Integrating Beamforming with Binaural Sound Reproduction using a Spherical Microphone Array

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Outline

Introduction

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  - Background noise.
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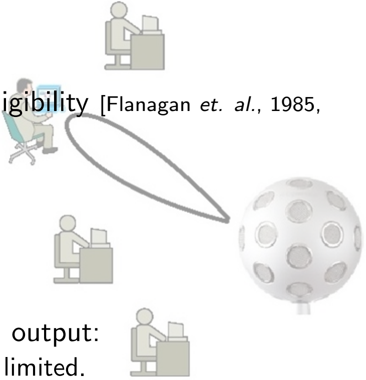
- Usually employing single-channel output:
  - Inherent spatial information is limited.
  - More compatible with machine receiver applications.



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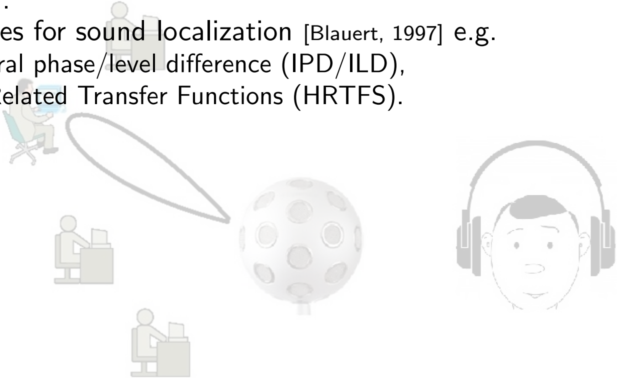
  - interaural phase/level difference (IPD/ILD),
  - Head Related Transfer Functions (HRTFS).



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- Beamformers which preserve binaural cues:
  - Binaural Wiener filtering [Klasen *et. al.*, 2007, Doclo *et. al.*, 2009].
  - Partial communication between sensors in hearing aids [Bertrand and Moonen, 2009, Bertrand and Moonen, 2010].
  - Model-based dereverberation for binaural cues preservation [Jeub *et. al.*, 2010].
  - Binaural extension of spectral-subtraction dereverberation [Tsildis *et. al.*, 2011].

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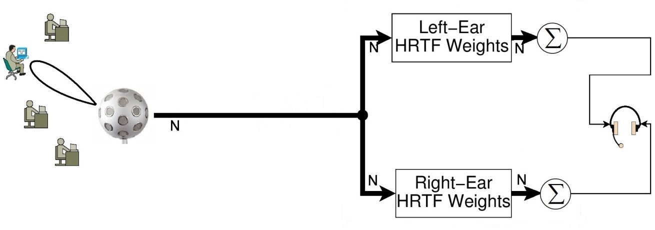
- The preserved spatial information is limited to the target source.

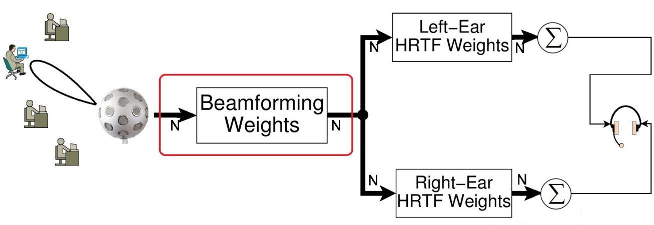
Binaural Reproduction- Plane Wave Domain



- Every direction of arrival is given its own binaural cue using the HRTFs. [Rafaely and Avni, 2010],

$$y_{l/r}(k) = \int_{\Omega \in S^2} H_{l/r}(k, \Omega) a(k, \Omega) d\Omega$$

Generalized Spherical Beamforming



- The product is multiplied by a beamforming weight function to suppress interference [Shabtai and Rafaely, 2014],

$$y_{l/r}(k) = \int_{\Omega \in S^2} w^*(k,\Omega) H_{l/r}(k,\Omega) a(k,\Omega) d\Omega$$

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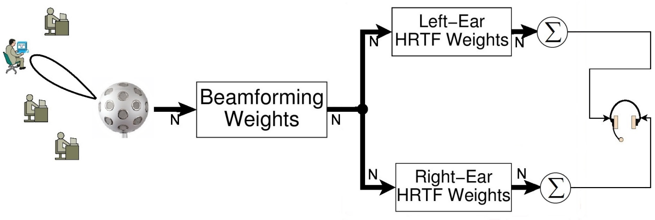

