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A Comparative Performance Study of Sound Zoning Methods in a Reflective Environment

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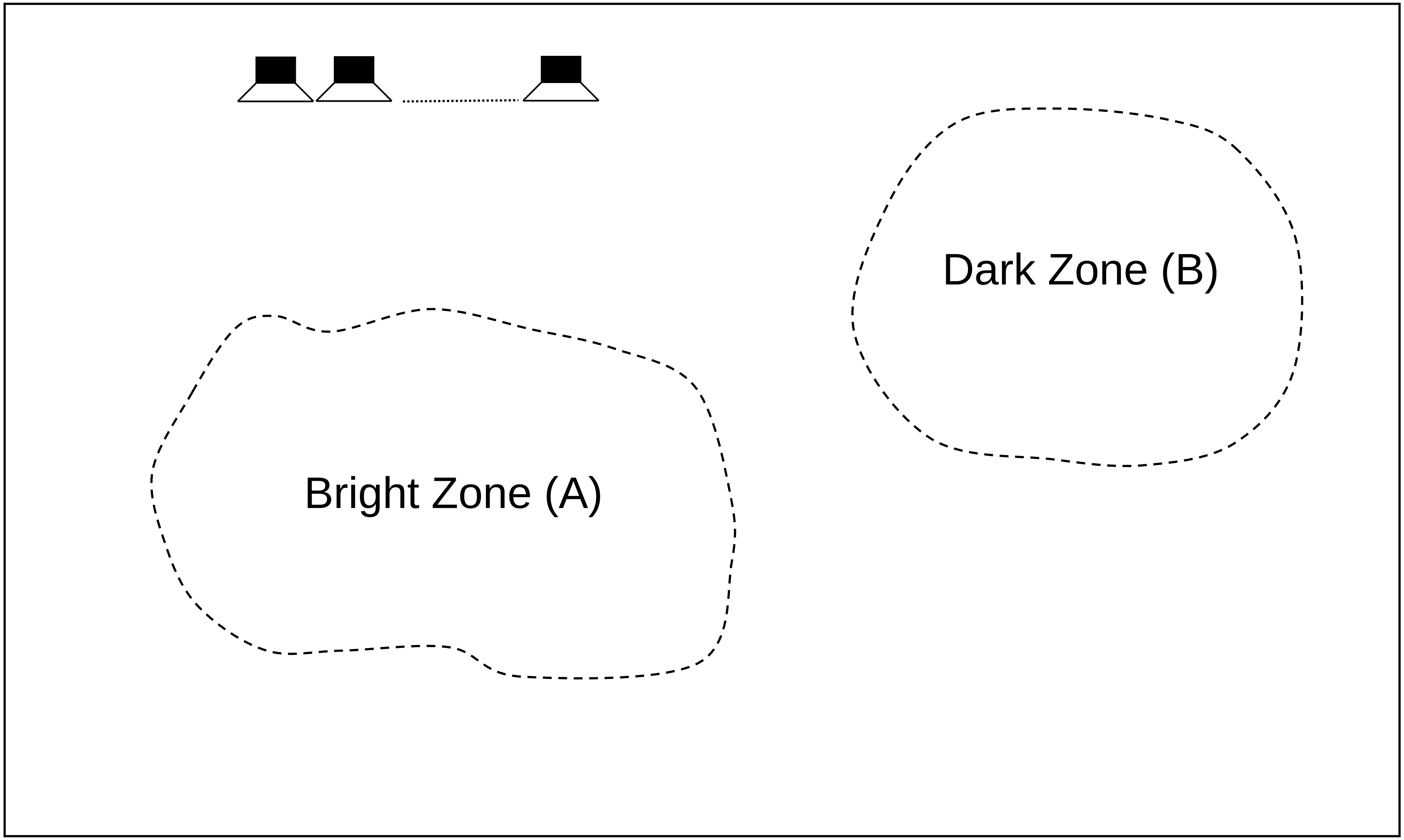
AES 52nd International Conference, Sound Field Control

Paper Session 5: Sound Zones

3rd September 2013

POSZ

Sound Zone Problem



Motivation

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- **Approaches to sound field control**

Sound Focusing	Sound Cancelling	Sound Field Synthesis
Delay and Sum [Veen and Buckley 1988]	**Acoustic Contrast Control** [Choi & Kim 2002]	**Analytical SFS** [Wu and Abhayapala 2010]
Brightness Control [Choi & Kim 2002]	**Acoustic Energy Difference Maximisation** [Shin *et al*. 2010]	**Pressure Matching** [Poletti 2008]

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Brightness Control [Choi & Kim 2002]	**Acoustic Energy Difference Maximisation** [Shin *et al*. 2010]	**Pressure Matching** [Poletti 2008]

- **There are limited examples of comparative evaluation of these methods** [Jacobsen *et al.* 2011, Møller *et al.* 2012, Coleman *et al.* 2013]
- **Also, limited examples of studies investigating performance of these methods under reflective conditions** [Elliott and Jones 2006, Jacobsen *et al.* 2011]

Scope

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- **We compare the performance of key sound zone methods implemented in a room**
- **One representative method from each group: DS, ACC and PM**
- **Two loudspeaker arrays: linear and circular**

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- **We compare the performance of key sound zone methods implemented in a room**
- **One representative method from each group: DS, ACC and PM**
- **Two loudspeaker arrays: linear and circular**
- **Evaluation based on physical metrics:**
  - Acoustic separation between zones (acoustic contrast)
  - Characteristics of the bright zone sound field (planarity)
- **Perceptual evaluation: listening tests based on recordings in the zones to evaluate distraction from the interfering audio**

Outline

1. **Evaluation metrics and sound zone methods**
2. **Experimental setup and sound zone reproduction procedure**
3. **Results based on physical metrics**
4. **Perceptual evaluation: distraction**
5. **Summary and further work**

Physical Evaluation Metrics

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To evaluate acoustic separation between the zones:

- **Acoustic contrast: ratio between average squared pressures in the bright and dark zones. For equal number of microphones in zone A and B:**

$$C_{AB} = 10\log_{10}\left(\frac{\boldsymbol{p}_A^H \boldsymbol{p}_A}{\boldsymbol{p}_B^H \boldsymbol{p}_B}\right)$$

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To evaluate spatial characteristics of bright zone sound field:

- **Planarity** [Jackson *et al.* (2013)]**: ratio of energy in the direction of principal plane wave component to total energy in the bright zone**

$$\eta_\mathrm{A} = \frac{\sum_i w_i \boldsymbol{u}_i \cdot \boldsymbol{u}_\alpha}{\sum_i w_i}$$

$$i = 1 \ldots N, \text{ where } N \text{ is the number of angles}$$

$$\alpha = \mathbf{arg\,max}_\mathrm{i} w_i$$

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Control Methods

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Sound Focusing: Delay and Sum Beamforming

$$\boldsymbol{q}_{DS} = [e^{-j\omega\tau_1} \quad e^{-j\omega\tau_2} \quad \cdots \quad e^{-j\omega\tau_L}]^T$$

$\tau_1, \tau_2, \ldots, \tau_L$ - time delays with respect to the largest distance to bright zone

Control Methods

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$\tau_1, \tau_2, \dots, \tau_L$ - time delays with respect to the largest distance to bright zone

