Hearing4all with two ears: Benefit of binaural signal processing for users of hearing aids and cochlear implants

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Carl von Ossietzky University Oldenburg

Dynamically evolving research university

Oldenburg

Hearing Research

Marine Environment & Biodiversity

Renewable Energy

Neurosensory Science

Safety

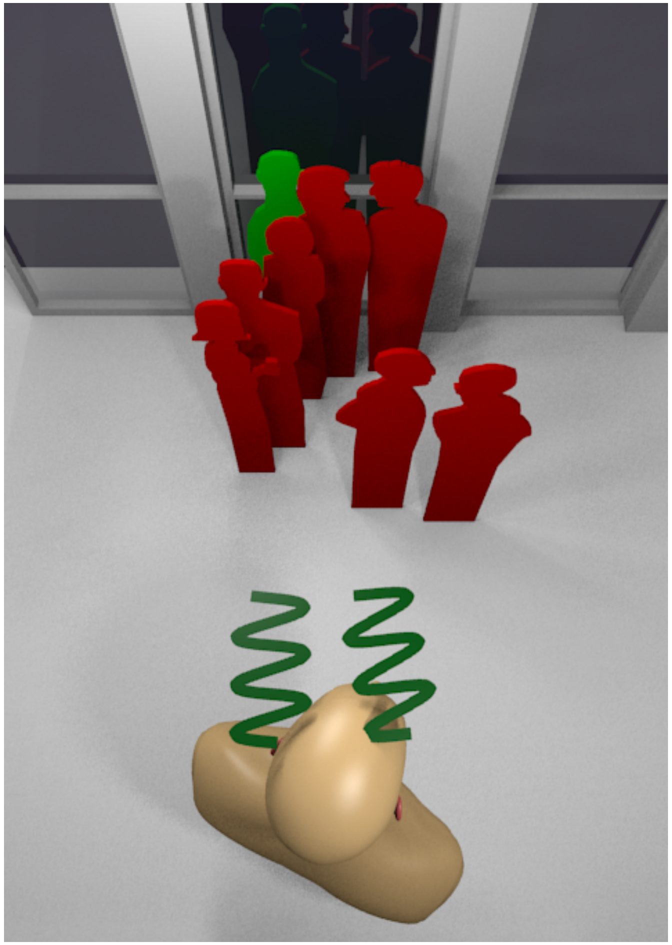
Education

Hearing4all with two ears: Benefit of binaural signal processing for users of hearing aids and cochlear implants

- Why binaural?
- How to measure?
- How can we understand?
- How can we improve the devices?

Acoustically difficult “Cocktail party” situations

- Background noise, reverberation
- Hearing impaired listeners (18% of our population) have significant problems →avoid social situations!
- Binaural (two-ear) hearing: directional perception, dereverberation, separation of desired speech from noise in the brain
- Specific binaural hearing impairment



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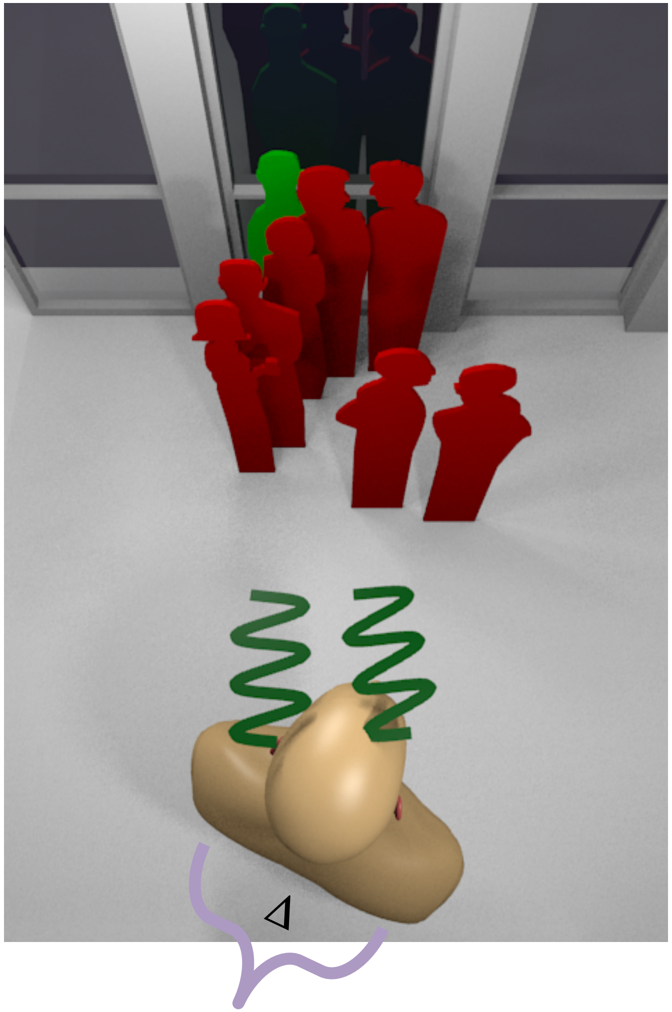

Binaural signal processing – spatial hearing for everybody

Acoustically difficult "Cocktail party" situations

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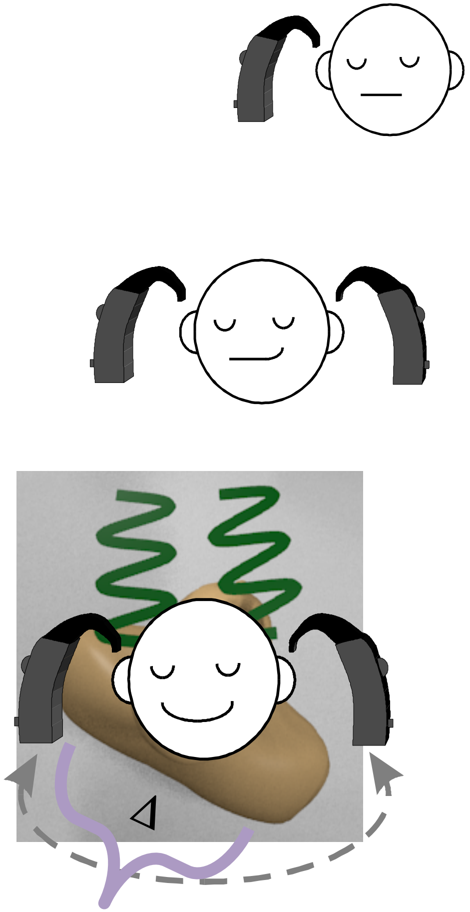


Go Binaural!

- Target group for hearing devices (hearing aids and cochlear implants) is steadily increasing (advances in technology & audiology)
- Binaural devices promise superior noise reduction abilities (utilize distance across ears)
- Even normal listeners might profit from some hearing aid features
  - Binaural directional filter
  - Noise suppression/ speech enhancement
  - Increasing compensation of hearing loss with increasing age

→ Need solutions for scalable „true“ binaural Hearing devices and the science behind…

