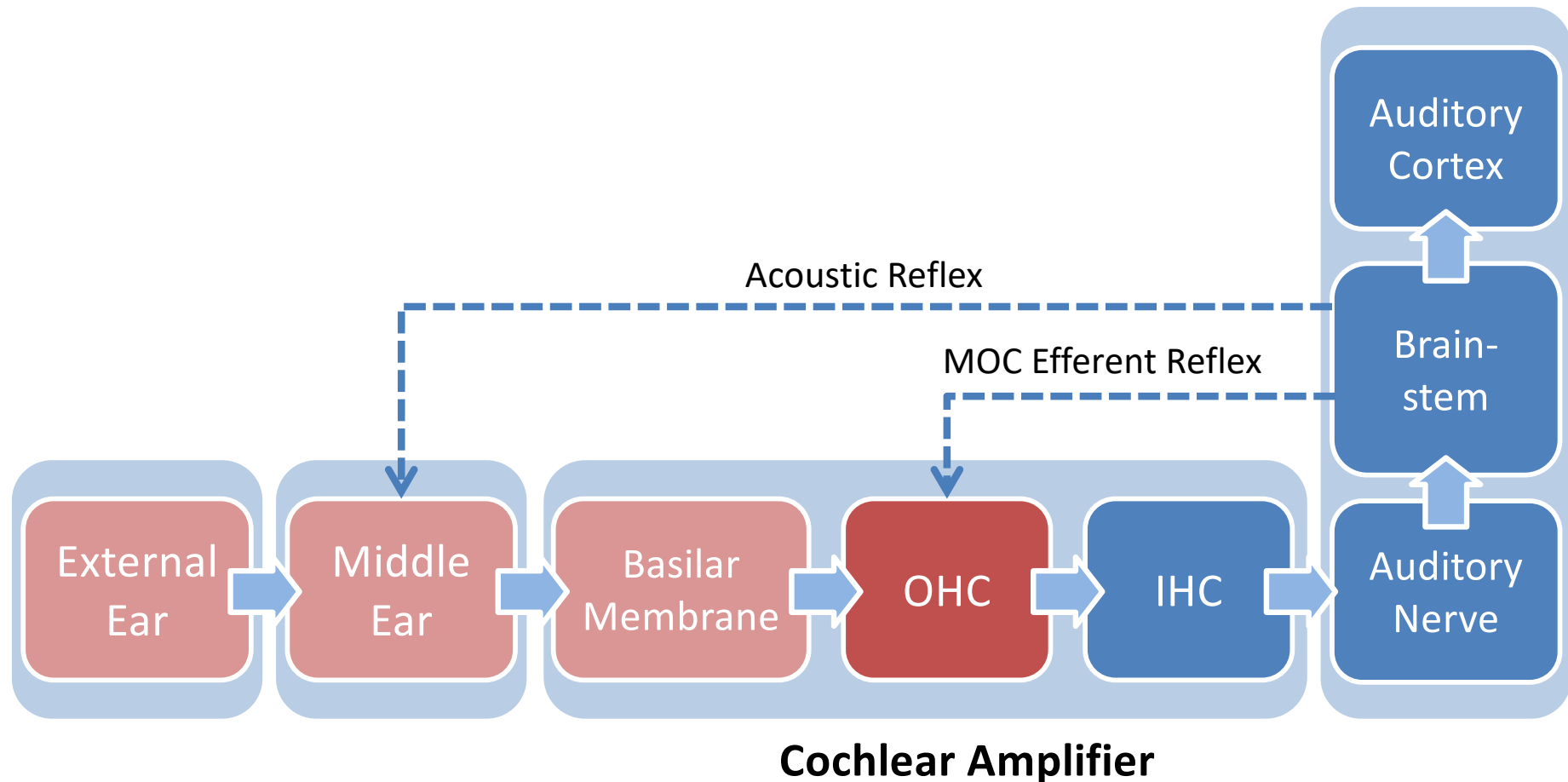
$$f_2/f_1 = 1.2$$

$p_I(t)$ – nonlinear-generation component

$p_{II}(t)$ – coherent reflection component

PTPV – primary tone phase variation (Whitehead et al., 1996)