Sound Cancelling: Acoustic Contrast Control

$$J_{ACC} = \frac{\boldsymbol{p}_A^H \boldsymbol{p}_A}{\boldsymbol{p}_B^H \boldsymbol{p}_B} = \frac{\boldsymbol{q}^H \boldsymbol{G}_A^H \boldsymbol{G}_A \boldsymbol{q}}{\boldsymbol{q}^H \boldsymbol{G}_B^H \boldsymbol{G}_B \boldsymbol{q}}$$

$\boldsymbol{q}_{ACC}$ is proportional to eigenvector of the matrix $[\boldsymbol{G}_B^H \boldsymbol{G}_B]^{-1} \boldsymbol{G}_A^H \boldsymbol{G}_A$ that corresponds to largest eigenvalue. With regularisation: $[\boldsymbol{G}_B^H \boldsymbol{G}_B + \lambda \boldsymbol{I}]^{-1} \boldsymbol{G}_A^H \boldsymbol{G}_A$

Control Methods

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Sound Focusing: Delay and Sum Beamforming

$$\boldsymbol{q}_{DS} = [e^{-j\omega\tau_1} \quad e^{-j\omega\tau_2} \quad \dots \quad e^{-j\omega\tau_L}]^T$$

$\tau_1, \tau_2, \dots, \tau_L$ - time delays with respect to the largest distance to bright zone

Sound Cancelling: Acoustic Contrast Control

$$J_{ACC} = \frac{\boldsymbol{p}_A^H \boldsymbol{p}_A}{\boldsymbol{p}_B^H \boldsymbol{p}_B} = \frac{\boldsymbol{q}^H \boldsymbol{G}_A^H \boldsymbol{G}_A \boldsymbol{q}}{\boldsymbol{q}^H \boldsymbol{G}_B^H \boldsymbol{G}_B \boldsymbol{q}}$$

$\boldsymbol{q}_{ACC}$ is proportional to eigenvector of the matrix $[\boldsymbol{G}_B^H \boldsymbol{G}_B]^{-1} \boldsymbol{G}_A^H \boldsymbol{G}_A$ that corresponds to largest eigenvalue. With regularisation: $[\boldsymbol{G}_B^H \boldsymbol{G}_B + \lambda \boldsymbol{I}]^{-1} \boldsymbol{G}_A^H \boldsymbol{G}_A$

Sound Field Synthesis: Pressure Matching

$$J_{PM} = \boldsymbol{e}^H \boldsymbol{e} + \lambda \boldsymbol{q}^H \boldsymbol{q}$$

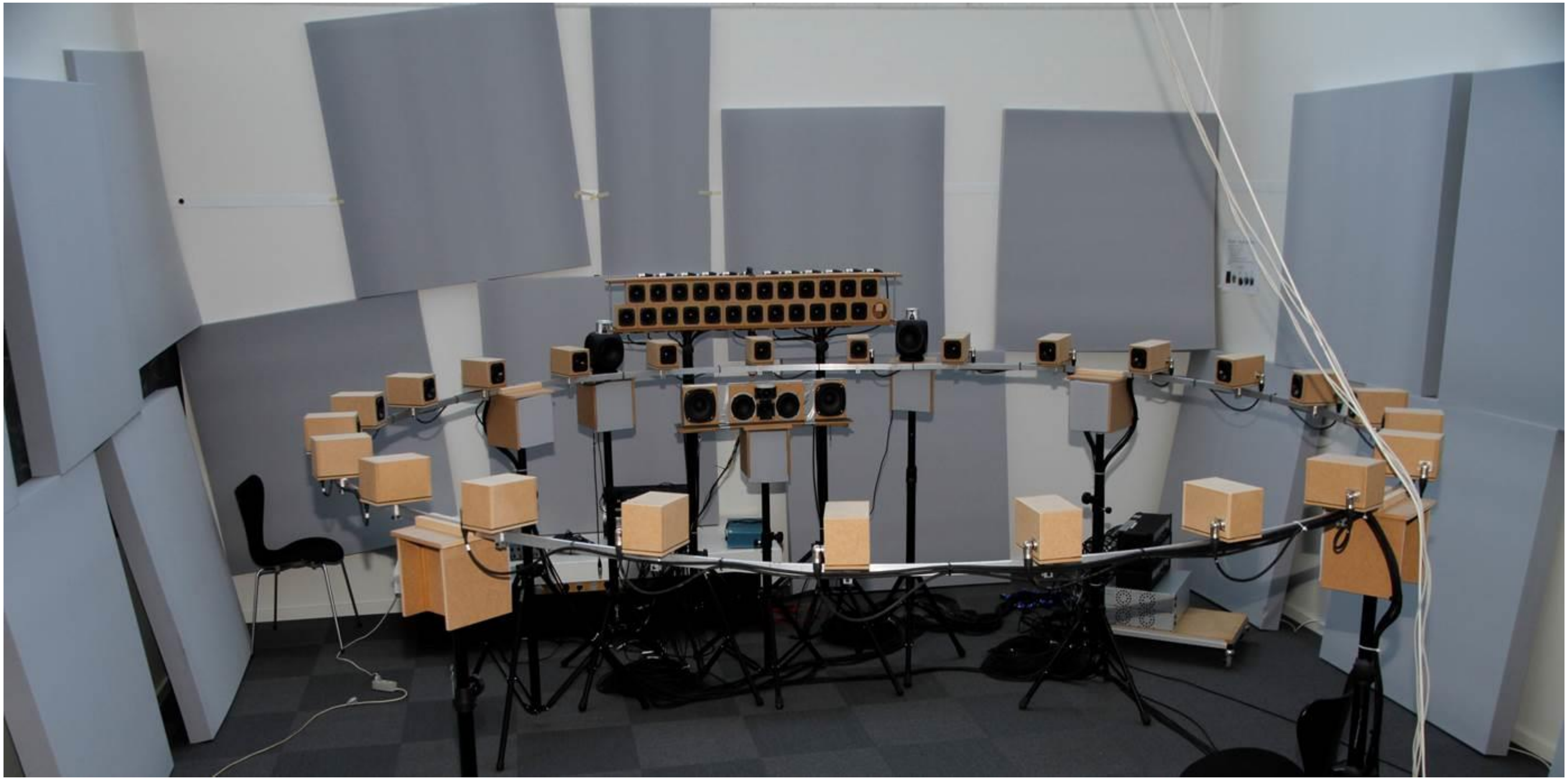
$\boldsymbol{e}$ – error between the desired sound field $\boldsymbol{d}$ and reproduced sound field

$\boldsymbol{q}^H \boldsymbol{q}$ – power constraint

λ – regularisation parameter

$$\boldsymbol{q}_{PM} = (\boldsymbol{G}^H \boldsymbol{G} + \lambda \boldsymbol{I})^{-1} \boldsymbol{G}^H \boldsymbol{d}$$