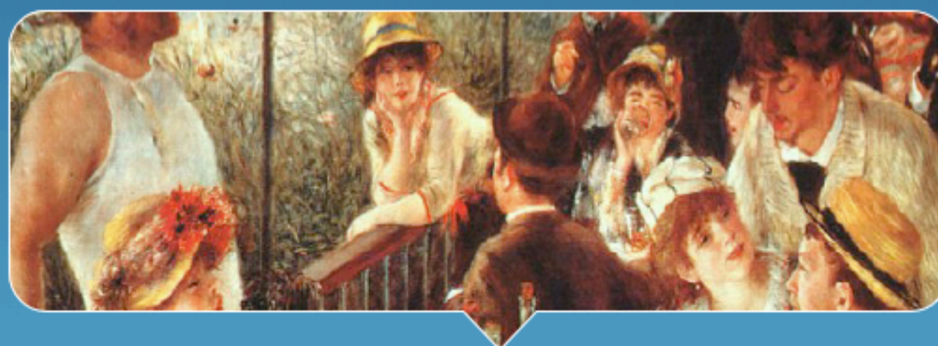
German Presidents Award 2012

A quick test of your cocktail-party-processor

Oldenburg sentence test OLSA

A quick test of your cocktail-party-processor

Oldenburg sentence test OLSA



Normal listeners, optimum conditions

Normal listeners, poor conditions

Hearing impaired, optimum conditions

Hearing impaired, poor conditions

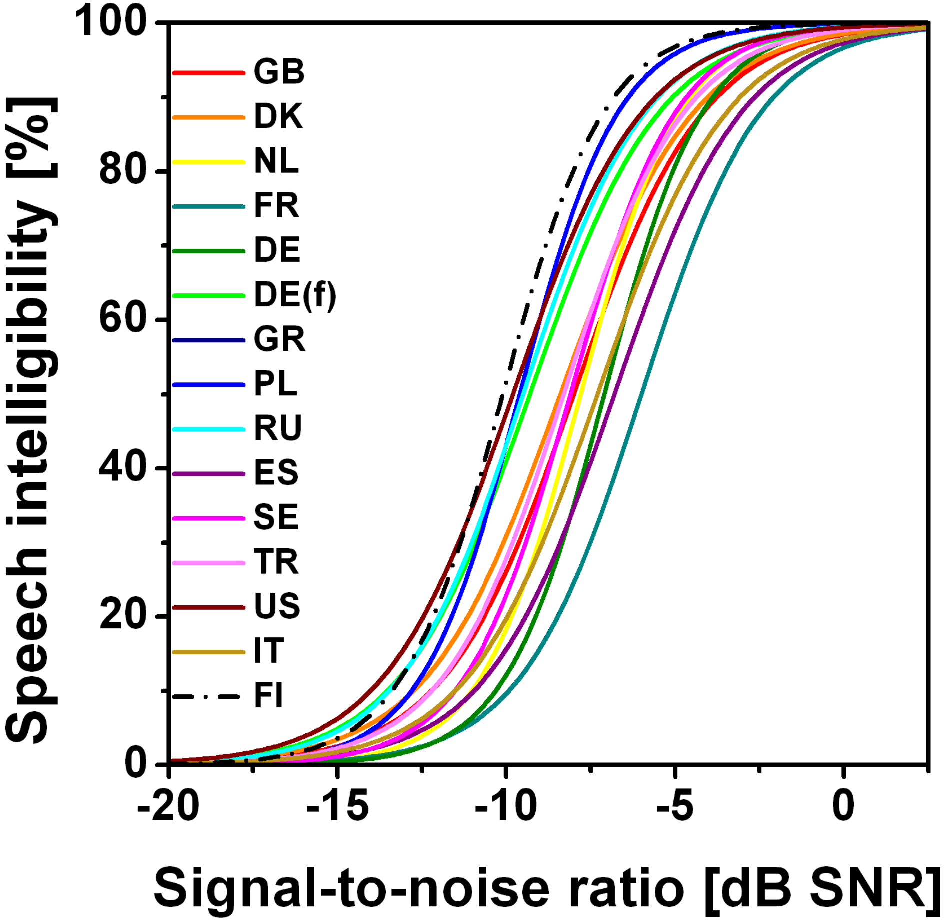
CI users, poor conditions

-10 dB | -5 dB | 0 dB | 5 dB | 10 dB

Matrix sentences (Hagerman/Olsa): Multilingual speech test

Name	Verb	Number	Adjective	Noun
Peter	got	three	large	desks.
Kathy	sees	nine	small	chairs.
Lucy	bought	five	old	shoes.
Alan	gives	eight	dark	toys.
Rachel	sold	four	thin	spoons.
Barry	likes	six	green	mugs.
Steven	has	two	cheap	ships.
Thomas	kept	ten	pink	rings.
Hannah	wins	twelve	red	tins.
Nina	wants	some	big	beds.

Matrix sentences (Hagerman/Olsa): Reference curves



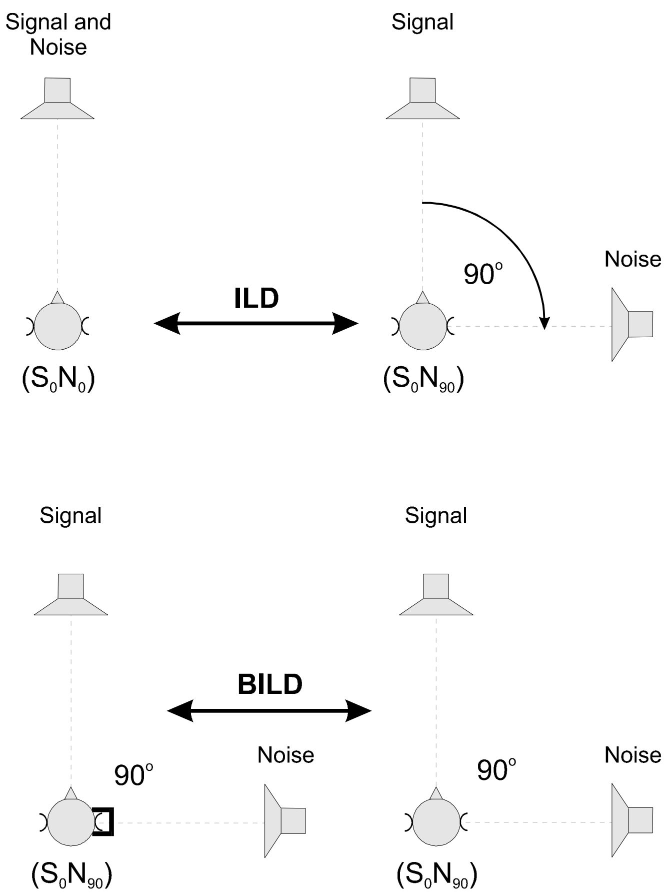
SRTs between -6.0 and -10.1 dB SNR
slopes between 13.0 and 17.1 %/dB

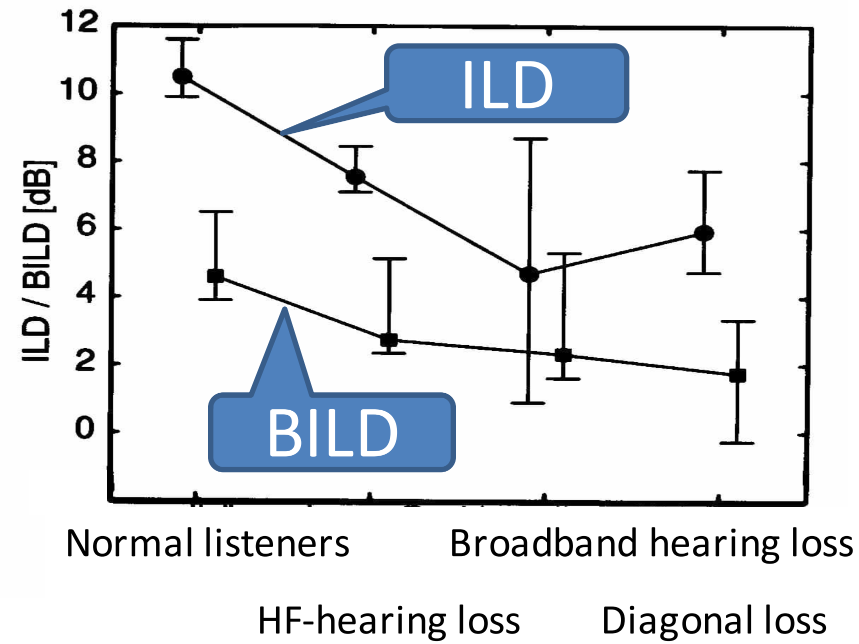
SRT-correction factor to enable comparison between languages

Closed-set response format to enable testing in patients own language with visual response buttons → self-paced, experimenter may not understand the test language

→ International standardization (ICRA recommendations for multilingual tests) available

Binaural advantage in Speech Reception threshold (SRT): Intelligibility level difference (ILD) and Binaural ILD



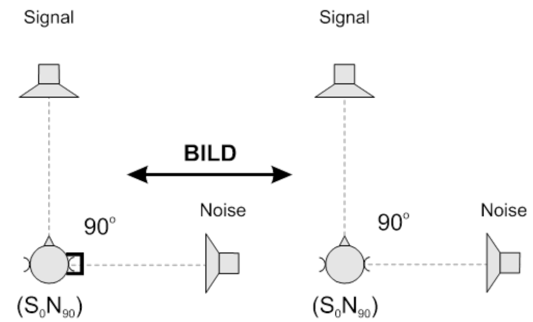


Assessing the advantage of binaural listening in a (simulated) free-field setup

- Target speech S always from the front S_0
- Interferer noise N from the front N_0 or the side N_{90}
- BILD: Advantage by adding the worse ear (binaural „squelch“)

Intermediate conclusions

- Speech perception in noise as one of the major customer complaints
- Can be assessed with the Matrix test in a multilingual society
  - (→ American English version: Ruth Bentler et al.!)
- Correlates with, but not predictable from the Audiogram
- Binaural auditory deficits for speech in noise can be assessed with
  - ILD: Better ear effect + binaural „squelch“
  - BILD: „True“ binaural processing advantage by adding the „worse“ ear in speech testing