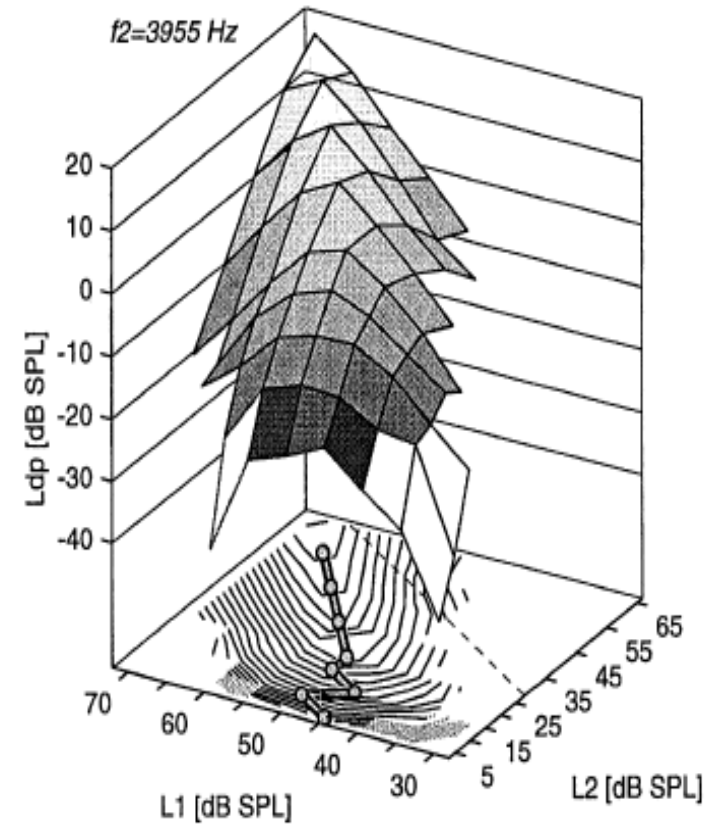
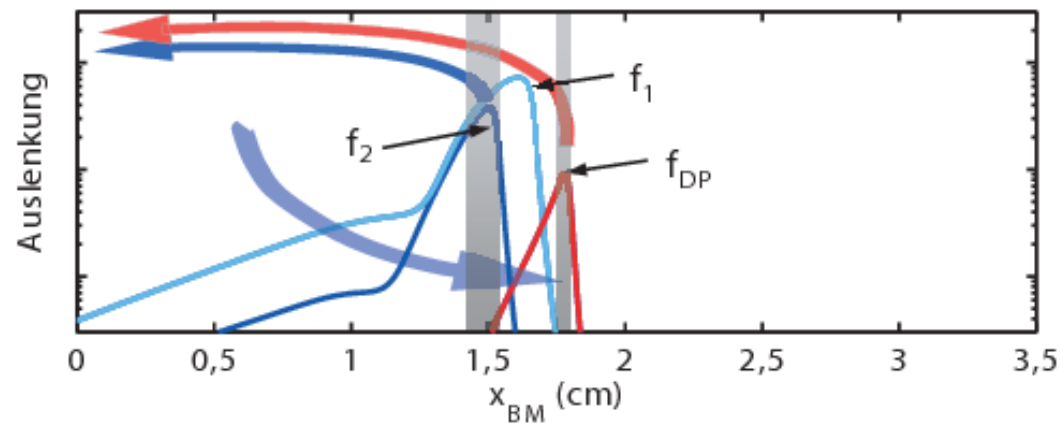
Function Diagnosis of the Auditory System