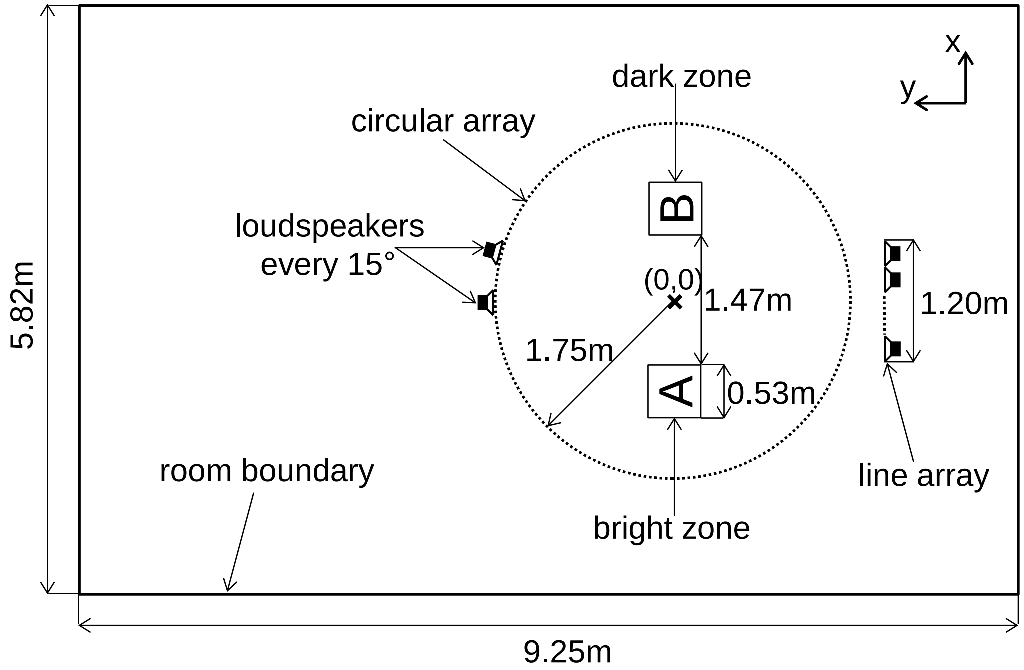
Experimental Setup
Overview



Experimental Setup

Details

$V \approx 320\ m^3$



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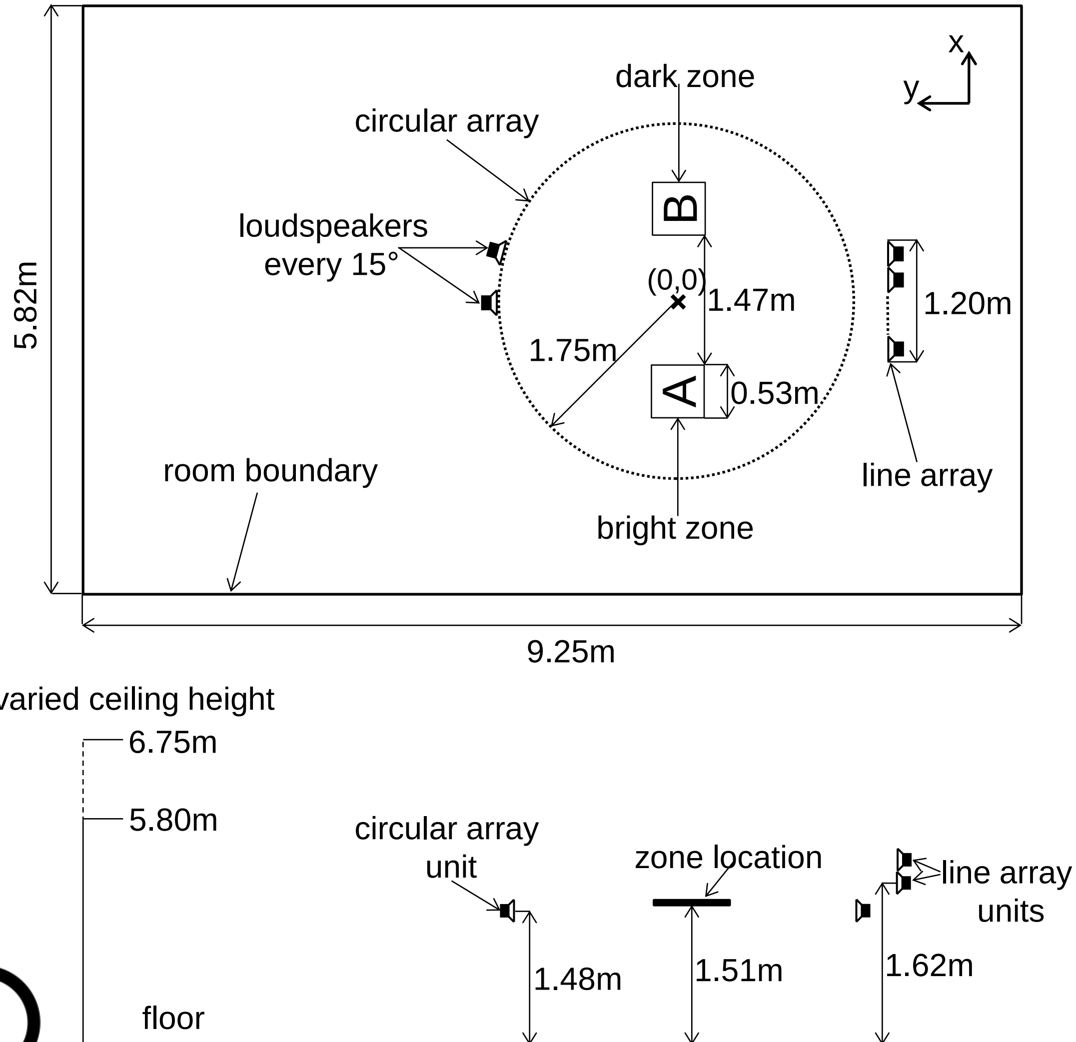