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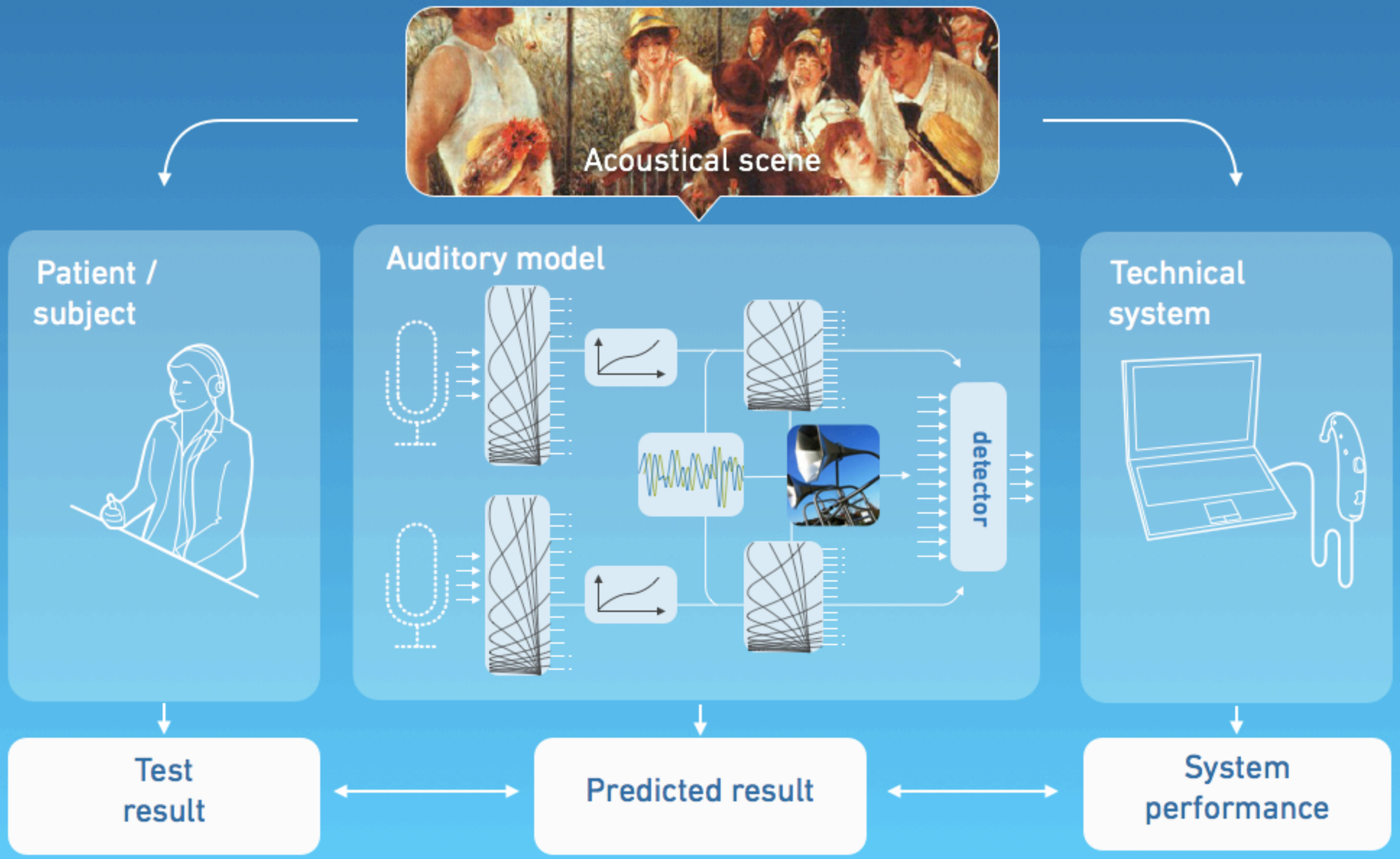
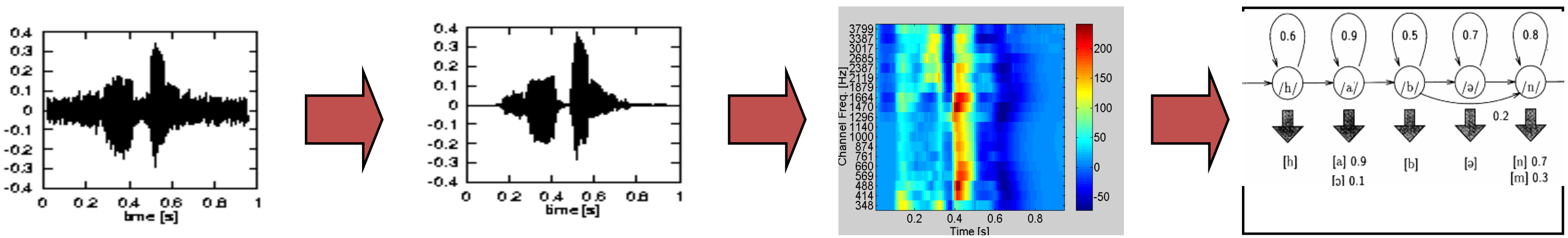
Cross-referencing experiment, model & applications



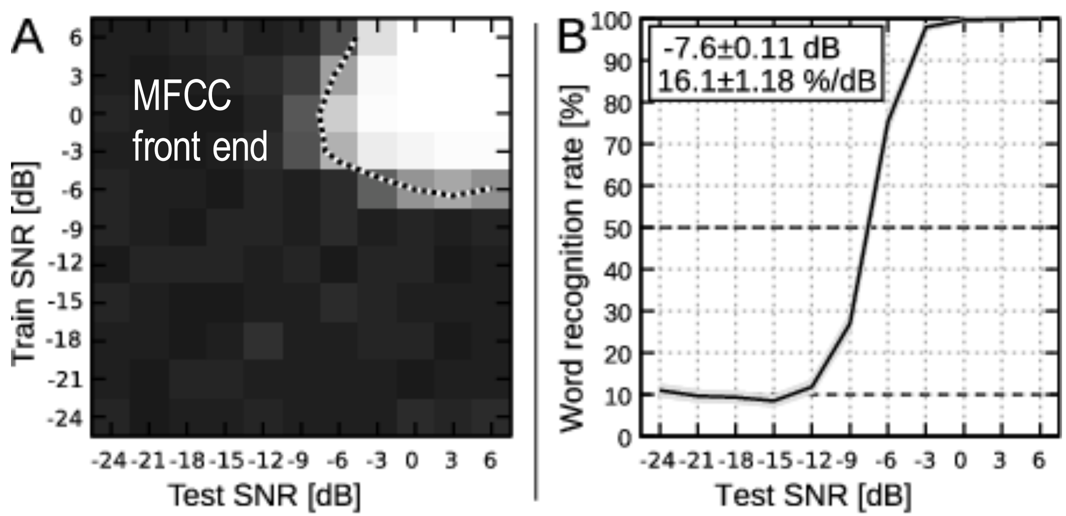
Using ASR/ machine learning to model human performance



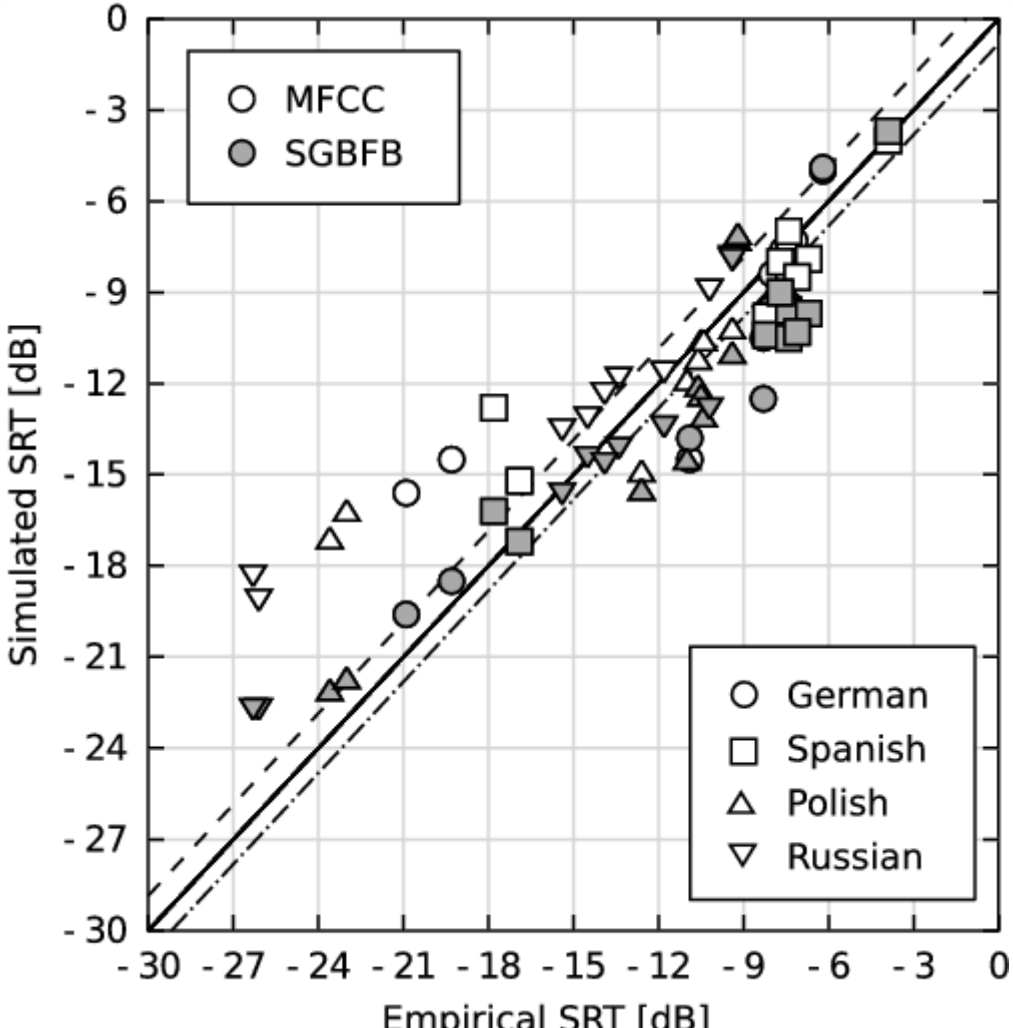
Time signal → Preprocessing → Feature extraction → Classification (HMM)

