# Acoustically transparent sound presentation in hearing devices: algorithms, devices and models

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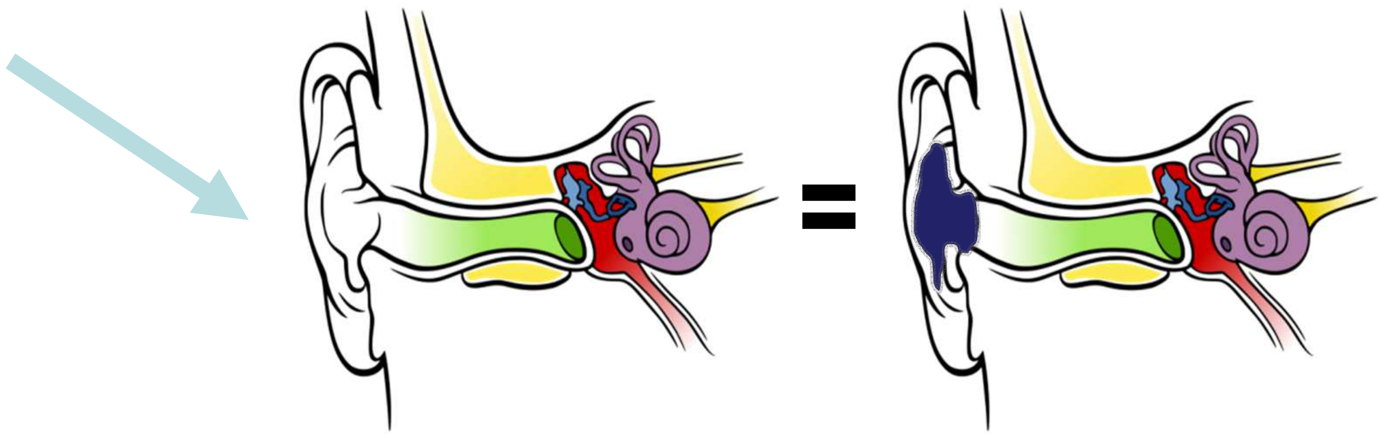
# Acoustically Transparent Earpiece

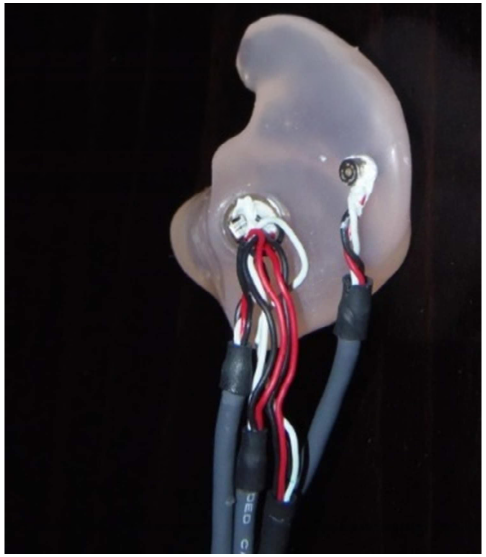
- Current hearing devices: **sound quality still limited** (e.g., distortion, non-individualized, own voice, spatial impression)
- **Acoustic transparency:** enable hearing comparable to the open ear while providing desired sound enhancement (e.g., amplification, dynamic range compression, noise reduction)

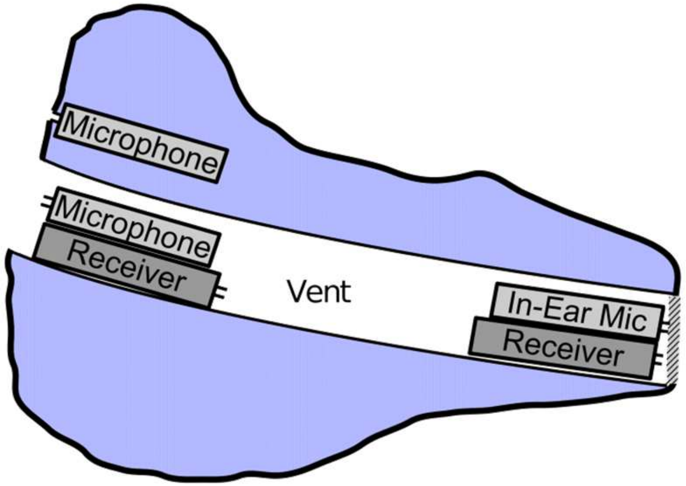


[Denk et al., *International Journal of Audiology*, 2018]
[Denk et al., *Proc. International Workshop on Challenges in Hearing Assistive Technology*, Aug. 2017.]

# Acoustically Transparent Earpiece

- **Custom in-the-ear earpiece** with multiple integrated microphones and receivers and relatively open acoustics
  - Vent/core: **2 microphones and 2 receivers** (woofer/tweeter)
  - Concha: **1 microphone**
- Insertion into individual silicone ear mould or generic earplugs






[Denk et al., *International Journal of Audiology*, 2018]