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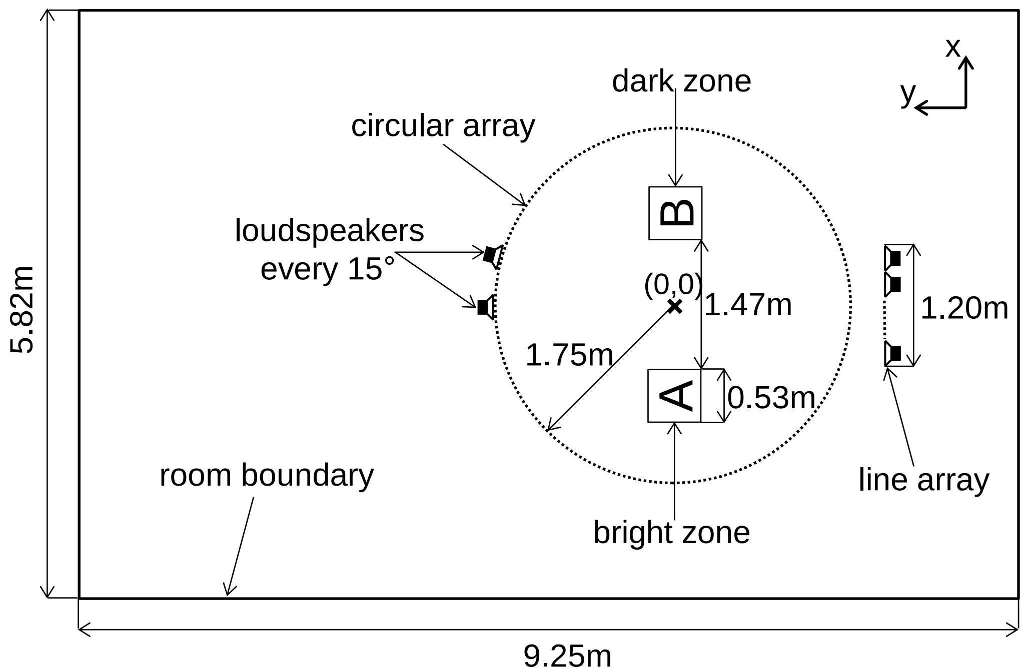
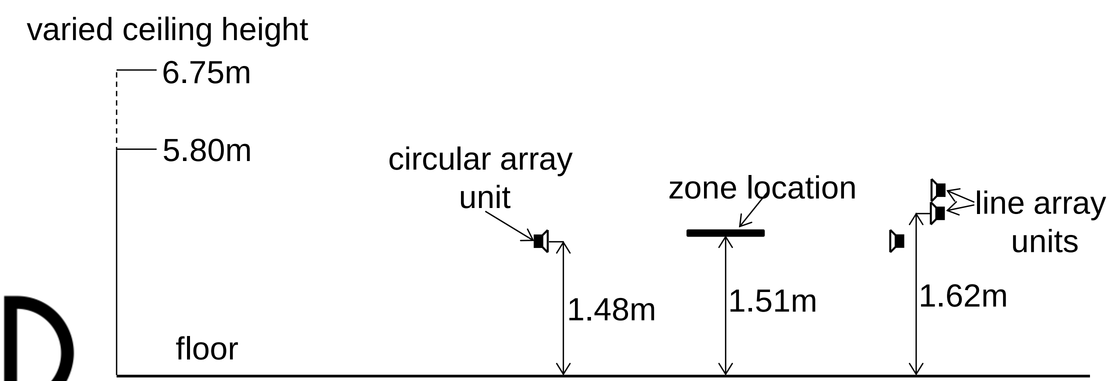


Centre Frequency (Hz)	RT60 (s)
250	0.33
500	0.30
1000	0.28
2000	0.27
4000	0.25



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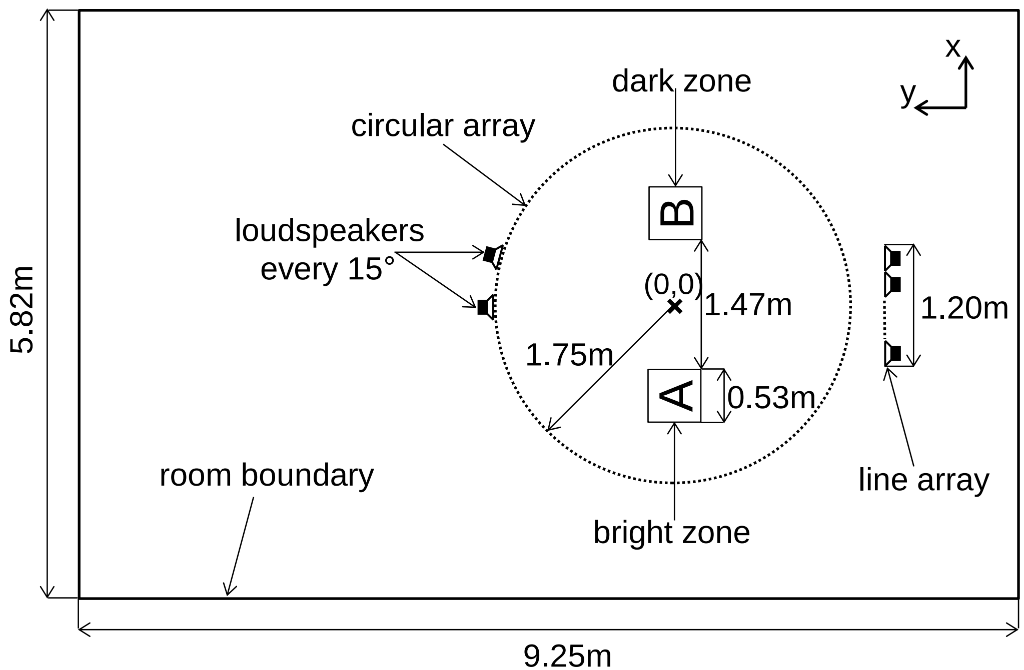

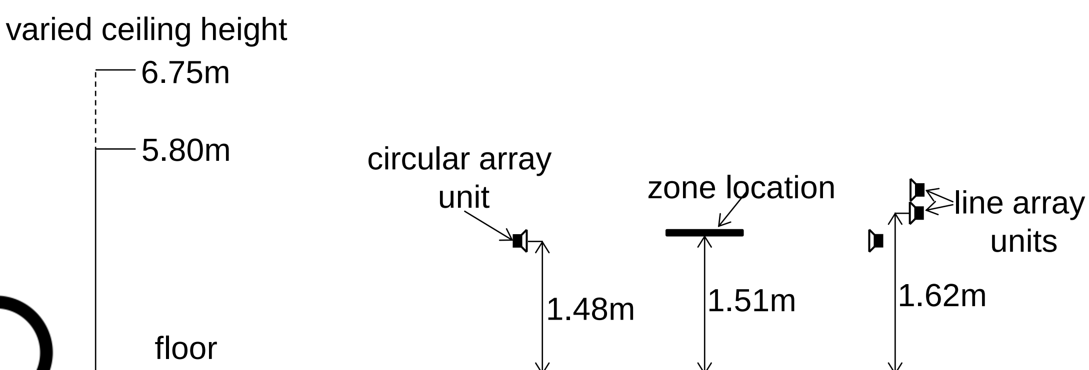

Centre Frequency (Hz)	RT60 (s)
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- **Setup: 72 mics per zone**
- **Monitoring: 144 mics per zone**
- **Numerically independent responses included in performance predictions to reduce bias** [Akeroyd *et al.* 2007]

System Diagram

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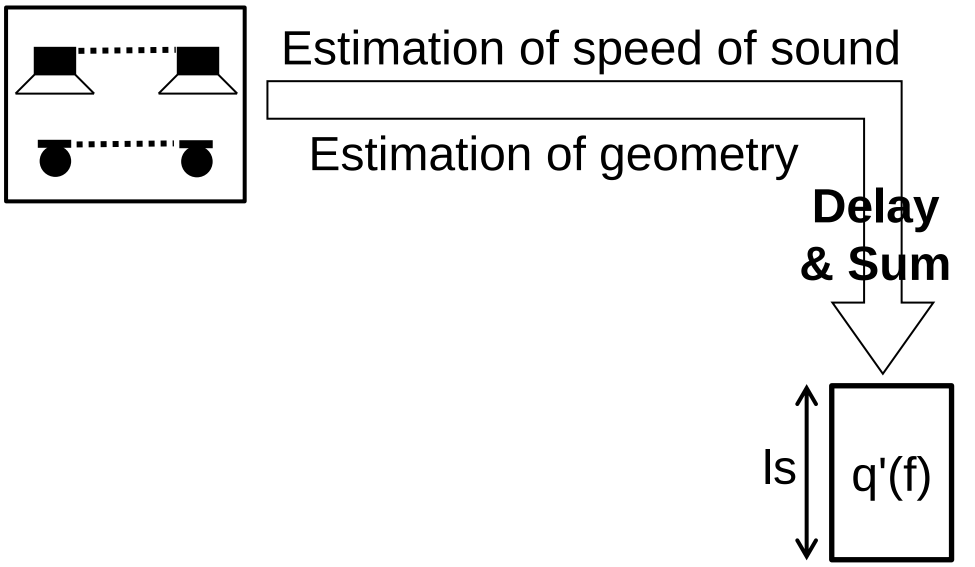