- System trained at different SNR with the limited Matrix sentence set
- Select training SNR with lowest SRT prediction
- Applicable as well to any discrimination experiment

→ ***F**ramework for **A**uditory **D**iscrimination **E**xperiment simulation (**FADE**)*



Prediction of Speech Reception thresholds for 4 languages in 7 different noises

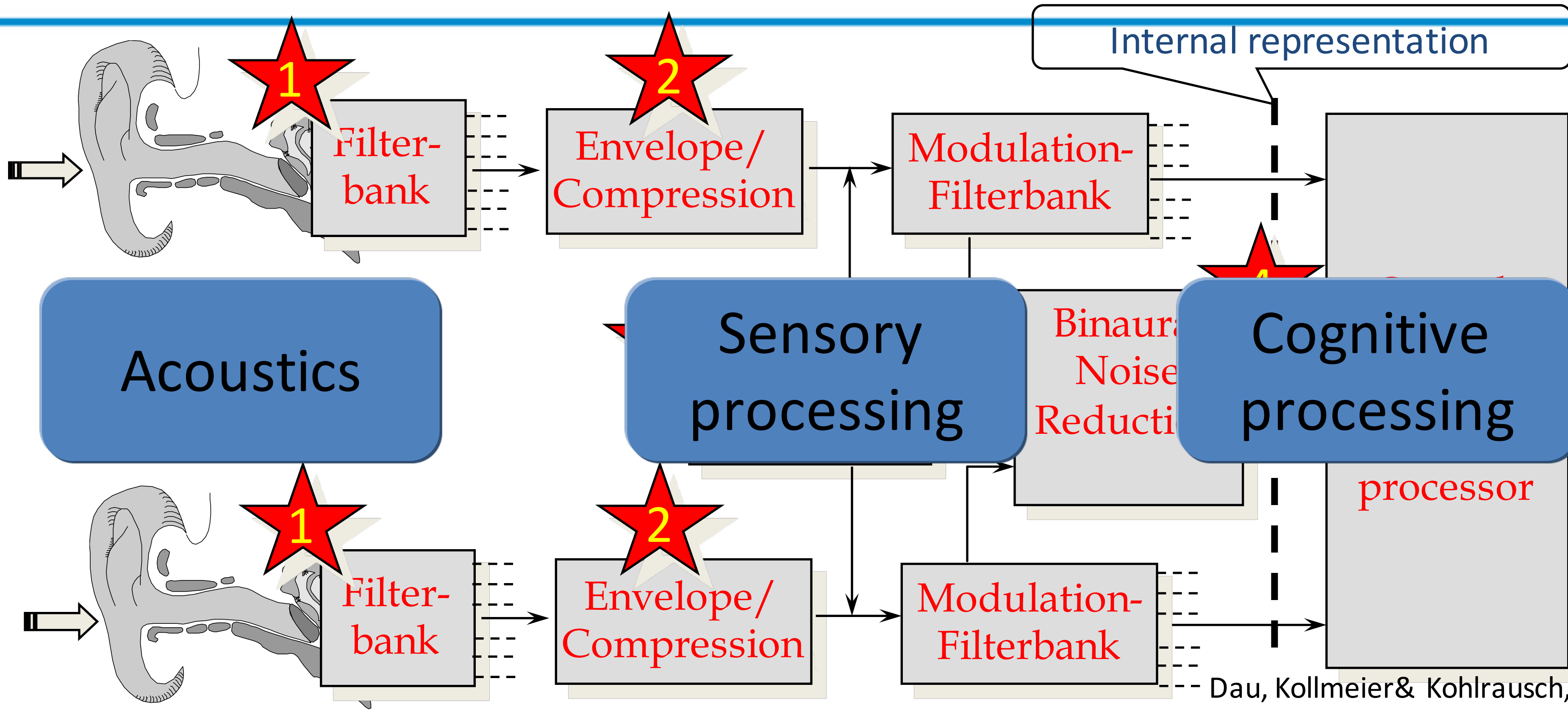


- Correlation between Measurement and prediction range between 0,77 (Polish, MFCC) und 0,95 (Russian, SGFB)

→ Good understanding on how speech intelligibility is produced by the auditory system across languages, speakers, noises for normal and hearing-impaired listeners

Schaedler et al. (submitted)

The ear from a modelling perspective



Dau, Kollmeier& Kohlrausch, 1997, Zerbs, 2000. Kollmeier, 2000, Derleth et al., 2001

Model of the „effective“ processing in the auditory system *& Impairments*

Perceptual factors and resulting hearing aid strategies

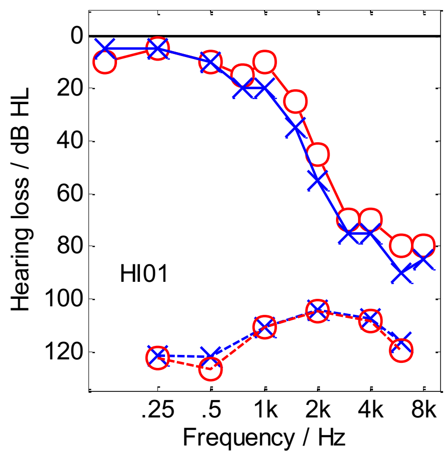
Factor	Perceptual consequence	Rehabilitation strategy	Technical challenges
Attenuation component 1	Loss of sensitivity; increased threshold level	Increase audibility by a) frequency-specific amplification b) frequency compression	Acoustical Feedback cancellation Acoustical Distortion
Distortion component 2	a) Loss of sensitivity; reduced dynamic range ('Recruitment') b) reduced frequency selectivity c) increased susceptibility to background noise	a) Automatic Gain Control (AGC), Multiband dynamic compression b) spectral enhancement c) noise reduction (see also: 'neural component')	a) Compression characteristics, time constants, band coupling b) Artifact removal c) Estimation/ Classification of speech and noise signals
Neural component 3 4	a) increased susceptibility to background noise ('Cocktail-Party Effect') b) impaired binaural capabilities	a) monaural noise reduction b) directional microphones c) beamformer d) binaural noise reduction	a) Estimation error & Artifact removal b) Lower corner frequency c) Beam characteristics d) Estimation error removal & transmission across ears

Next problem: The Recruitment phenomenon – after too soft comes too loud!