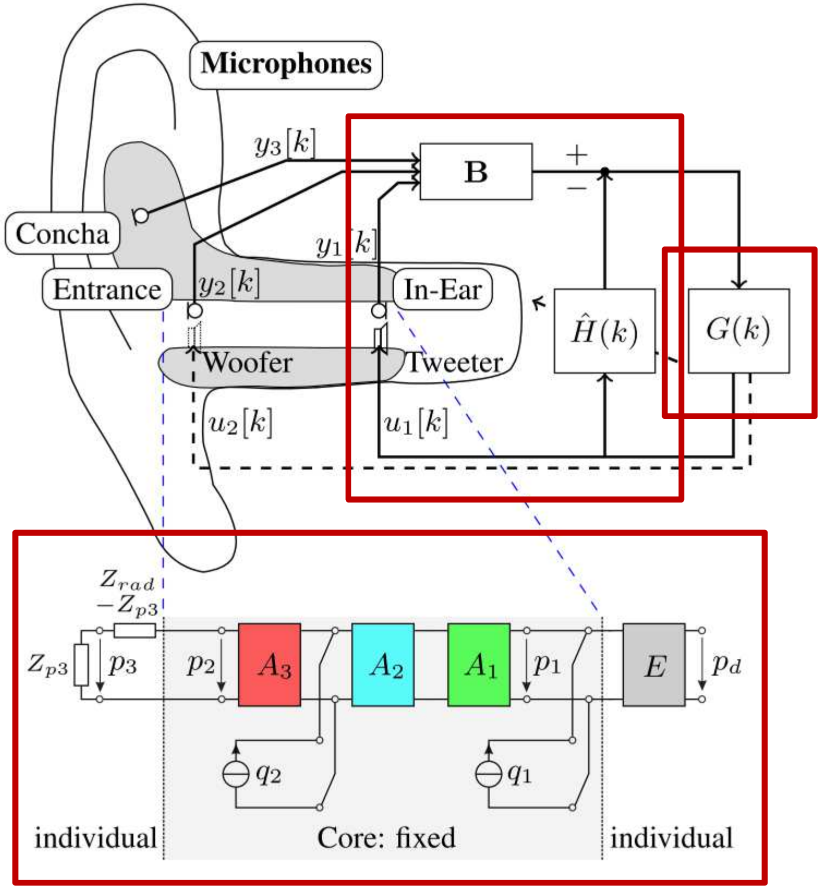
# Acoustically Transparent Earpiece

**1. Transparent sound presentation:**

- Natural sound quality by equalizing to open-ear target response at eardrum (using single/multiple receivers)

**2. Individualized Electro-Acoustic Model:**

- Better understand acoustics
- Predict sound pressure and transfer functions (eardrum)




**3. Acoustic Feedback cancellation**

- Exploit multiple microphones to steer null towards position of receiver
- Exploit multiple receivers

**4. Hearing support:**

- Amplification and dynamic range compression
- *Noise reduction (active/passive)*
- *Occlusion management*

[Denk et al. , *Proc. International Workshop on Challenges in Hearing Assistive Technology*, Aug. 2017.]

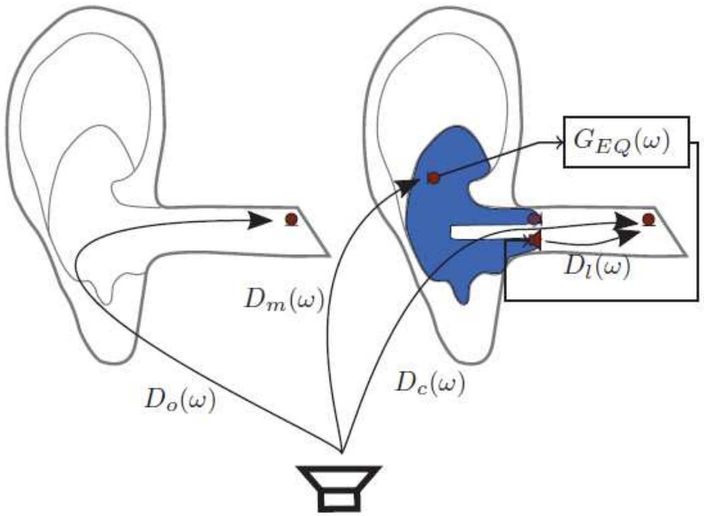
# 1. Transparent sound presentation

- **Single-loudspeaker Equalization**
  - **Goal:** Achieve target sound pressure at aided ear that is (physically or perceptually) equivalent to pressure at open ear (i.e. individual HRTF)

$$\hat{D}_o(\omega) = D_{aided}(\omega) = D_m(\omega) G_{EQ}^{(opt)}(\omega) D_l(\omega) + D_c(\omega),$$

$$G_{EQ}^{(opt)}(\omega) = \frac{\hat{D}_o(\omega) - D_c(\omega)}{D_m(\omega) D_l(\omega)}$$

1. **Estimate target pressure** based on outer microphone(s), e.g., frequency-dependent gain
2. **Equalization with hearing device:** adjust filter *G* such that direct sound + device output = target




- **In-Situ calibration routine,** assuming that pressure at eardrum is known using in-ear microphone

[Denk et al., International Journal of Audiology, 2018] [Denk et al., ITG 2018]