MOC – Medial Olivocochlear
OHC – Outer Hair Cell
IHC – Inner Hair Cell

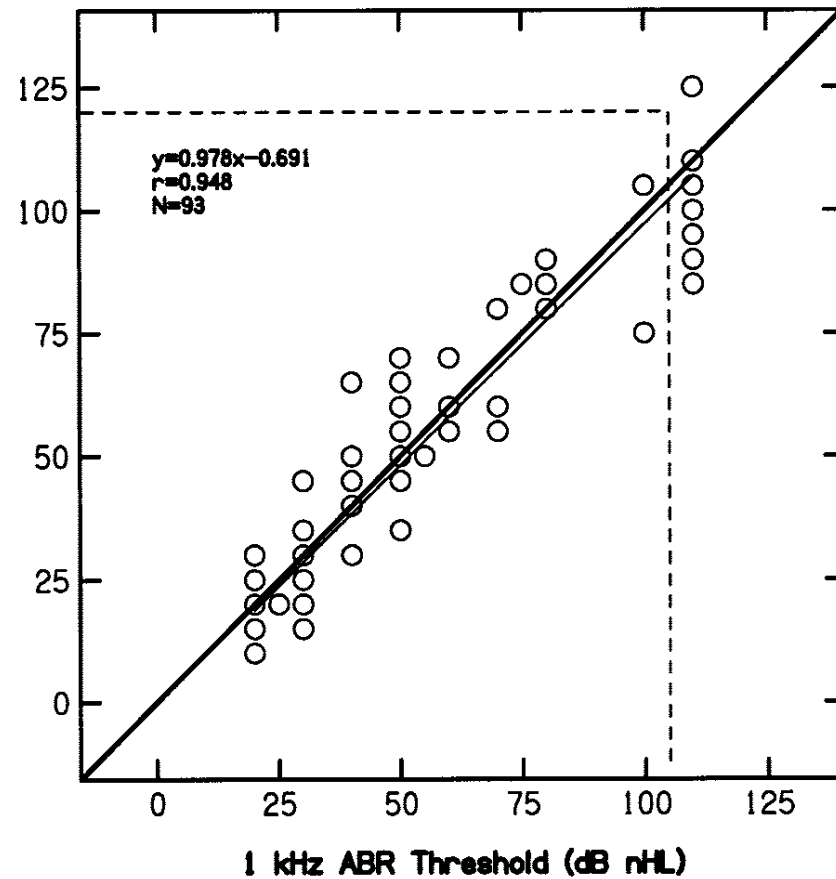
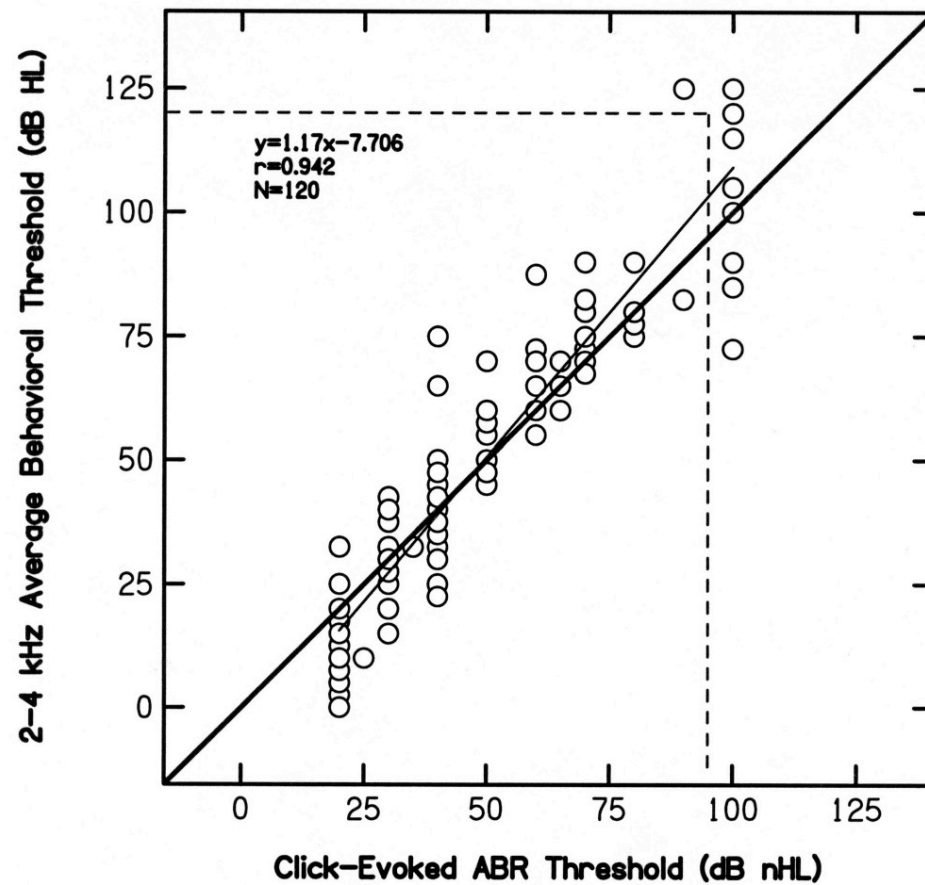
Acoustical. DPOAE – stimulus levels