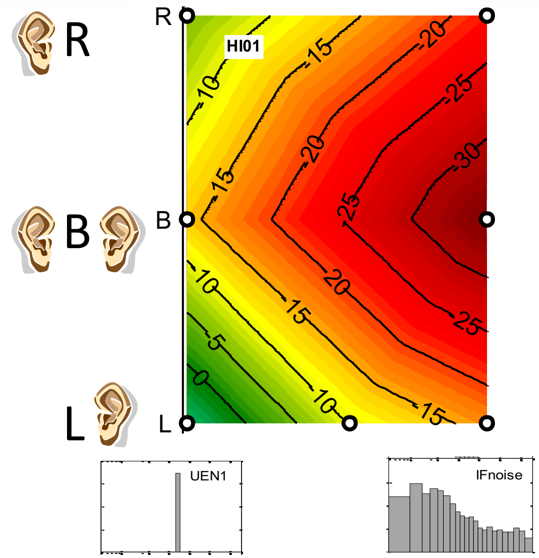
Normal listener

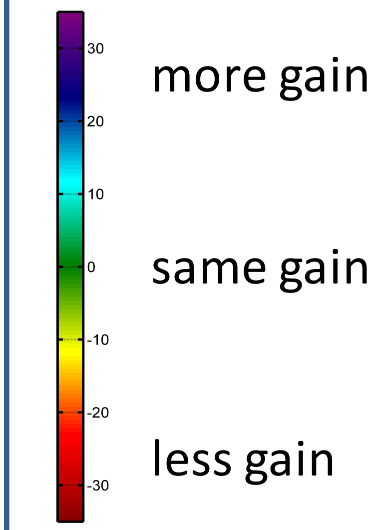
Hearing-impaired

Aided binaural loudness summation



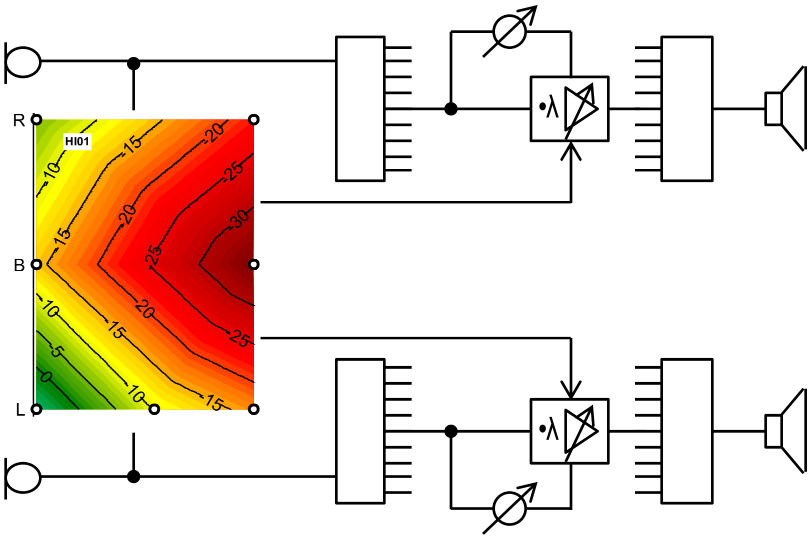
Audiogram

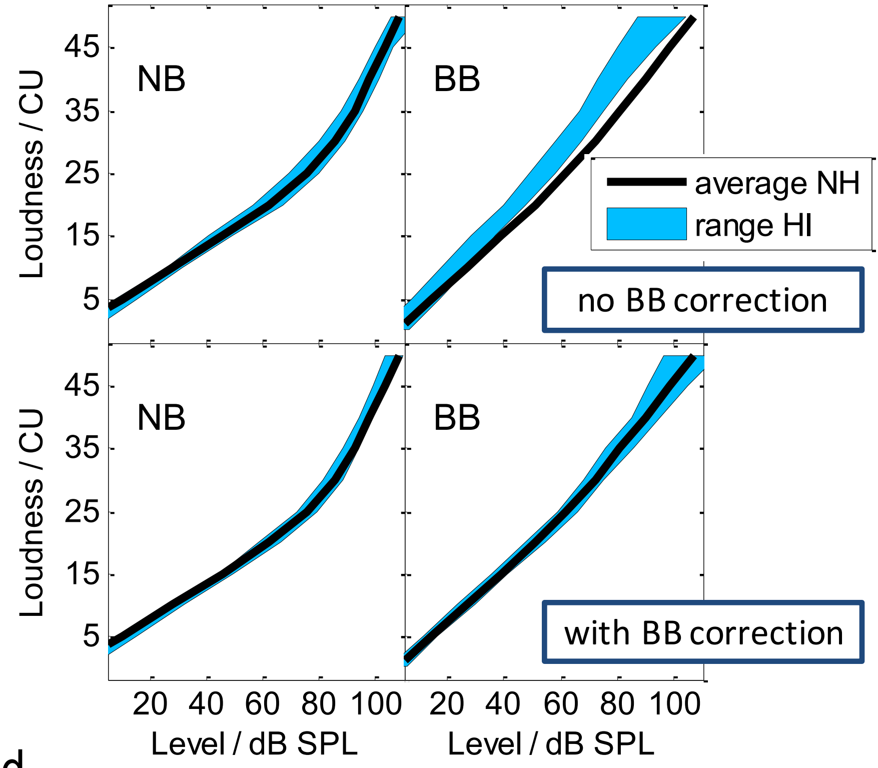




- Initial settings: gains to compensate loudness of narrow-band signals
- Less gain for loudness compensation of binaural broad-band signals
- But highly individual:
  - Subject with same gains for broad-band signals
  - Subject with large gain reduction for broad-band signals

Compression algorithm with gain correction for binaural broad-band (BB) signals





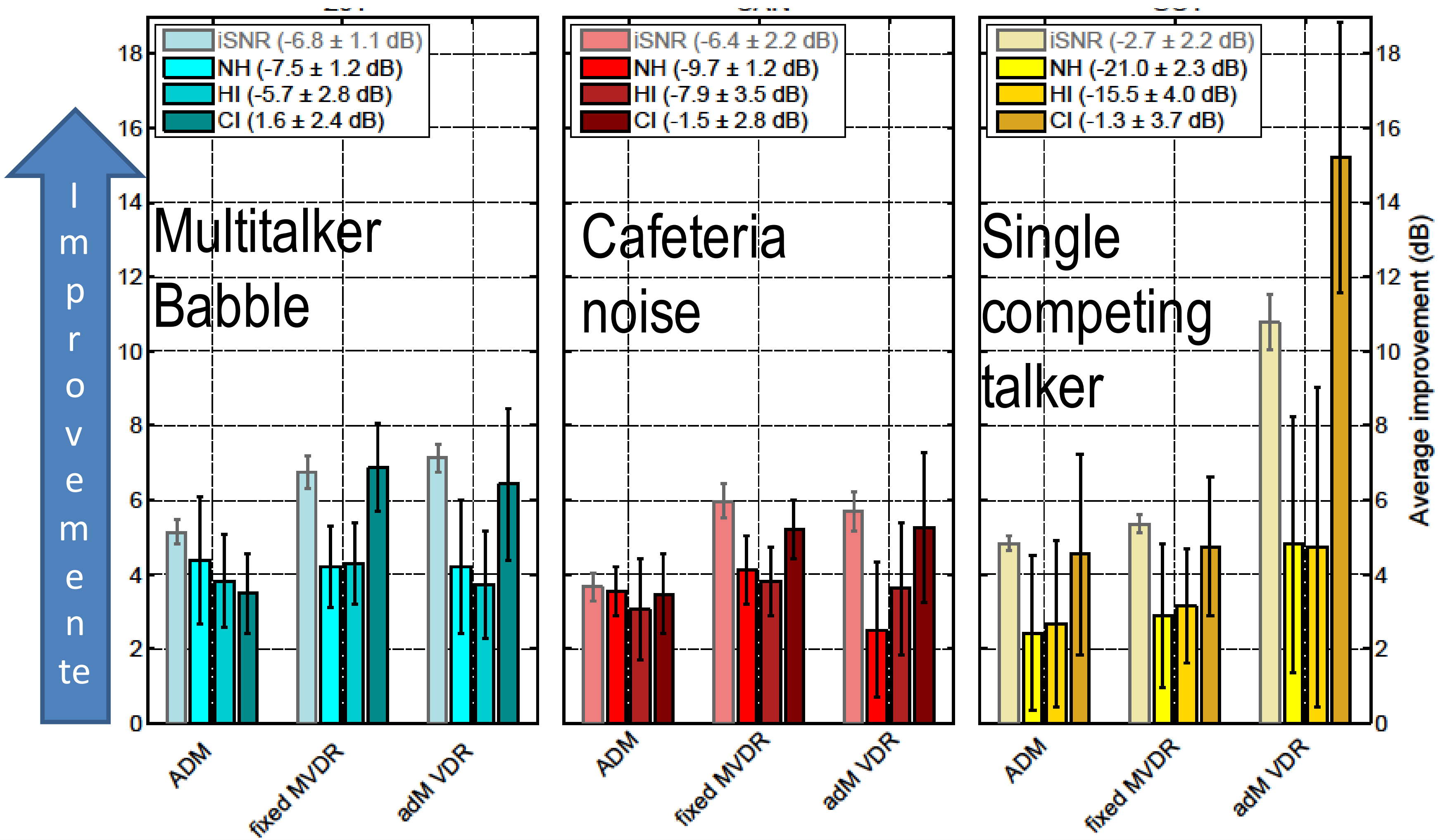
- Dynamic compression algorithm with additional broad-band gain table
  - Narrow-band gains corrected by broad-band differences
  - Normal loudness restored for NB and BB signals

Benchmark of Binaural Noise Reduction for hearing aids and CIs

- Implementation of several noise reduction algorithms on the same experimental device (MHA) with CI interface
- Highly reverberant environment
  - T_{60} = 1250ms
- Speech material: Oldenburg sentence test (OLSA)
- 3 Noise scenarios:
  - 20 Talker-Babble (20T)
  - Cafeteria Ambient Noise (CAN)
  - Single interfering talker (SCT)
- Comparison with Normal Listeners & Objective measures

Christoph Völker et al. 2015, Baumgärtel et al., 2015 (Trends inHearing, in press)

Performance with Binaural Noise Reduction: Instrumental, normal listeners, HI & CI users

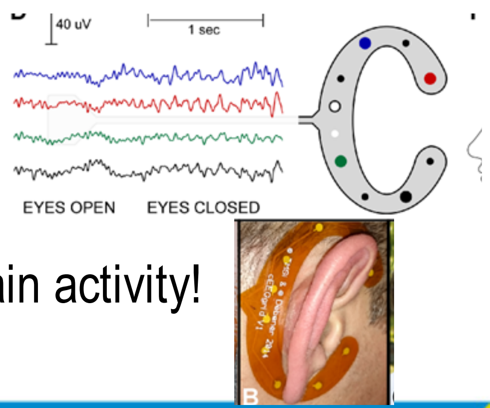


Intermediate conclusion binaural signal processing

- Substantial gain achieved by binaural algorithms (replacing human binaural processing) across all user groups in the lab
  - fixed MVDR beamformer is among the best-placed algorithms in each noise condition
- Instrumental benefit estimate (related to SNR improvement) overestimates gain in NH and HI, but realistic for CI (at highest SNR!)
- Preservation of binaural cues „costs“ a bit, but provides naturalness and robustness
- Problems remain (beam steering, „locked in“, reverberation, many competing speakers,…..)