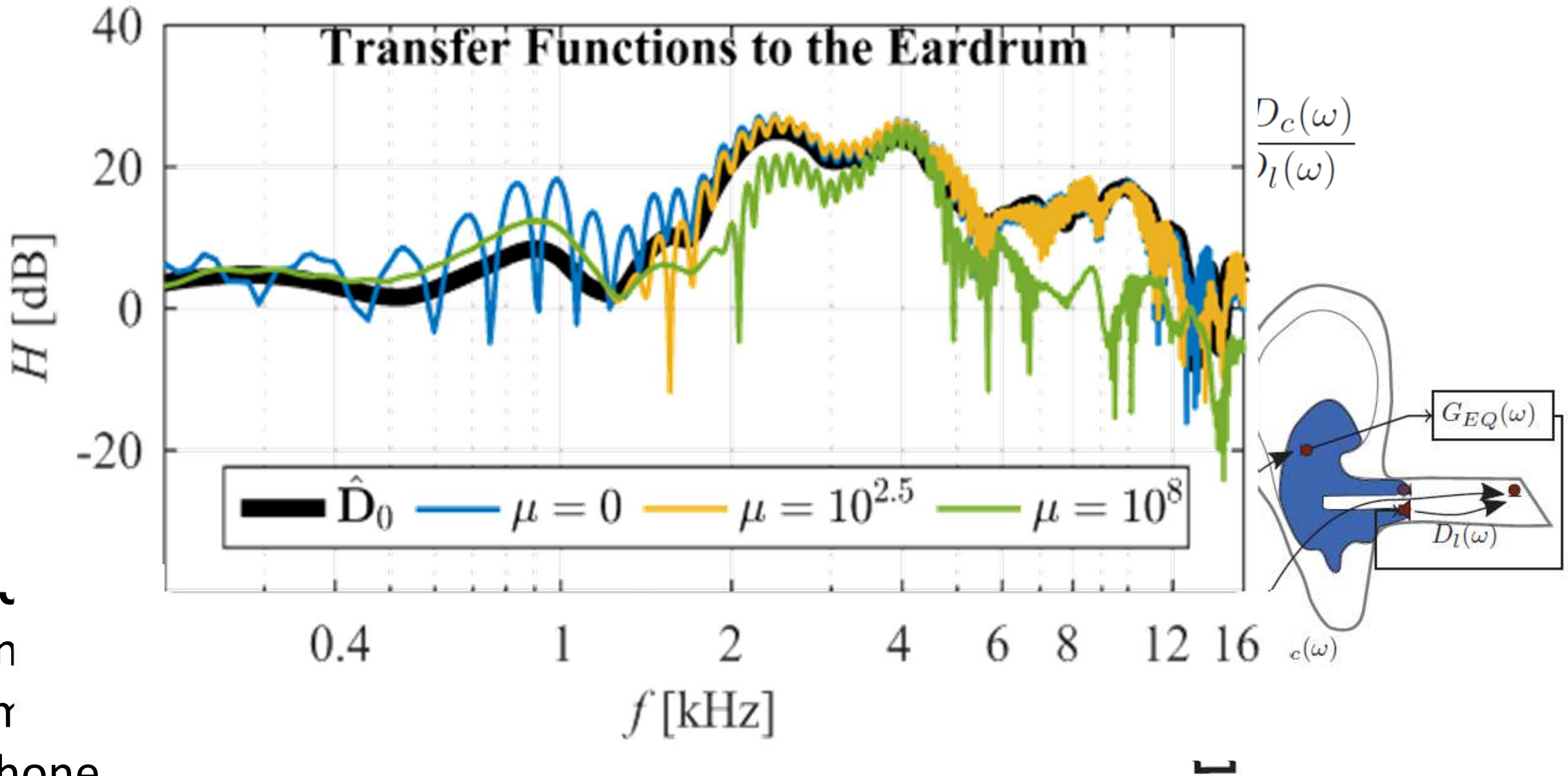
# 1. Transparent sound presentation

- **Single-loudspeaker Equalization**
  - **Goal:** Achieve target sound pressure at aided ear that is (physically or perceptually) equi

$\hat{D}_o$

1.

2.



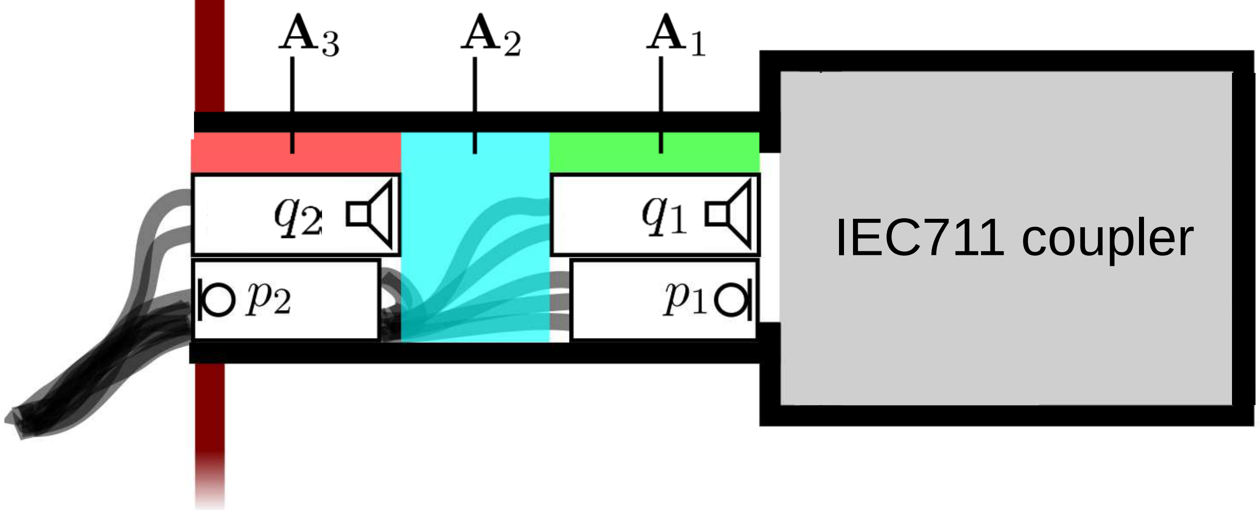

  - **In-Si**
    assumin
    eardrum
    microphone

[Denk et al., International Journal of Audiology, 2018]

[Denk et al., ITG 2018]

# 2. Electro-acoustic model

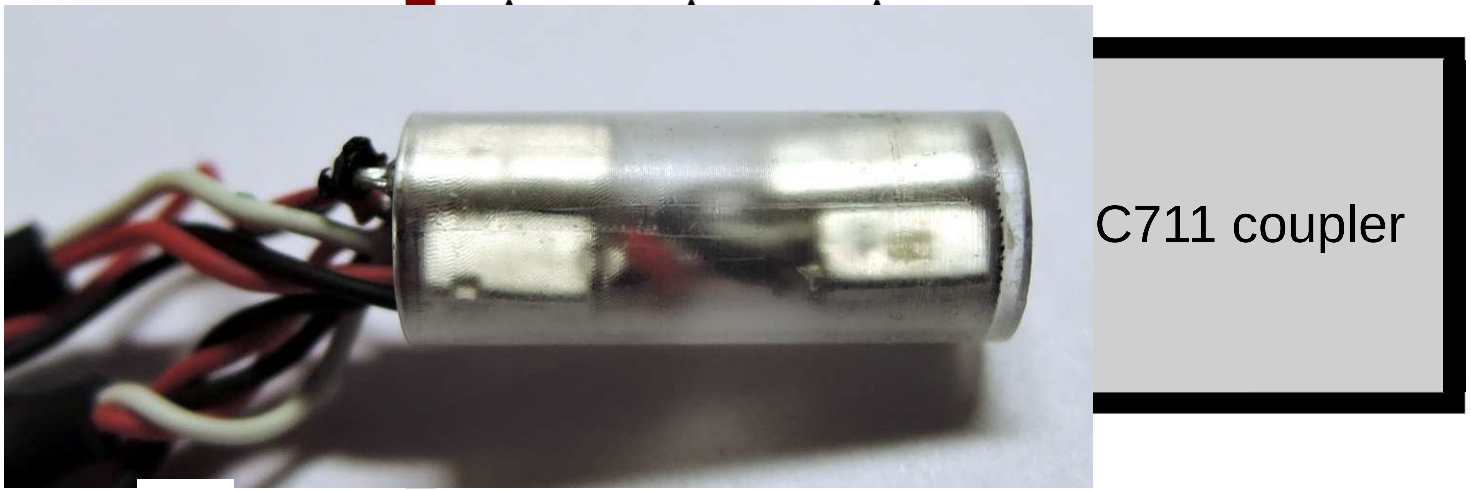
## - Earpiece Model (Fixed)