- The GSB incorporates beamforming and binaural reproduction [Shabtai and Rafaely, 2014],

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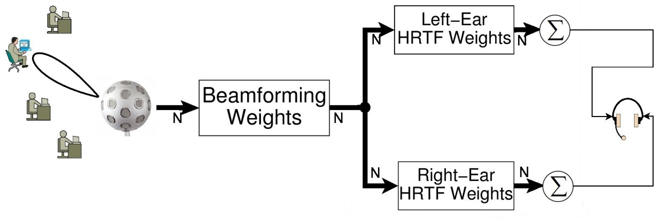

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$$y_{l/r}(k) = \int_{\Omega \in S^2} \underbrace{w^*(k,\Omega)H_{l/r}(k,\Omega)}_{\widetilde{w}^*_{l/r}(k,\Omega)} a(k,\Omega)d\Omega$$

- $\widetilde{w}_{l/r}(k,\Omega) = w(k,\Omega)H^*_{l/r}(k,\Omega)$- Generalized weight function.

Truncation Problem

- The GSB in the Spherical Harmonics domain,

$$y(k) = \int w^*(k,\Omega)H(k,\Omega)a(k,\Omega)d\Omega = \sum_{n_a=0}^{N_a} \sum_{m_a=-n_a}^{n_a} \widetilde{w}^*_{n_a m_a}(k) a_{n_a m_a}(k)$$

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- High orders of $w(k,\Omega)$ and $H(k,\Omega)$ are reflected in low orders of $\widetilde{w}(k,\Omega)$

No truncation of $\widetilde{w}(k, \Omega)$

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- How is the directivity of the GSB affected?
- Given N_w, does an increase in N_h improves the approximation of $H_{l/r}(k,\Omega)$?

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  - **Binaural Error(BE)**, binaural reproduction effectiveness estimation.

$$\frac{y_l(\Omega)}{y_r(\Omega)} \overset{(N_w+N_h)\leq N_a}{=} \frac{H_l(\Omega)}{H_r(\Omega)}$$

BLE- Normalized ILD error.
BPE- Normalized IPD error.

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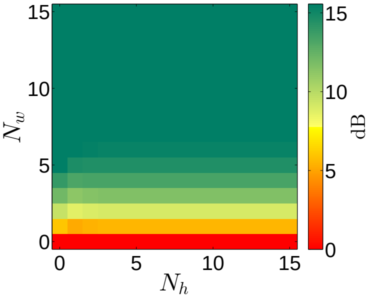
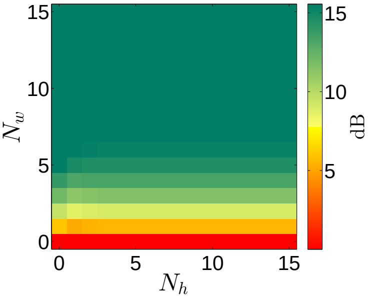
- **Smoothing**- The results were averaged over the look direction, Ω_l, to compensate for the HRTF variance.

Simulations- DF results



(a) Left ear



(b) Right ear

Figure: Average DF for $N_a = 5$ at frequency of 1000Hz.

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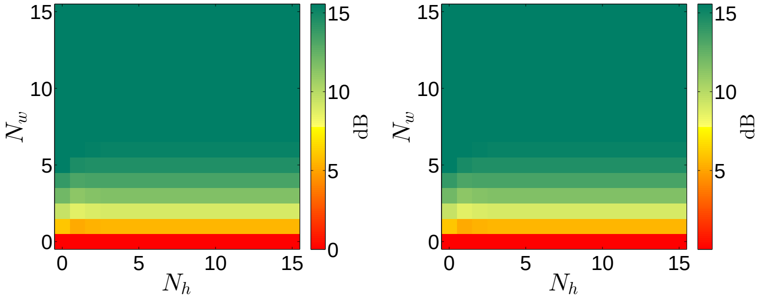
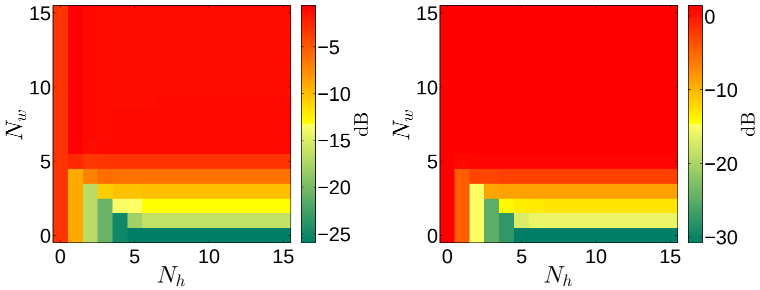