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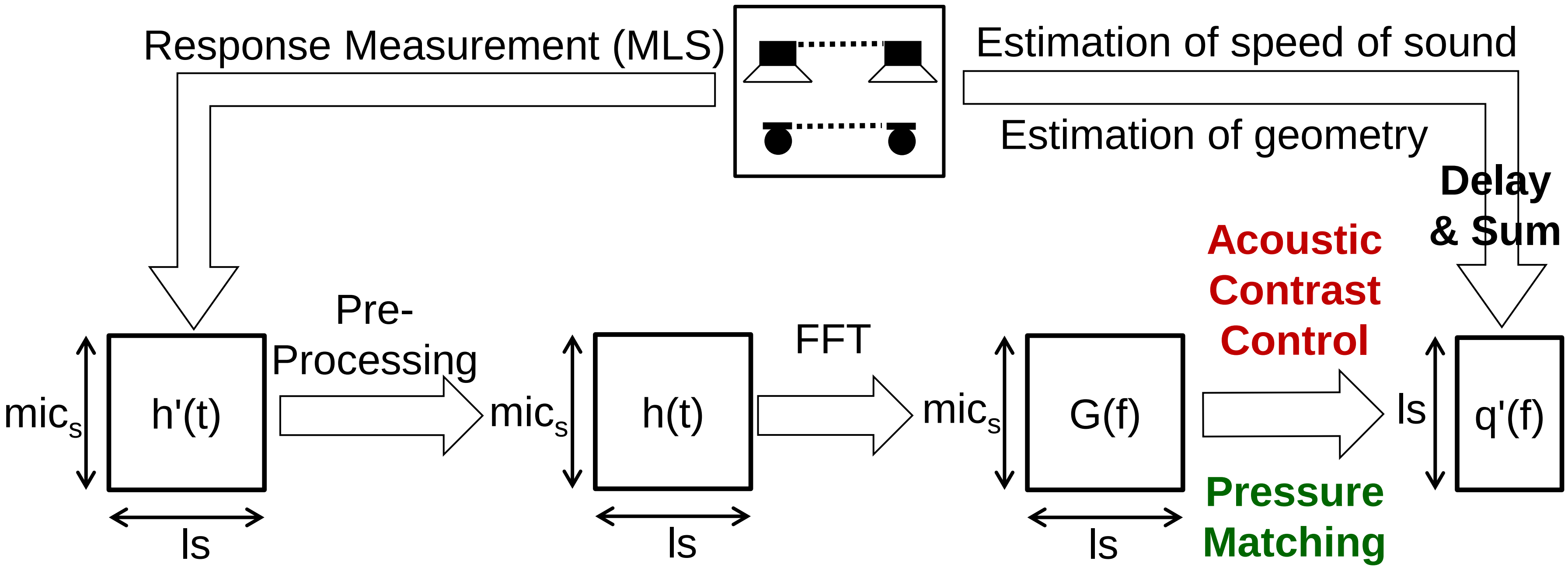

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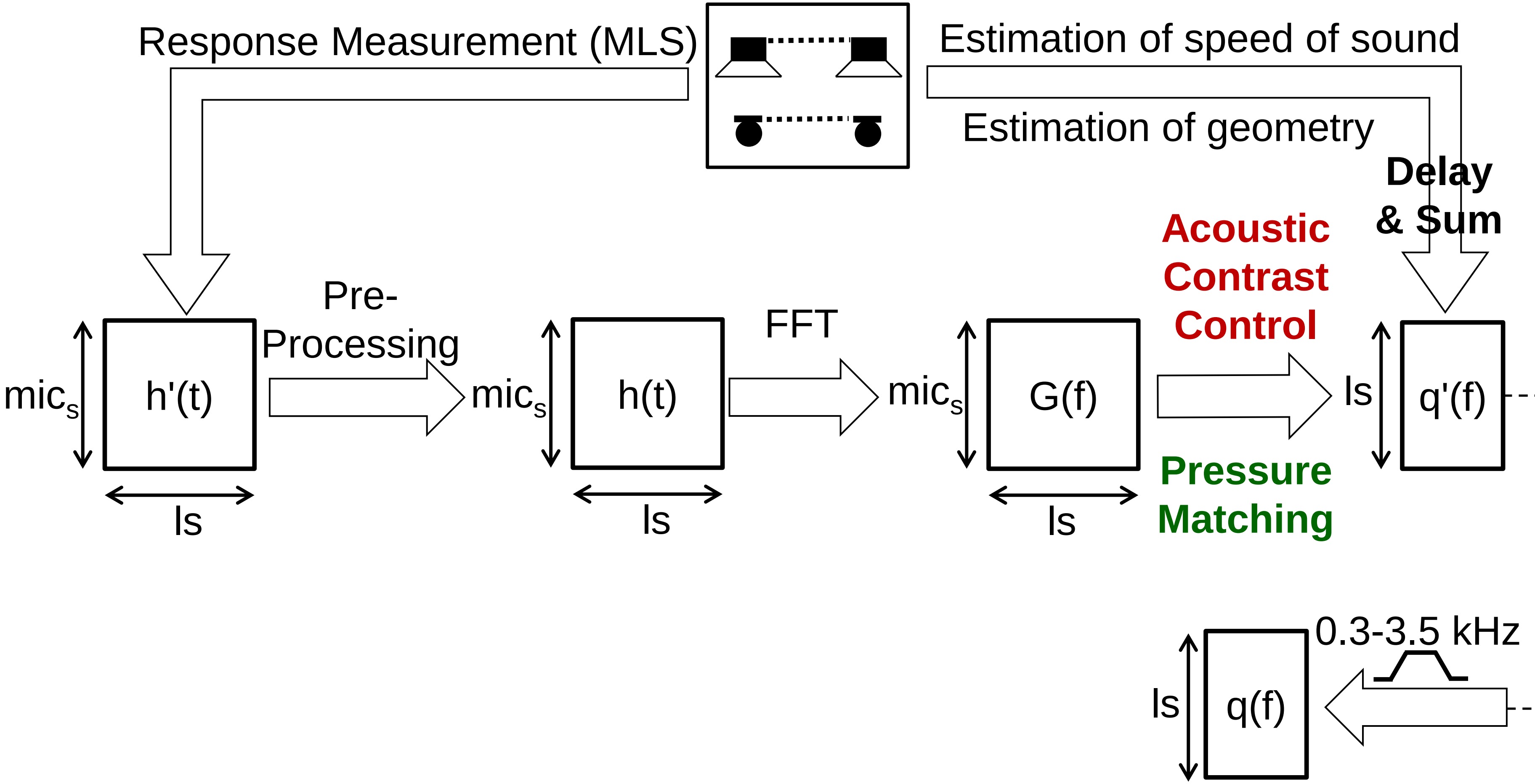