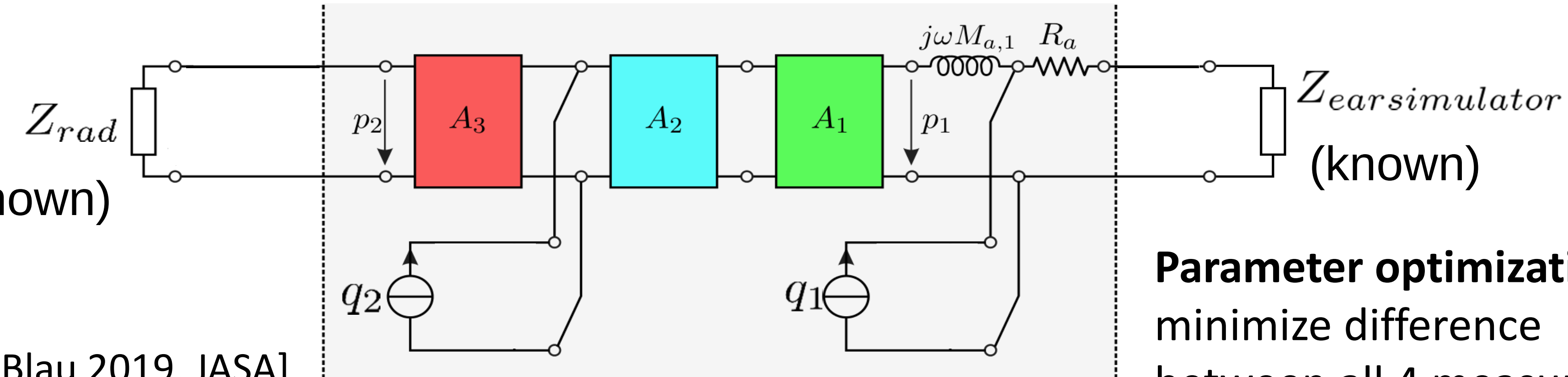



[Vogl and Blau 2019, JASA]

# 2. Electro-acoustic model

## - Earpiece Model (Fixed)



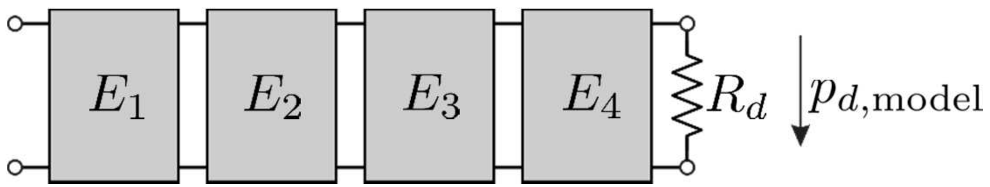



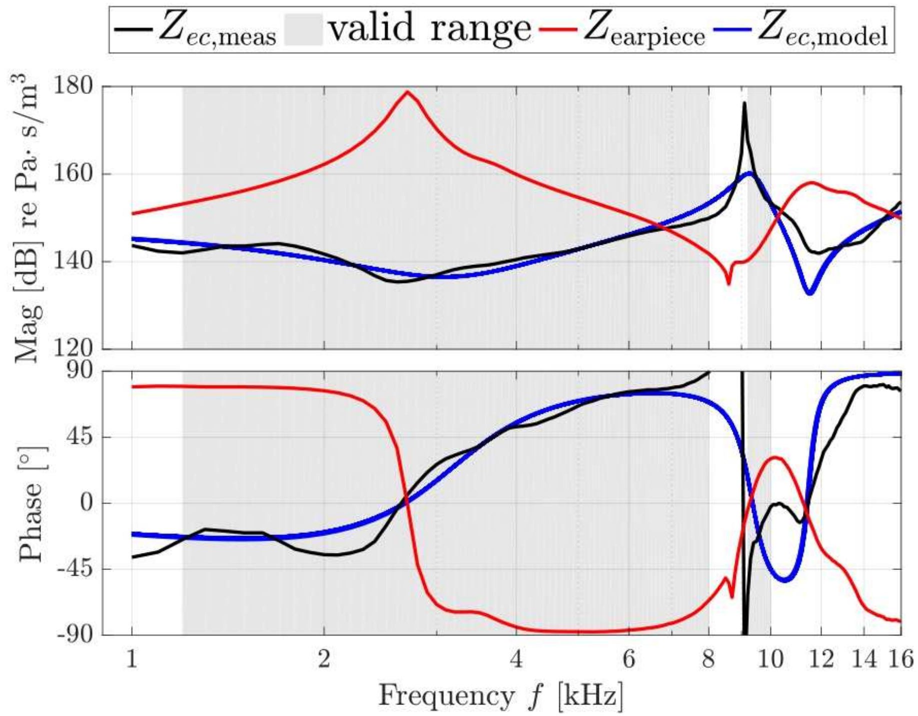

[Vogl and Blau 2019, JASA]