(a) Left ear (b) Right ear

Figure: Average DF for $N_a = 5$ at frequency of 1000Hz.

- The DF is mainly effected by N_w.

Simulations- BE results



(a) BLE (b) BPE

Figure: Average BE for $N_a = 5$ at frequency of 1000Hz.

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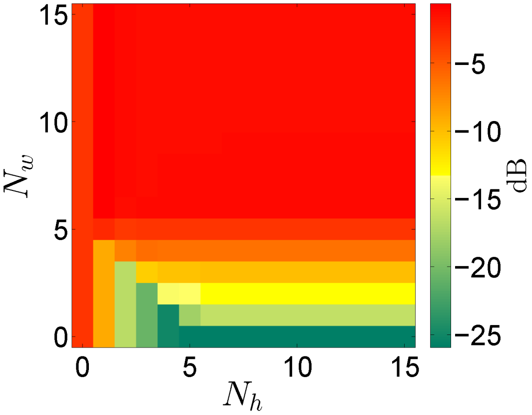

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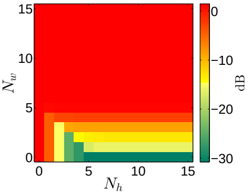

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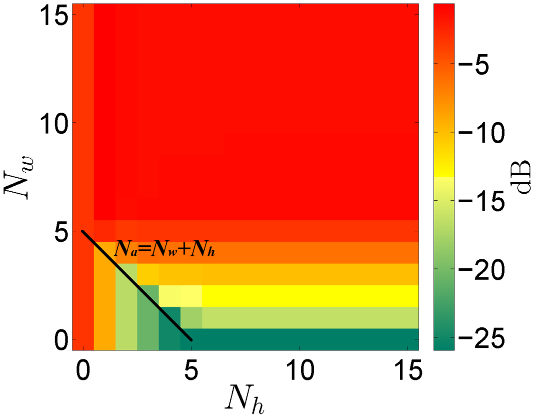

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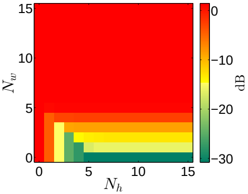

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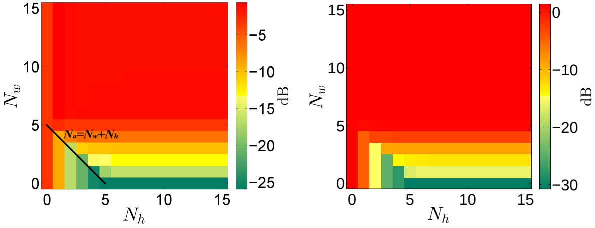

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- Best configurations on the line $N_a = N_h + N_w$.

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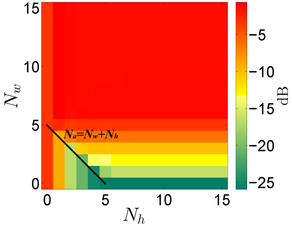

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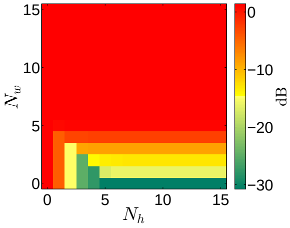

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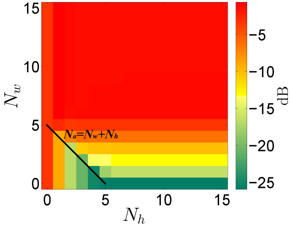

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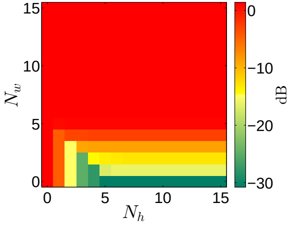

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Results

- Best configurations on the line $N_a = N_h + N_w$.
- Spatial selectivity vs. binaural reproduction trade-off.
- Is this relation perceptually noticeable?