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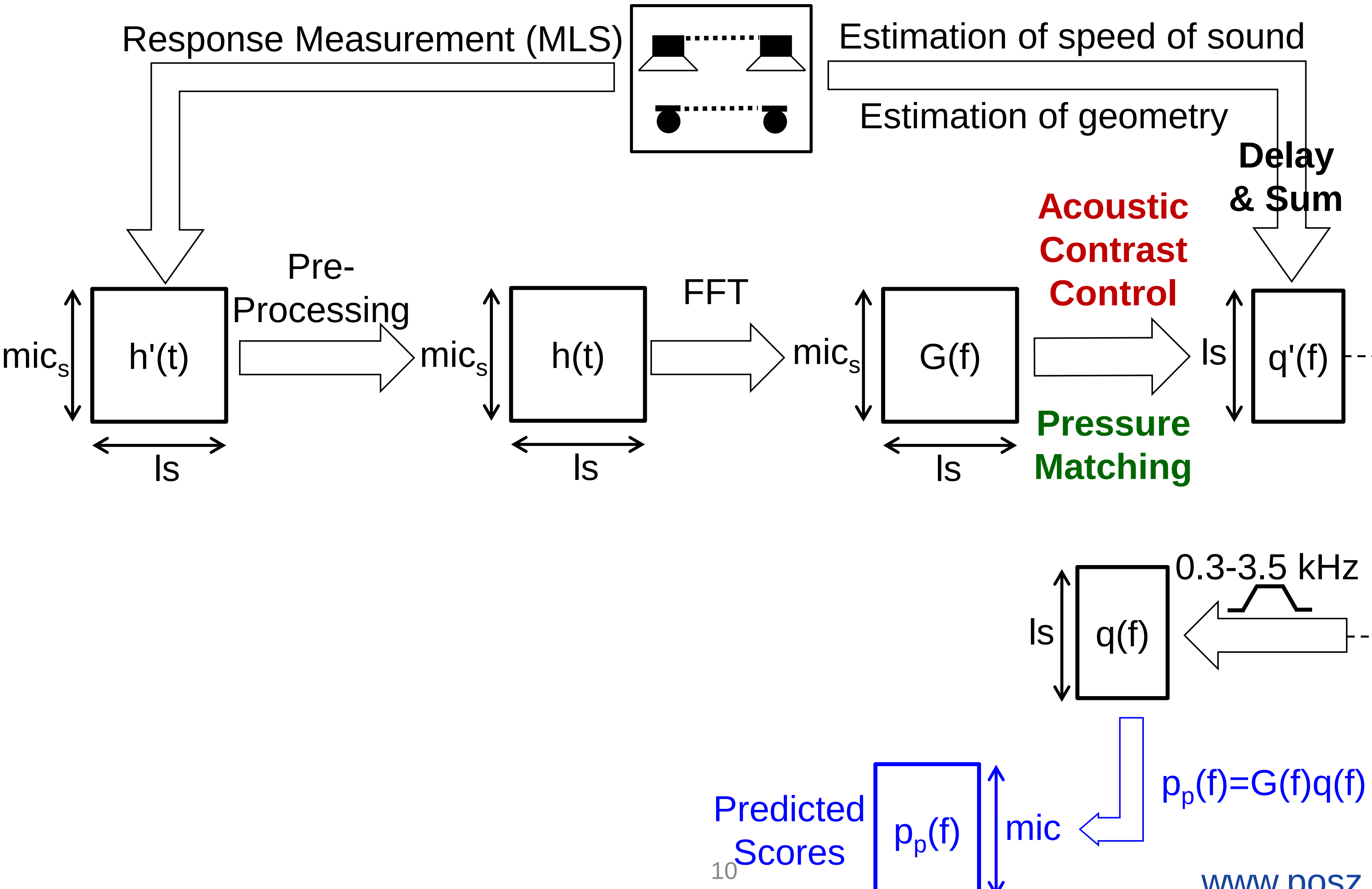