**Parameter optimization:**
minimize difference between all 4 measured and modeled transfer functions

# 2. Electro-acoustic model

## - Ear Canal Model (Individualized)



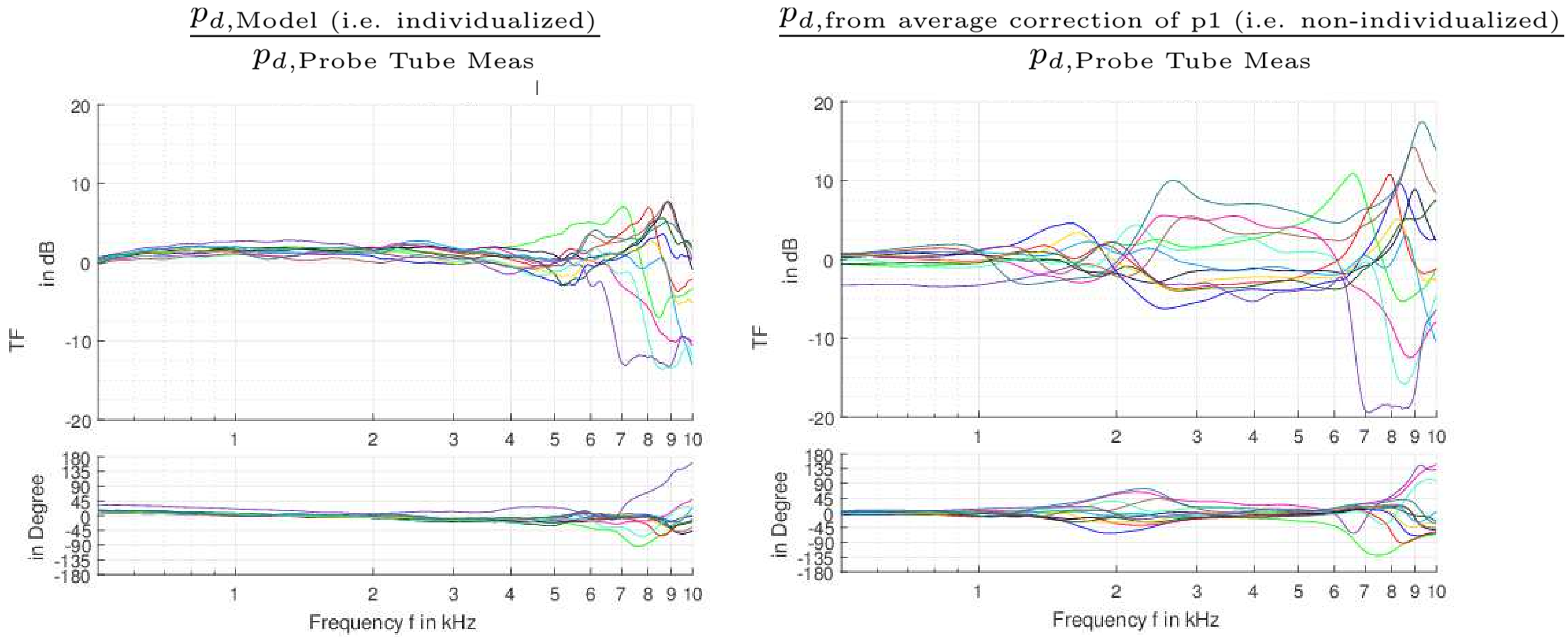




**Parameter optimization** (4 radii, 1 length, 1 resistive load) by minimizing the difference between measured and modeled ear canal (Nelder-Mead simplex optimization procedure):

$$J(p) = \sum_{f_{\mathrm{valid}}} \left(db(Z_{ec,\mathrm{meas}}) - db(Z_{ec,\mathrm{model}}(p))\right)^2 + 10 \cdot \left(arg(Z_{ec,\mathrm{meas}}) - arg(Z_{ec,\mathrm{model}}(p))\right)^2$$

# 2. Electro-acoustic model

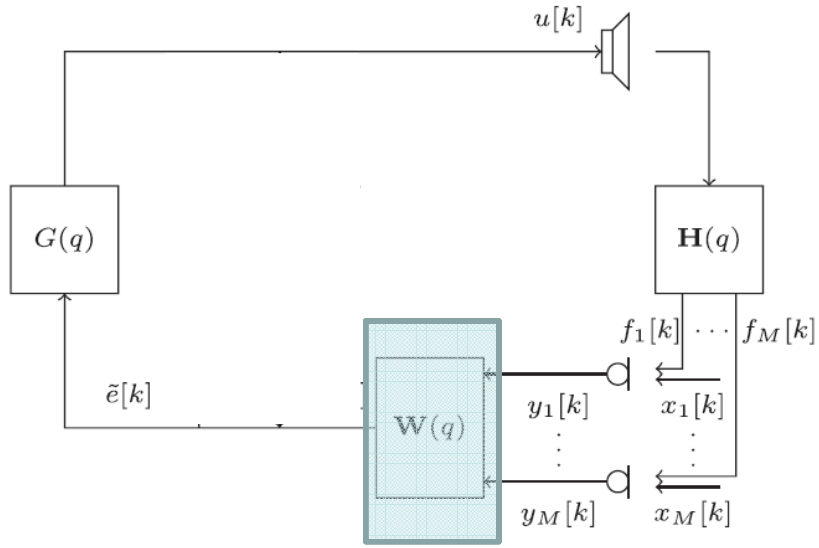
## - Evaluation (sound pressure at ear drum) for 12 subjects




**accurate prediction of sound pressure at ear drum possible using individualized electro-acoustic model up to about 6 kHz**

# 3. Acoustic feedback cancellation

- **Several approaches** for acoustic feedback cancellation in hearing devices:
  1. Feedforward suppression
  2. Adaptive feedback cancellation (e.g., prediction error method)
  3. **Spatial filtering methods** exploiting multiple microphones
- **Approach:** fixed beamformer steering spatial null towards position of hearing aid receiver → theoretically perfect feedback cancellation possible
- Similar principle possible with **multiple receivers** (active feedback cancellation)