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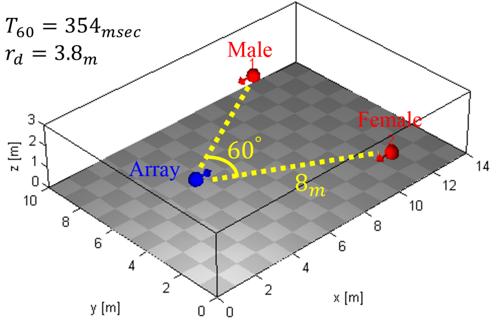

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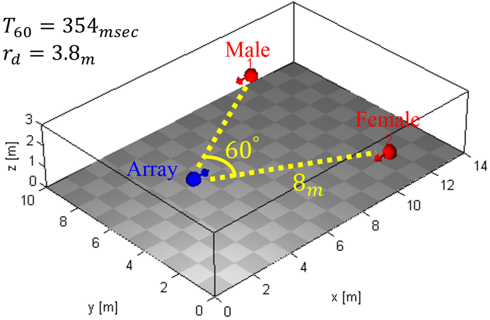

- **Criteria answered**:
  - **Spatial perception**- Realism of the sound scene.
  - **Interference suppression**- Clearly perceive the male speaker without the female speaker interfering.

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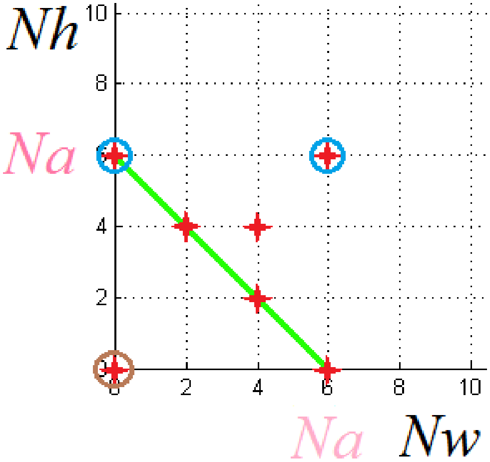

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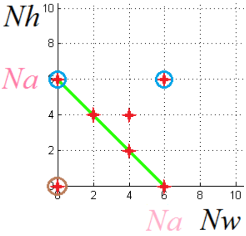

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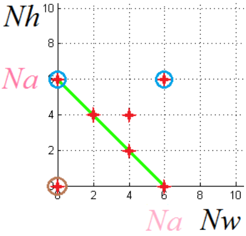

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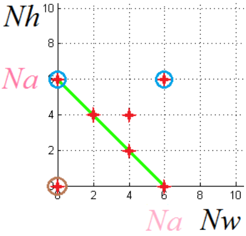

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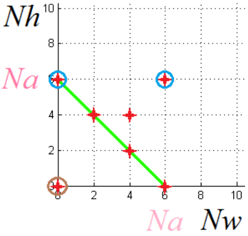

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- **Playback**- Sound Scape Renderer (SSR) auralization engine.

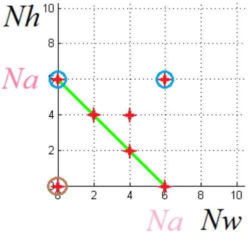
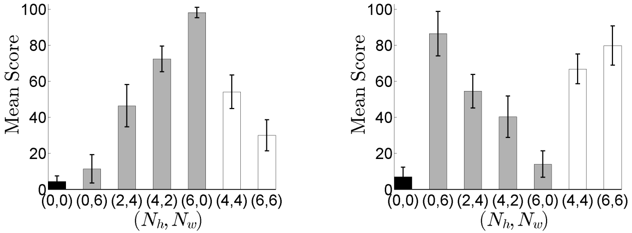