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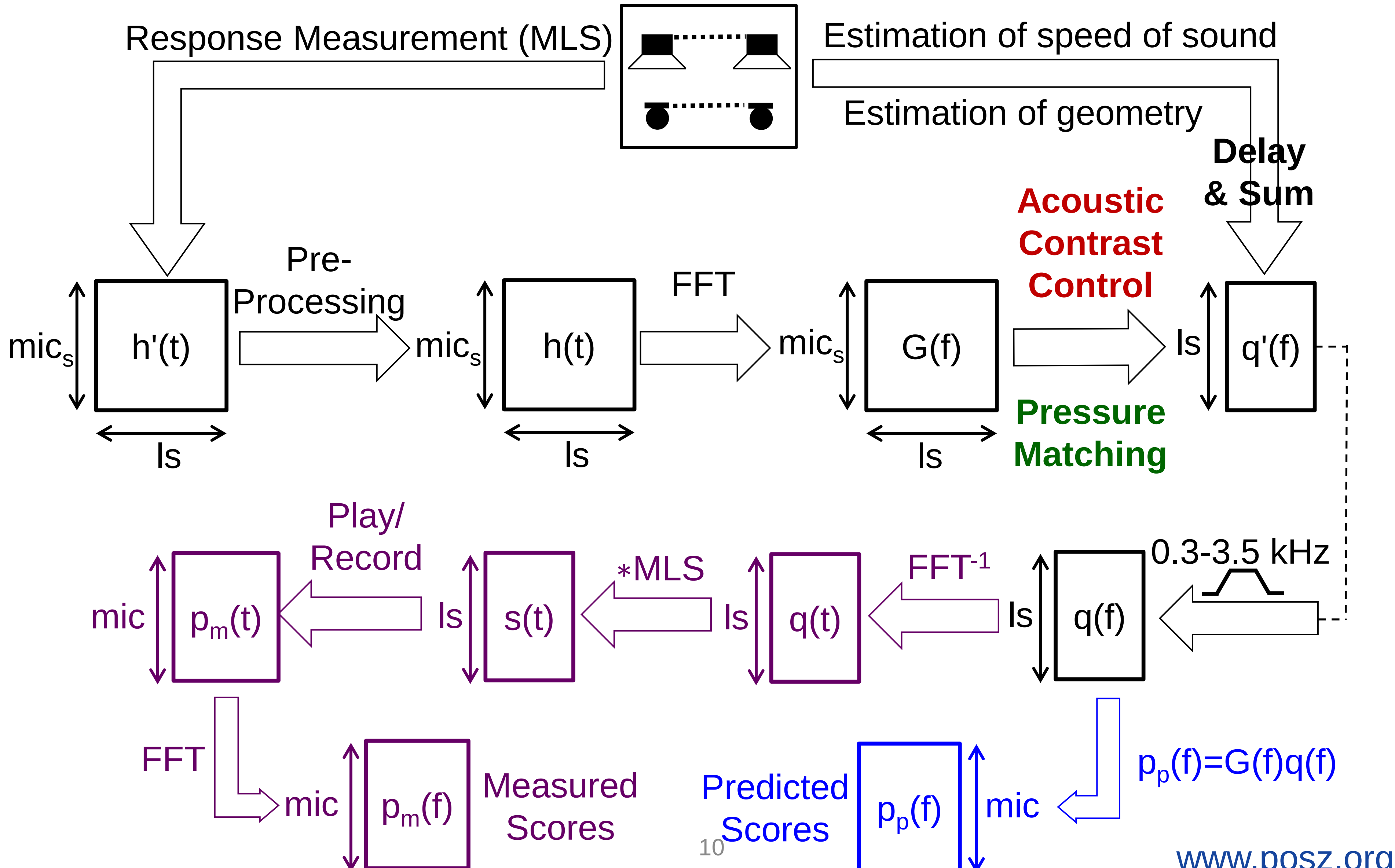
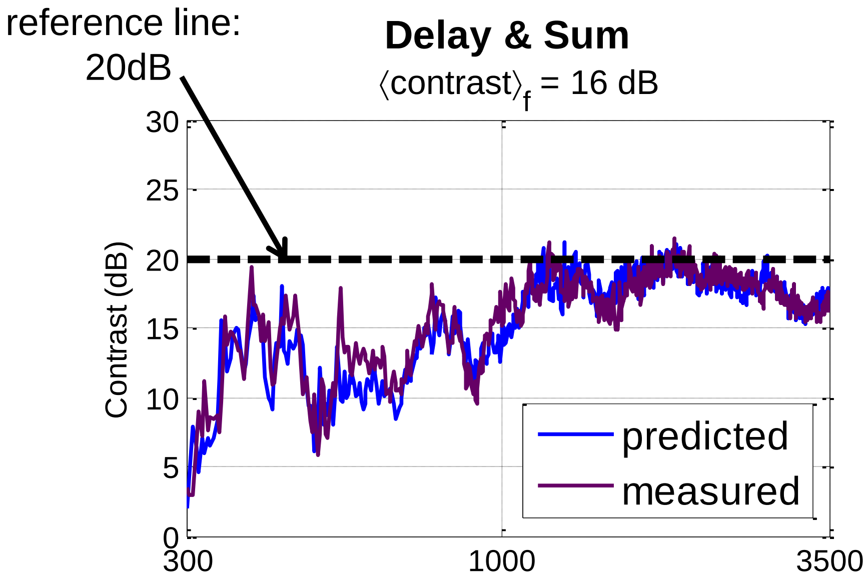
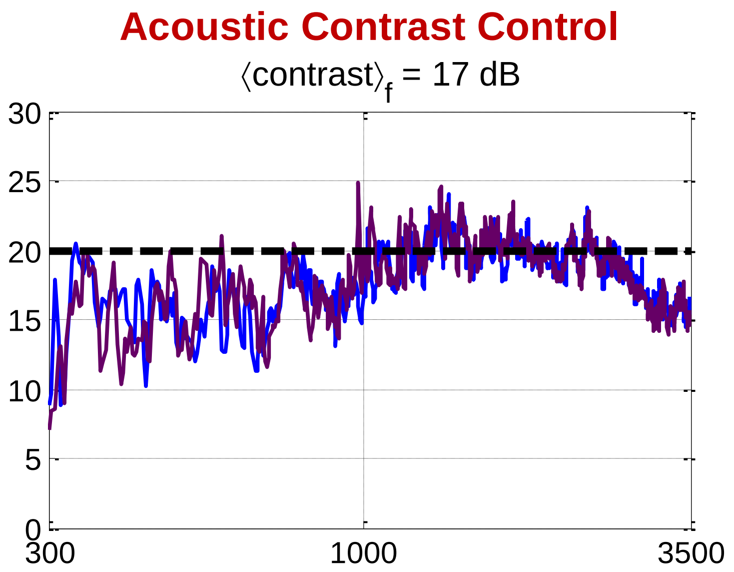