Conclusions & Clinical implications

- (True) Binaural hearing devices are required4all …
  - to support in “difficult” situations (many sources, reverberation)
  - for an increased range of hearing impairment (subclinical / hearing aid users/ CI receipients)
- Candidacy and Fitting should consider…
  - Multilingual Matrix sentence test to assess residual binaural abilities (ILD, BILD)
  - Individual binaural and broadband loudness summation effect
- Future developments
  - Effective binaural compensation schemes merging hearing aids and cochlear implants
  - Merging of Consumer Electronics with Hearing aid technology
  - Innovative ways of controlling the setting: By gestures or by brain activity!



Debener et al., 2015

Thank you!

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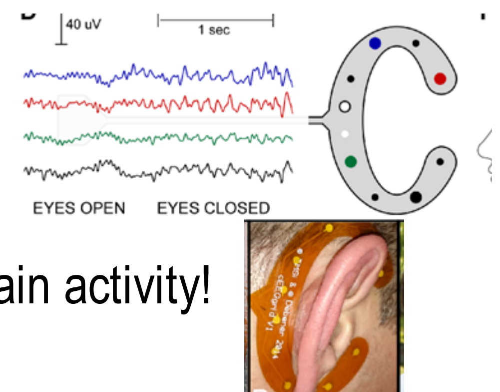
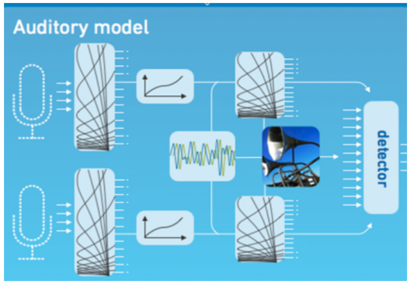


Binaural Enhancements: "Virtually" creating a larger head

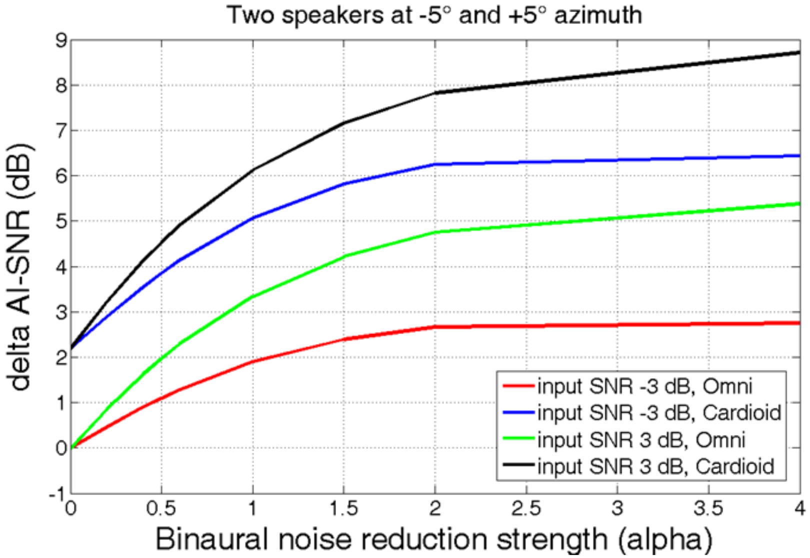


- $\tilde{Y}_L(\omega) = Y_L(\omega) \dfrac{Y_L^{\alpha}(\omega)}{Y_R^{\alpha}(\omega)}$
- $\tilde{Y}_R(\omega) = Y_R(\omega) \dfrac{Y_R^{\alpha}(\omega)}{Y_L^{\alpha}(\omega)}$

(Durlach & Pang, 1986, Kollmeier & Peissig, 1990)

Enhancement parameter α should yield a significant effect:

- AI- weighted SNR calculations at output
- +3 dB and – 3dB SNR at input

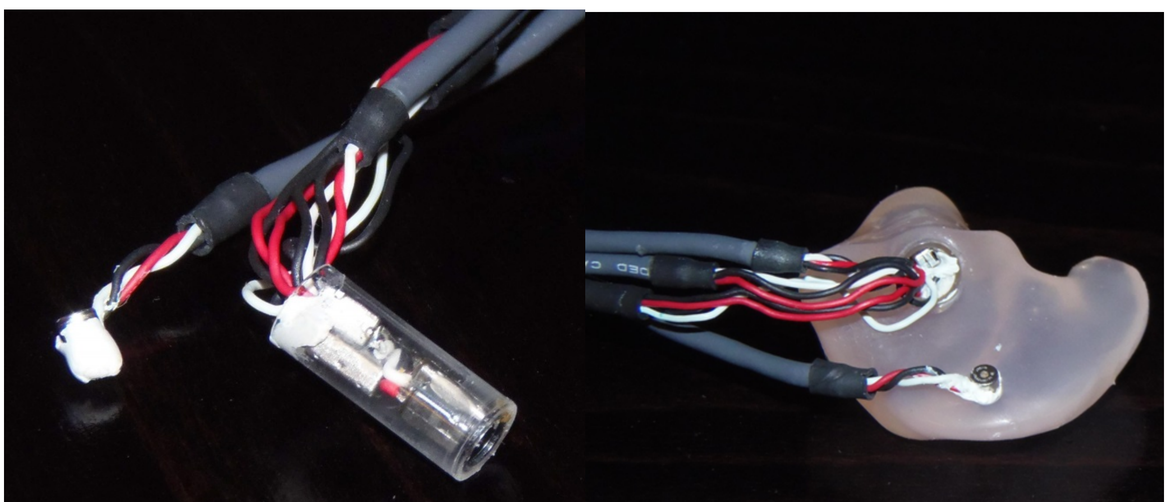


Hearing4All Highlights

- Matrix Test in 16 Languages, Supplement of Int. J. Audiol.
- Common Audiological Functional Parameters (CAFPAs)
- Common research platform Hearing Aids – Cochlea Implants (ABCIT/ModHG/Binaural Taskforce)
- Binaural loudness summation effect for hearing device fitting
- ASR-based speech recognition prediction (FADE with extentions)
- Scalable binaural Hearing Aid with Master hearing aid
- TASCAR system and acoustical Virtual Reality Room

Acoustic „transparent“ earpieces

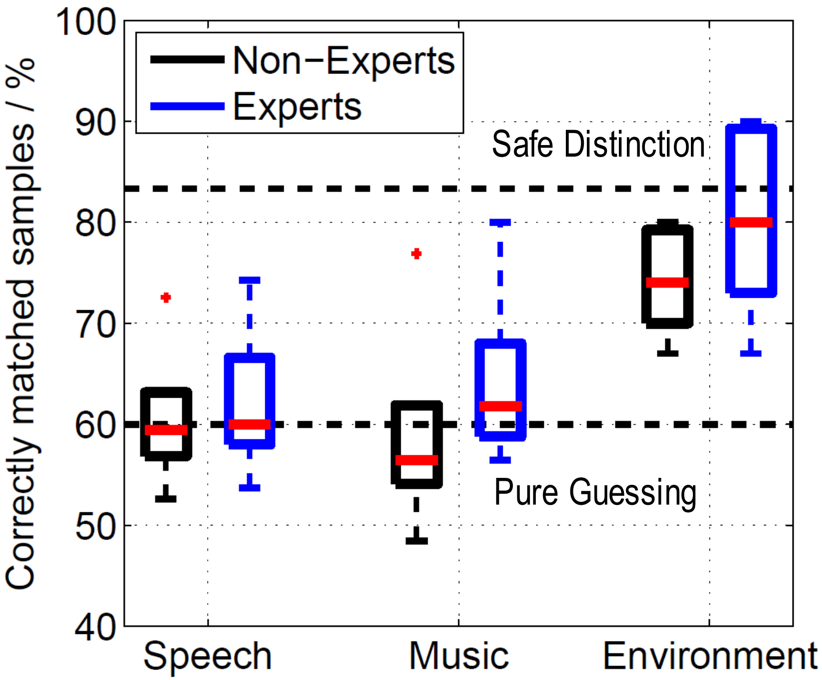
- Earpieces with 2 mics and 2 receivers each in 5 mm x 13 mm tube “cores” with venting
- Fitted into individually shaped silicon earmoulds & third mic (outside)
- Equalization to same modelled transfer function as (individual) open ear using real-time (binaural) programmable Master Hearing Aid (MHA)



Hiipakka & Kollmeier, 2014, Denk et al., 2014

Transparent Earpieces – Evaluation

- Evaluation of perceived transparency
  - 5 normal-hearing expert listeners & 5 non-experts
  - ABX-test, distinguish between
    - active earpiece and
    - simulated open ear canal (headphone playback producing target frequency response at the eardrum)
  - Microphone noise in „active earpiece“ may provide some unwanted cues
  - Only marginal discrimination above chance level