# 3. Acoustic feedback cancellation

- **Approach:** reduce acoustic feedback in the vent microphone by steering a (robust) spatial null towards the hearing aid receiver
- Perfect feedback cancellation if $\mathbf{H}^T(q)\mathbf{W}(q) = 0$
- **Different cost functions to design fixed beamformer:**
  - Requires (multiple) measurements of acoustic feedback paths
  - Additional constraint to preserve incoming signal

**Optimization Criteria**

- Residual feedback power (LS):

$$\min_{\mathbf{w}} \sum_{i=1}^{I} \|\mathbf{H}_i^T \mathbf{w}\|_2^2$$

- Maximum stable gain (MM):

$$\min_{\mathbf{w}} \max_{i,\omega_n} |\mathbf{H}_i^H(\omega_n)\mathbf{W}(\omega_n)|$$

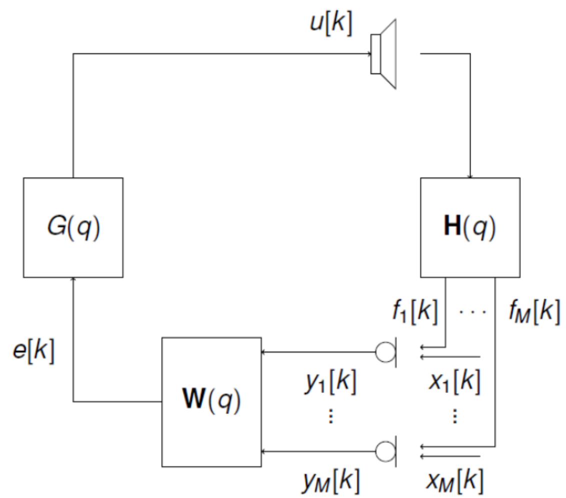
**Constraints**

- Fixed delay:

$$\mathbf{w}_{m_0} = [0 \ldots 0\ 1\ 0 \ldots 0]^T$$

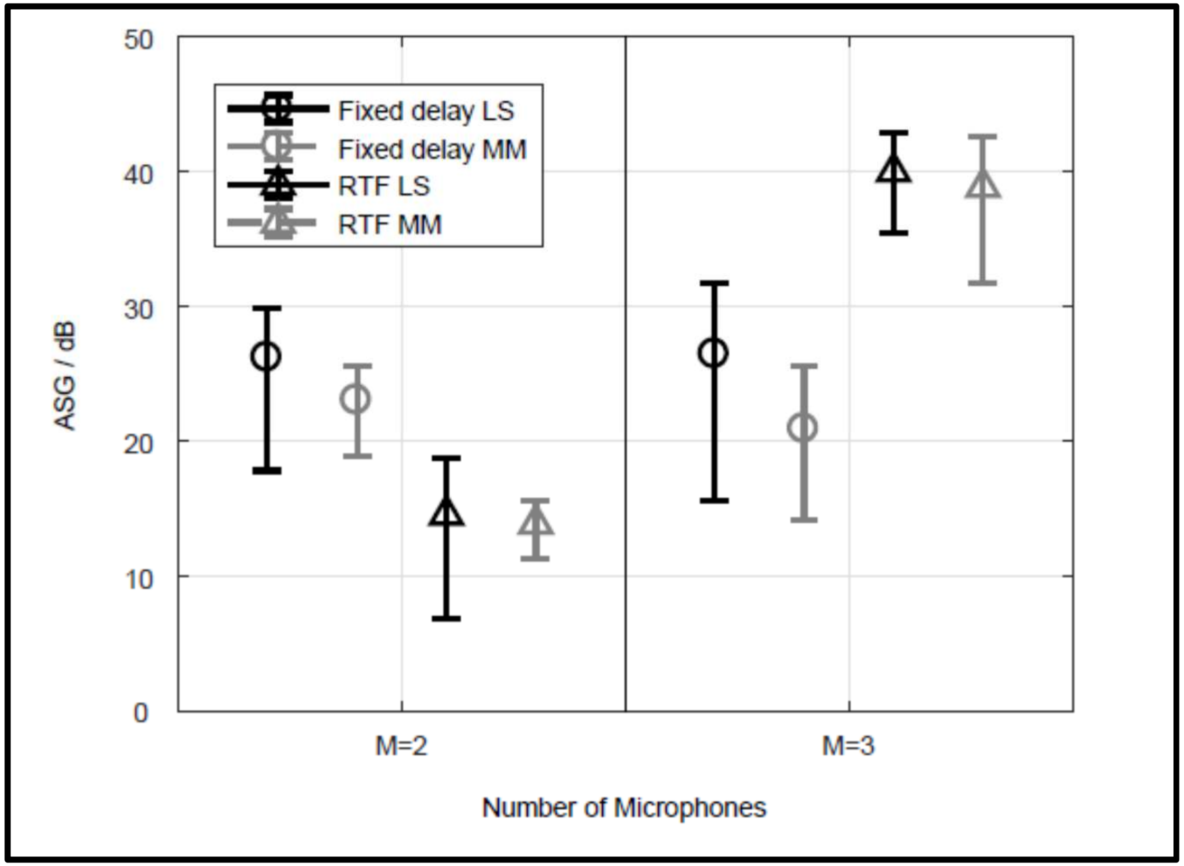
- Relative transfer function (RTF):

$$\mathbf{D}_{m_0}\mathbf{w} = [1\ 0 \ldots 0]^T$$




[Schepker et al., IWAENC 2016, ICASSP 2017, EUSIPCO 2017, IEEE TASLP 2019]

# 3. Acoustic feedback cancellation



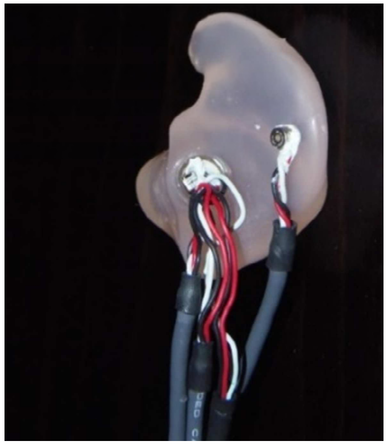

Proposed fixed beamformer allows for robust reduction of acoustic feedback of up to 40dB