Figure: Test stimuli setup points

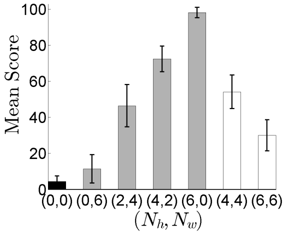
Listening Test- Results



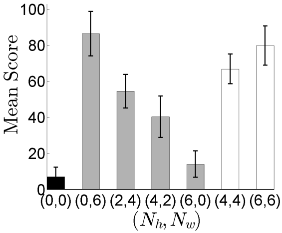
(a) Spatial perception (b) Interference suppression

Figure: Listening test results for $N_a = 6$

Listening Test- Results



(a) Spatial perception



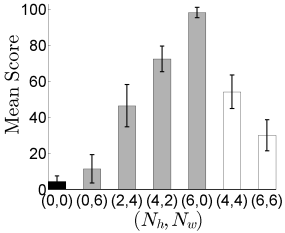
(b) Interference suppression

Figure: Listening test results for $N_a = 6$

Results

- On-the-line trade off, spatial selectivity vs. spatial perception.

Listening Test- Results



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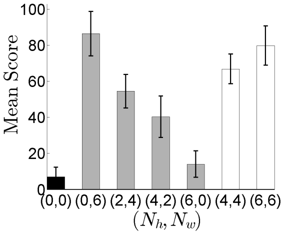


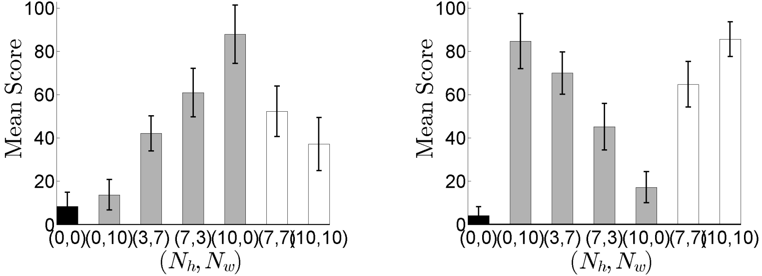
(b) Interference suppression

Figure: Listening test results for $N_a = 6$

Results

- On-the-line trade off, spatial selectivity vs. spatial perception.
- Potential future research for out-of-line stimuli.

Listening Test- Results



(a) Spatial perception

(b) Interference suppression

Figure: Listening test results for $N_a = 10$

Conclusions

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Conclusions

- Limited $N_a \rightarrow$ Spatial selectivity and spatial perception trade-off.
- Expected operation on the line $N_a = N_h + N_w$.
- Encapsulation of beamforming, binaural reproduction, or a mixed mode of operation.
- A Tunable GSB is proposed in order to benefit from the advantage of the two methods integration in a varying environment.

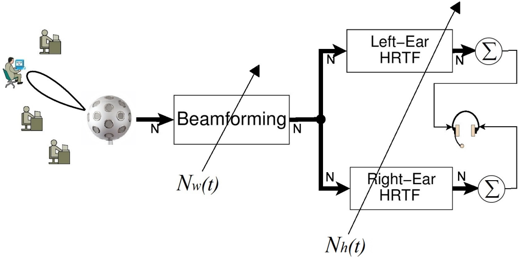

Figure: Tunable GSB

Thank you

GSB Evaluation Measures- Binaural Error

- The GSB's output maintain the following relation,

$$\frac{y_l^{\Omega_o}}{y_r^{\Omega_o}} \overset{Na \to \infty}{=} \frac{H_l(\Omega_o)}{H_r(\Omega_o)}$$

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- To account for the ILD and IPD binaural cues, the binaural level error (BLE) and the binaural phase error (BPE) should be examined separately,

$$BLE = \sqrt{\int_{\Omega_o \in S^2} \left(\frac{\left| y_l^{\Omega_o} H_r(\Omega_o) \right| - \left| y_r^{\Omega_o} H_l(\Omega_o) \right|}{\frac{1}{2}\left(\left| y_l^{\Omega_o} H_r(\Omega_o) \right| + \left| y_r^{\Omega_o} H_l(\Omega_o) \right| \right)} \right)^2 d\Omega_o}$$

$$BPE = \sqrt{\int_{\Omega_o \in S^2} \left(\angle \left(y_l^{\Omega_o} H_r(\Omega_o) \right) - \angle \left(y_r^{\Omega_o} H_l(\Omega_o) \right) \right)^2 d\Omega_o}$$