→ Promising concept of shaping the target frequency response of the earpiece to achieve "acoustic transparency"

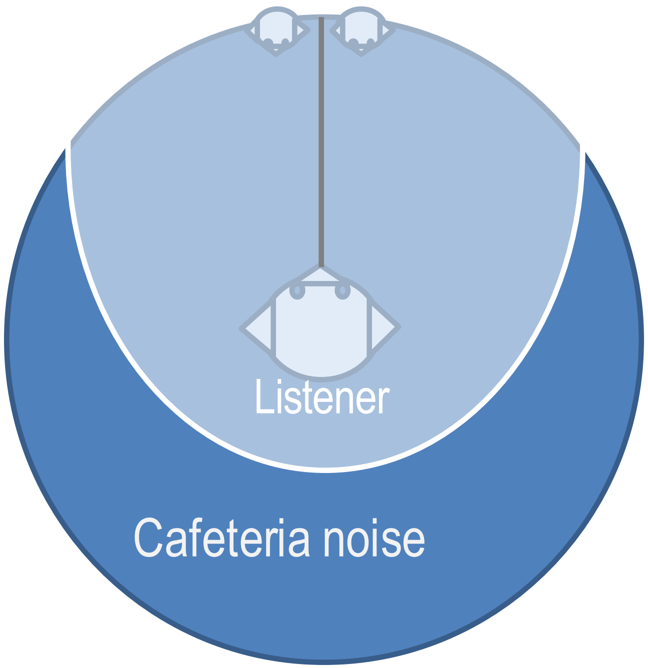
Binaural enhancement for Cocktail parties: Choice & Combination of algorithms

1

- Monaural Beamformers with ***cardioid characteristic***

2

3



Binaural enhancement for Cocktail parties: Choice & Combination of algorithms

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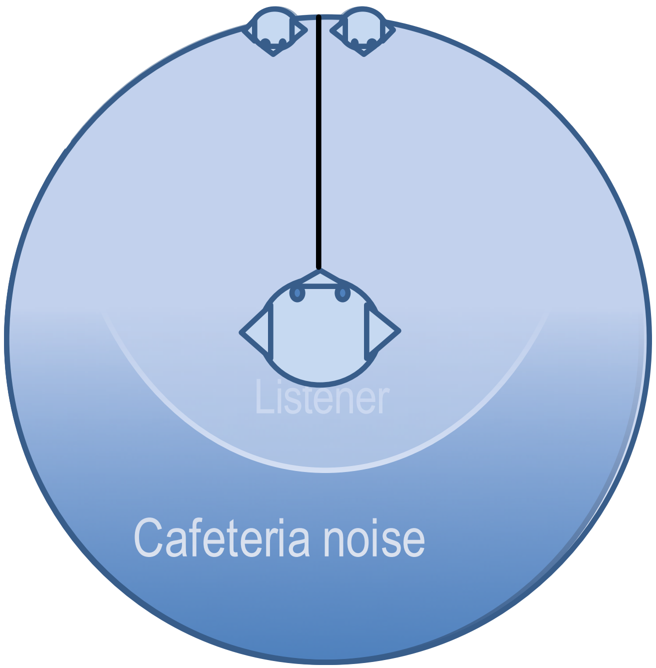
- Monaural Beamformers with ***cardioid characteristic***

2

- **Binaural** coherence filter for suppressing incoherent noise & reverberation

3

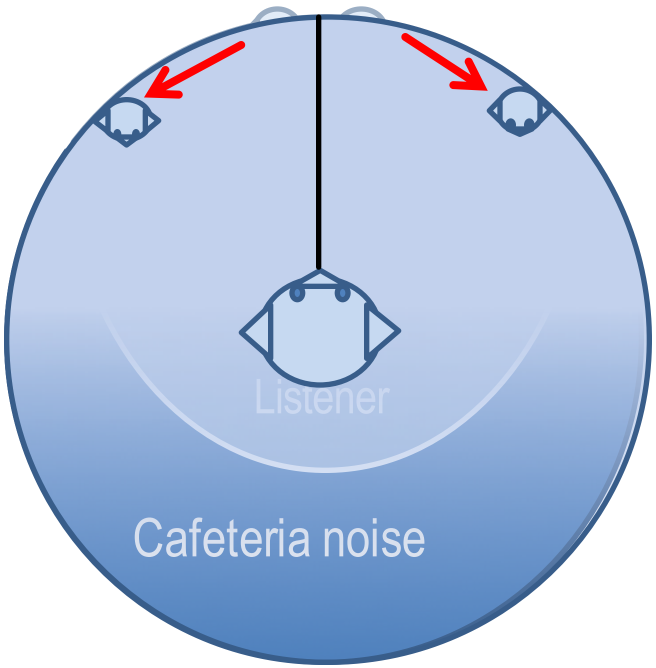


Binaural enhancement for Cocktail parties: Choice & Combination of algorithms

1 • Monaural Beamformers with ***cardioid characteristic***

2 • **Binaural** coherence filter for suppressing incoherent noise & reverberation

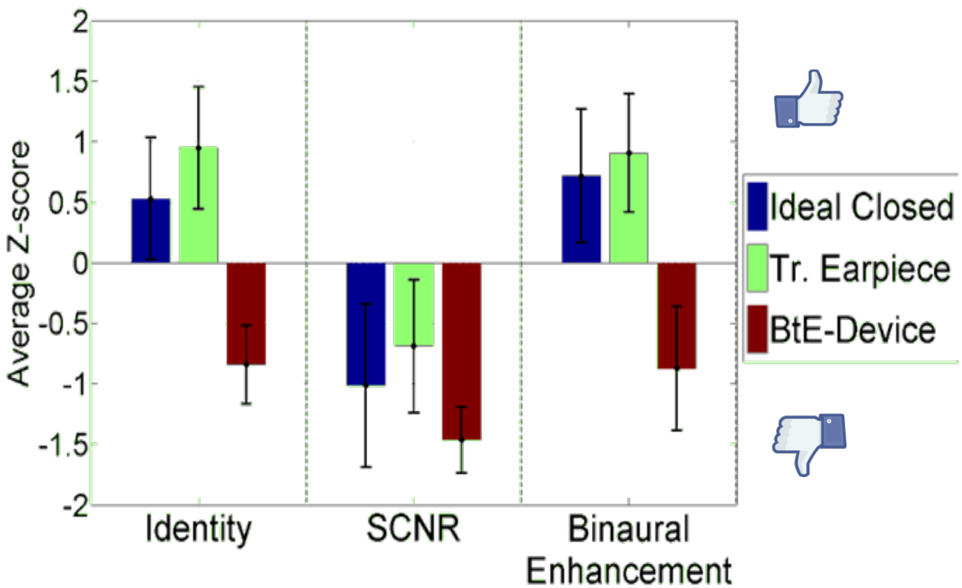
3 • **Binaural** Enhancement (IPD/ILD) to compensate for lost binaural interaction



Transparent Earpieces – Evaluation with binaural algorithms

- Quality evaluation for a combination with single-channel noise reduction (SCNR) or binaural enhancement

- Clear preference for the combination of binaural enhancement with the acoustically transparent earpiece



→ Promising concept of shaping the target frequency response of the earpiece to achieve “acoustic transparency” as prerequisite to gain from binaural processing

Rationale behind “transparent” earpieces

- Target frequency response at the eardrum with earpiece in place = response without earpiece (+ hearing aid amplification)
- Verification with microphone inside ear canal:
  - Circumaural headphones as external sound source, earpiece in position
  - Target response (“equalization”) of active, operational setup is applied via master hearing aid (MHA)) ,
  - compared with passive setup (+compensation of (modeled) change of outer ear transfer function due to presence of earpiece)

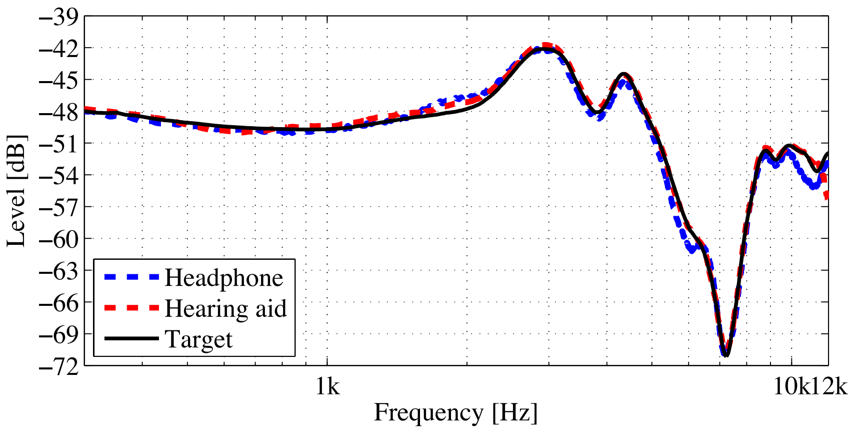
$$P_E = P_S \times \frac{Z_{ECE}}{Z_{ECE} + Z_{RAD}}$$