[Schepker et al., IEEE TASLP 2019]

# Real-time implementation

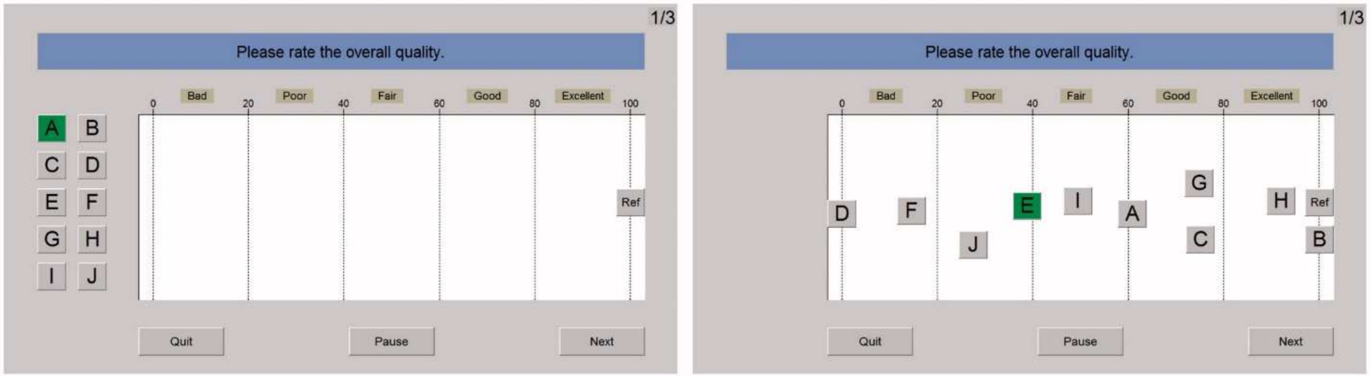
- Custom prototype
- RME Fireface UCX
- Algorithms implemented on Master Hearing Aid (MHA) run on Intel NUC PC
- Input-Output latency of 6.5 ms

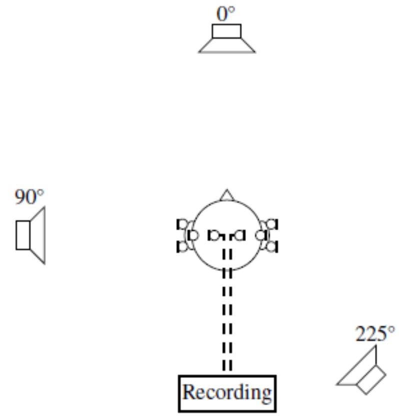
openMHA



# Subjective Quality Evaluation

- **Subjects:** N=15 self-reported normal-hearing
- **Task:** Evaluate overall quality compared to open ear in a MUSHRA-like framework
- **Stimuli:** Pre-recorded signals using KEMAR placed in varechoic lab presented over Sennheiser HD650 headphones

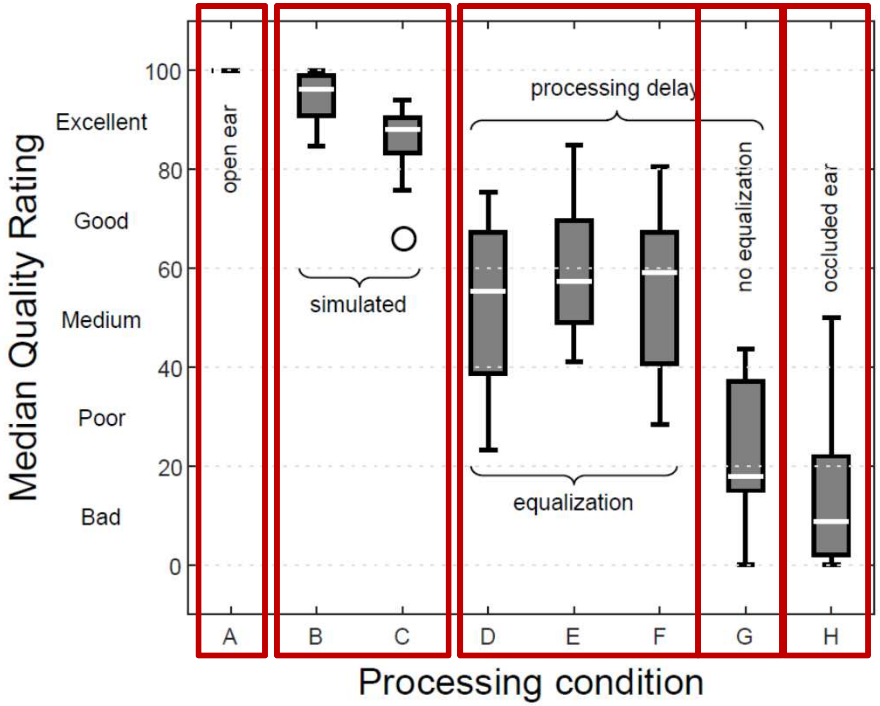



[Schepker et al. 2019, AES Conference Headphone Technology]

# Subjective Quality Evaluation

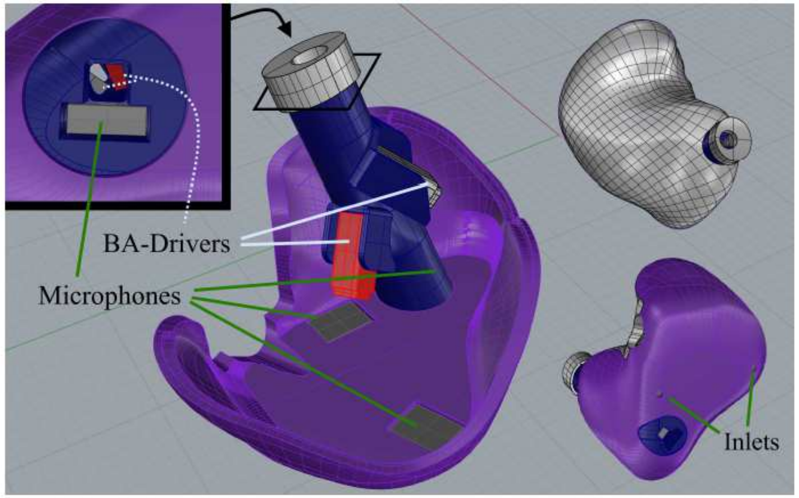
- **Influence of Processing condition:**
  - Equalization significantly improves quality compared to no equalization
  - Target definition very similar quality compared to open ear
  - Processing delay is most crucial limiting factor (comb filtering effects)
  - Absolute ratings have to be interpreted with care (direct comparison with open ear in practice difficult)