$$L_1 = 0.4 L_2 + 39 \text{ dB}$$



Electrical. ABR vs. Behavioural threshold

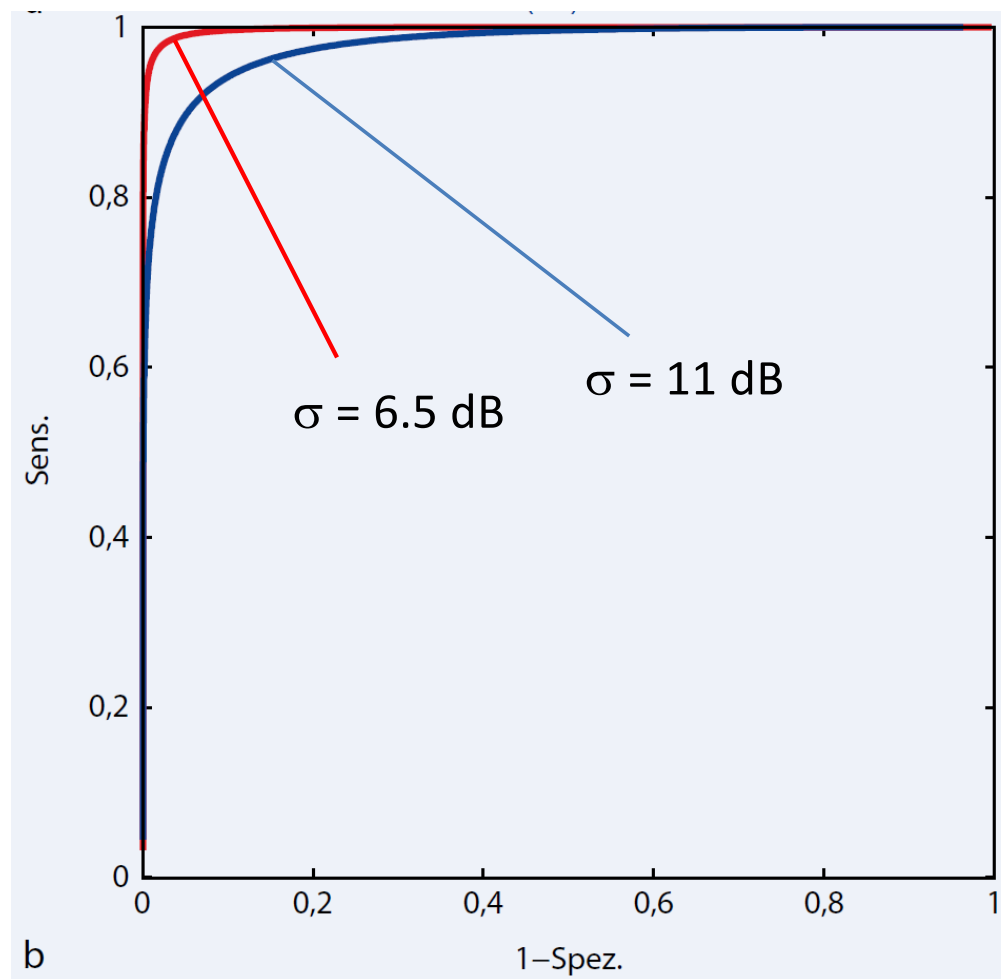
avg. age: 2.5/3 y