  - Fine tuning to compensate for deviations from model

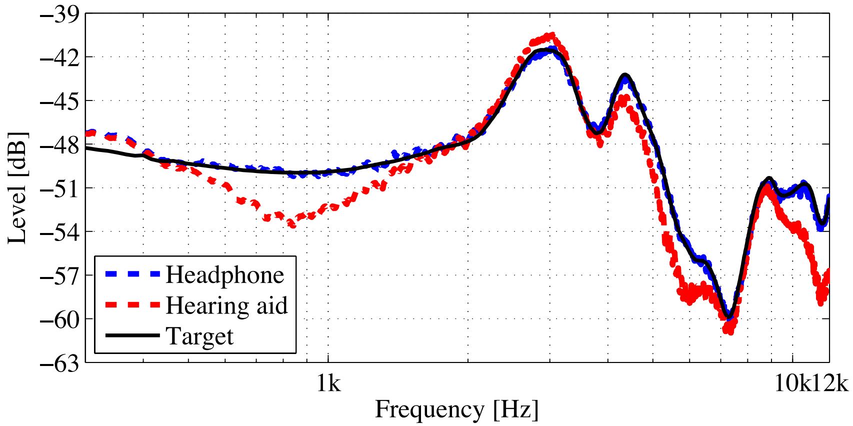
Results obtained with microphone

- In-ear responses of the test subjects
  - Almost identical responses at the in-ear mic location
- The pressure at the eardrum is also similar if no near-field effects are present

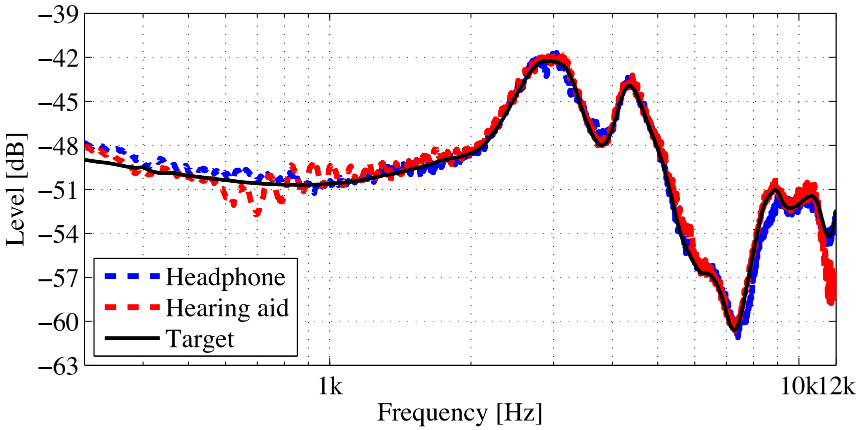
After adaptive filtering in the Output Only scenario:



After initial filtering in the Hearing Aid scenario:



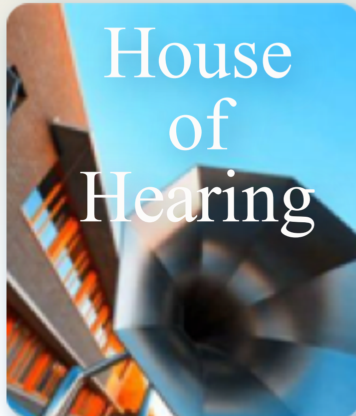
After adaptive filtering in the Hearing Aid scenario:



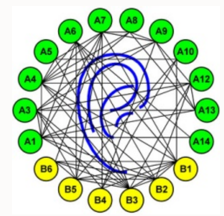
Dynamic build-up of Hearing Research in Oldenburg

Hearing 4all

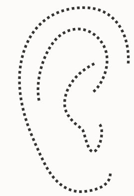
DFG Research Training groups
Psychoacoustics
(1990- 1999)
Neurosensory Science, Systems & Applications
(2000-2010)



DFG SFB
Active auditory system



Centre for Hearing Research



DFG
Research Unit
Individual Hearing acoustics

1996 — 2000 — 2004 — 2008 — 2012

Adjunct institutions:

HÖRZENTRUM OLDENBURG

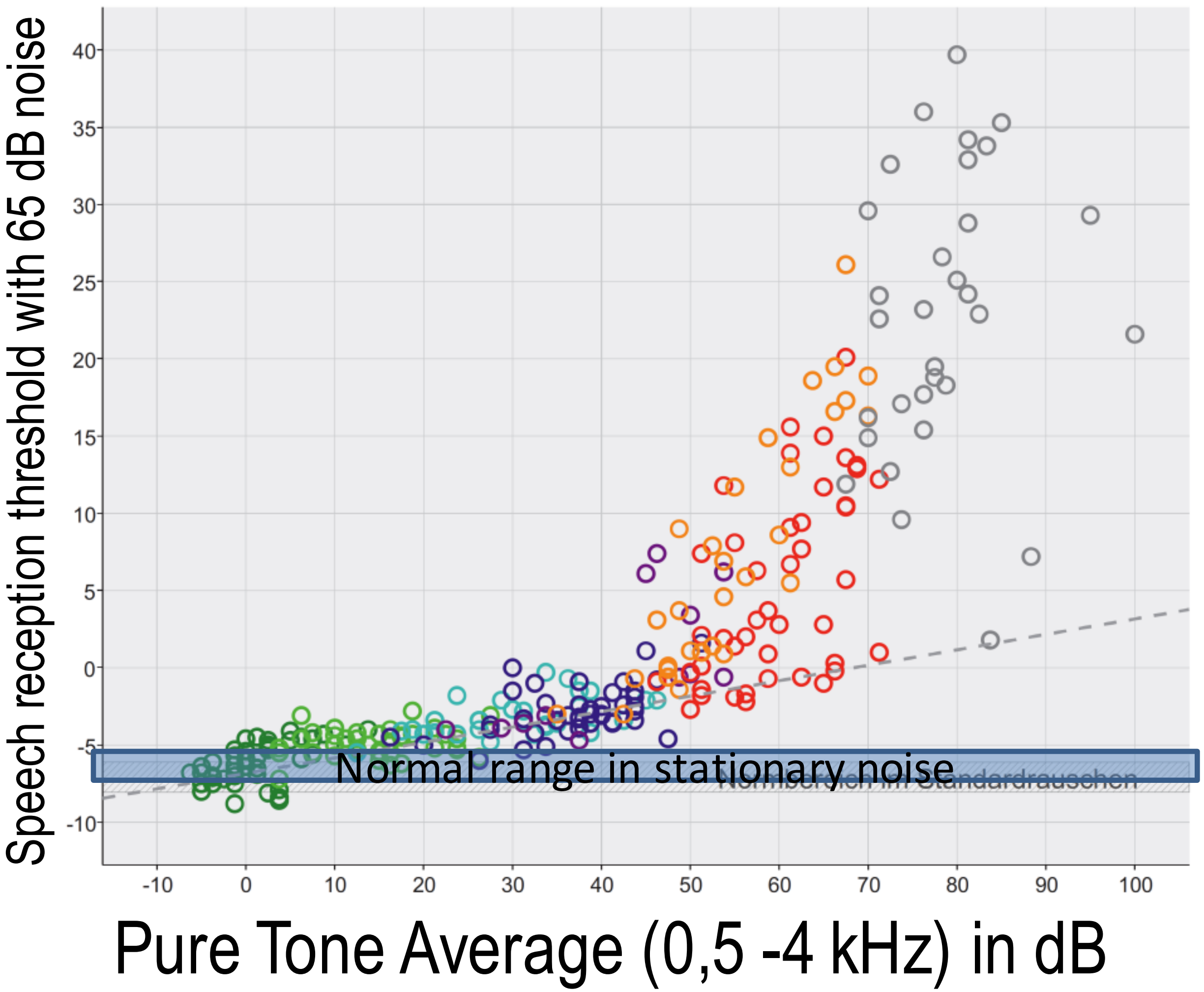
HörTech

JADE HOCHSCHULE Wilhelmshaven Oldenburg Elsfleth

Fraunhofer IDMT

80% of all hearing aids worldwide with „Oldenburg inside“

Altered speech perception in stationary noise (65 dB HL) due to hearing impairment



- German Matrix Test (OLSA):

  N=158 (Wardenga et al, 2012)

Type of audiogram

→ General increase in SRT with increasing hearing loss

→ large individual spread!

Remaining challenges for the future

- Dependence on Input SNR
  - Noise reduction potential usually optimal for SNR > 0 dB which matches better the need of CI users than (nearly) normal listeners
  - Remaining individual binaural processing only active for SNR < 0 dB (?)
  - SRT-Tests with sentences targeted to be < 0 dB
  - → Activation of different algorithms depending on input SNR
- Dependence on Complexity of acoustic situation
  - Noise reduction algorithms assume strict adherence to a certain mixing model and fail if this is violated (more sources, more reverberation, head movements)
  - Binaural enhancement may hamper localization cues but rely on still available human scene decomposition
  - → Activation of different algorithms and/or parameters if input scene alters

→ Exact knowledge of presented scene and its interaction with human perception would be desired!

The most common complaint of approx. 18% of our population – how should it be tested?