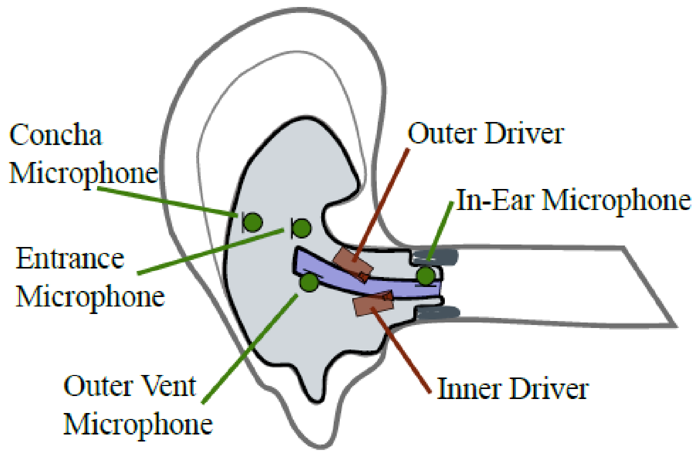

[Schepker et al. 2019, AES Conference Headphone Technology]

# Novel Hardware Design

- One-size-fits-all design: fits about 90% of human ears
- Vent: **2 microphones, 2 receivers**
- Concha: **2 microphones**
- Two versions: vented + closed
- ***Available soon at InEar/Hoertech***








[Denk et al., *AES Conference Headphone Technology*, 2019]

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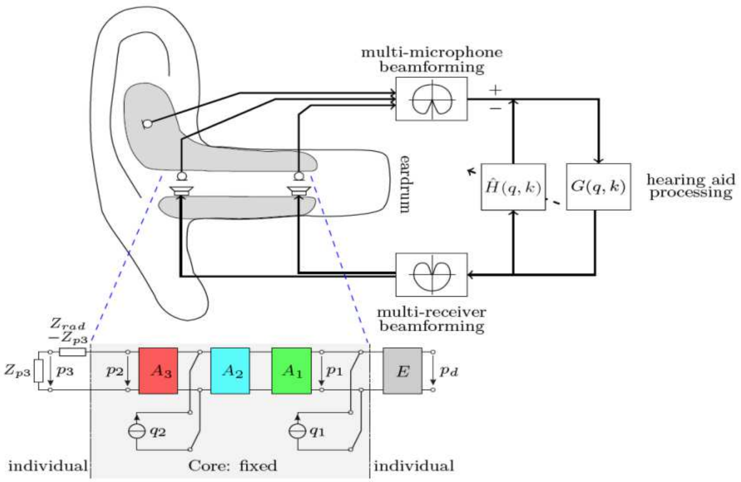
Fraunhofer IDMT
Hearing4all

# Conclusion

- **Acoustically transparent hearing device:**
  - Custom earpiece with multiple integrated microphones and receivers
  - Allows for individualized sound pressure equalization and beamforming for acoustic feedback cancellation
    - **Transparency mode almost indistinguishable from open ear canal in blind comparison**
    - **Comb-filtering effects are the crucial limiting factors**
    - **Robust ASG improvement of up to 40 dB using fixed beamformer**
- **Real-time demonstrator available**

# Current / Next steps

- **Sound pressure equalization:**
  - Integration of *individualized* electro-acoustic model (ear canal)
  - Improve calibration routine (not requiring additional equipment)
  - Reduce latency to avoid comb filtering
- **Combined solutions for equalization and feedback cancellation** (exploiting multiple microphones and receivers)
- Integration with **active noise and occlusion control**




# Acknowledgments / references


- F. Denk et al., "The acoustically transparent hearing device: Towards integration of individualized sound equalization, electro-acoustic modelling and feedback cancellation," in Proc. 1st International Conference on Challenges in Hearing Assistive Technology (CHAT), Stockholm, Sweden, Aug. 2017, pp. 89-94.
- F. Denk et al., "An Individualised Acoustically Transparent Earpiece for Hearing Devices," *International Journal of Audiology,* vol. 57, no. S3, pp. S62-S70, June 2018.
- F. Denk et al., "A one-size-fits-all earpiece with multiple microphones and drivers for hearing device research," in *Proc. AES Conference on Headphone Technology*, San Francisco, USA, Aug. 2019.
- F. Denk et al., „Equalization filter design for achieving acoustic transparency in a semi-open fit hearing device," in *Proc. ITG Conference on Speech Communication*, Oldenburg, Germany, Oct. 2018, pp. 226-230.
- H. Schepker et al., „Multi-loudspeaker equalization for acoustic transparency in a custom hearing device," in *Proc. ITG Conference on Speech Communication*, Oldenburg, Germany, Oct. 2018, pp. 31-35.
- H. Schepker, et al., "Subjective sound quality evaluation of an acoustically transparent hearing device," in *Proc. AES Conference on Headphone Technology*, San Francisco, USA, Aug. 2019.
- H. Schepker, S. Doclo, "Active feedback suppression for hearing devices exploiting multiple loudspeakers," in *Proc. IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, New Paltz, USA, Oct. 2019.
- H. Schepker, et al., "Null-steering beamformer-based feedback cancellation for multi-microphone hearing aids with incoming signal preservation," *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, vol. 27, no. 4, pp. 679-691, Apr. 2019.
- S. Vogl and M. Blau, "Individualized prediction of the sound pressure at the eardrum for an earpiece with integrated receivers and microphones," *The Journal of the Acoustical Society of America*, vol. 145, no. 2, pp. 917-930, Feb. 2019.