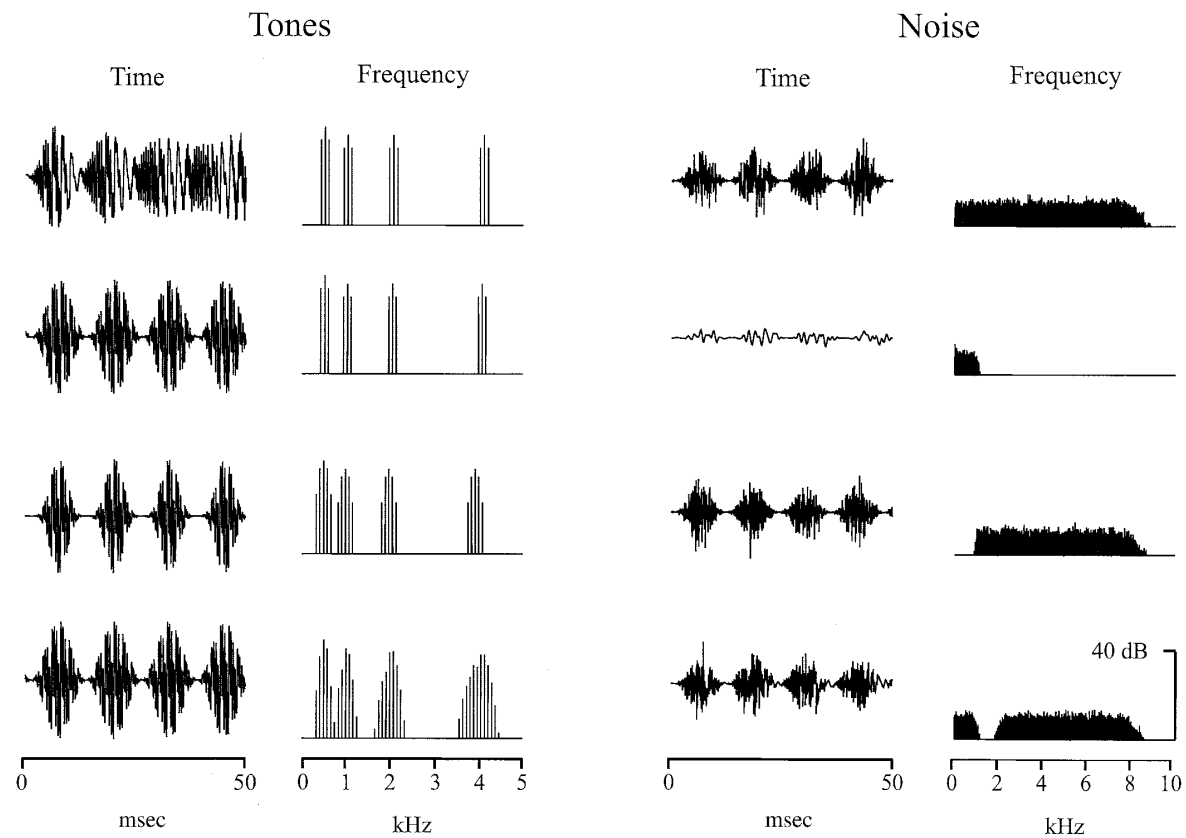
-> limited frequency specificity

Gorga et al., 2006

Acoustical. DPOAE I/O functions



Electrical. ASSR



John et al., 2003