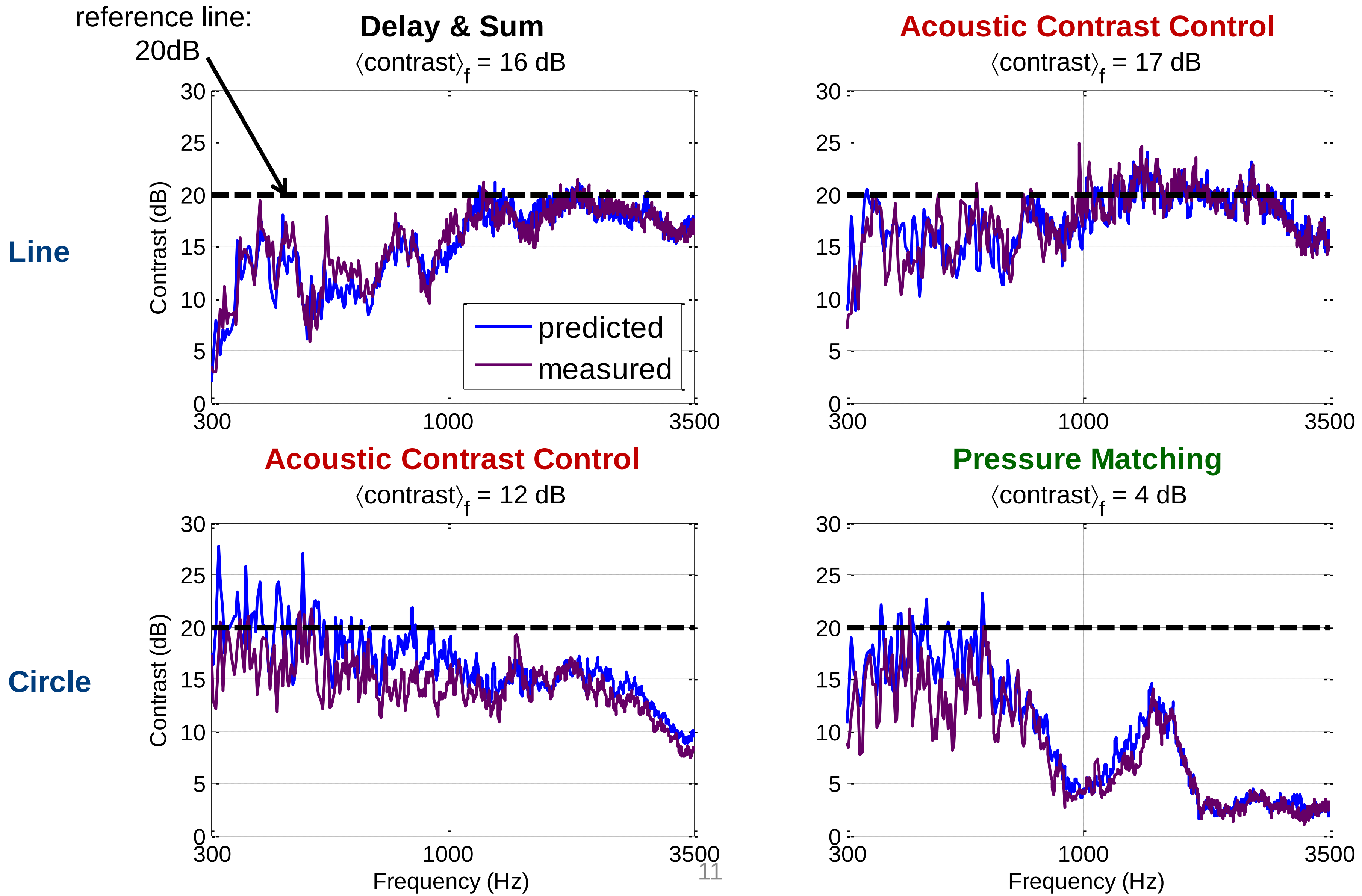
Physical Evaluation: Contrast

Line





Physical Evaluation: Contrast



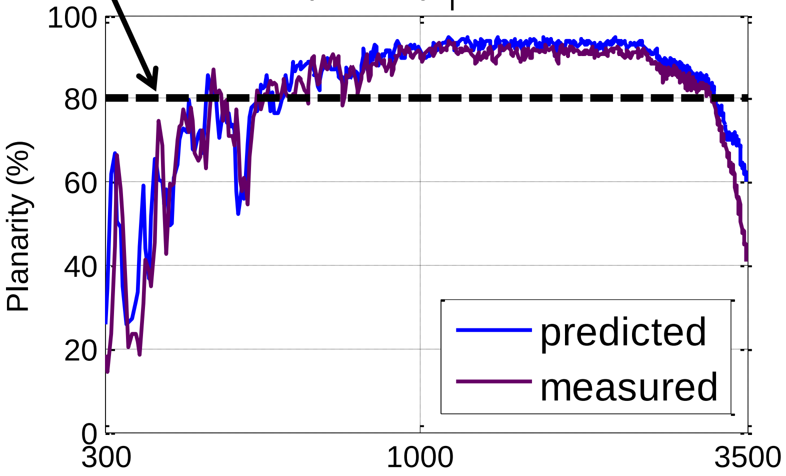
Physical Evaluation: Planarity

Line

reference line: 80%

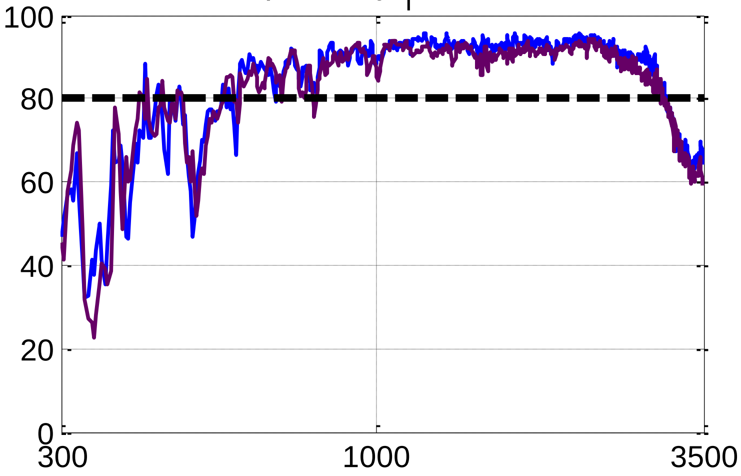
Delay & Sum

⟨planarity⟩$_f$ = 83 %

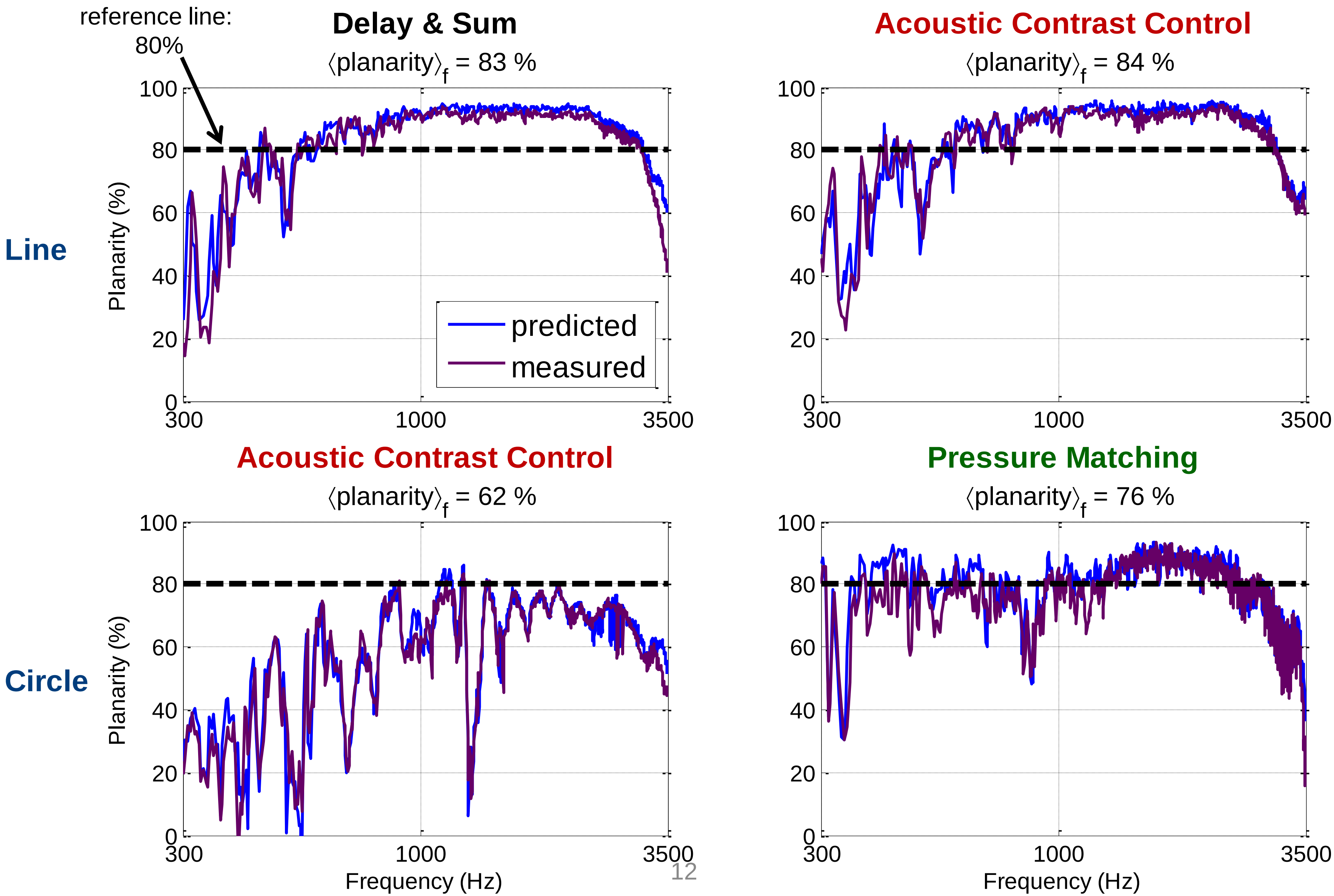


Acoustic Contrast Control

⟨planarity⟩$_f$ = 84 %



Physical Evaluation: Planarity



Zone A Pressure Maps: 1. 5 kHz
Measured Data

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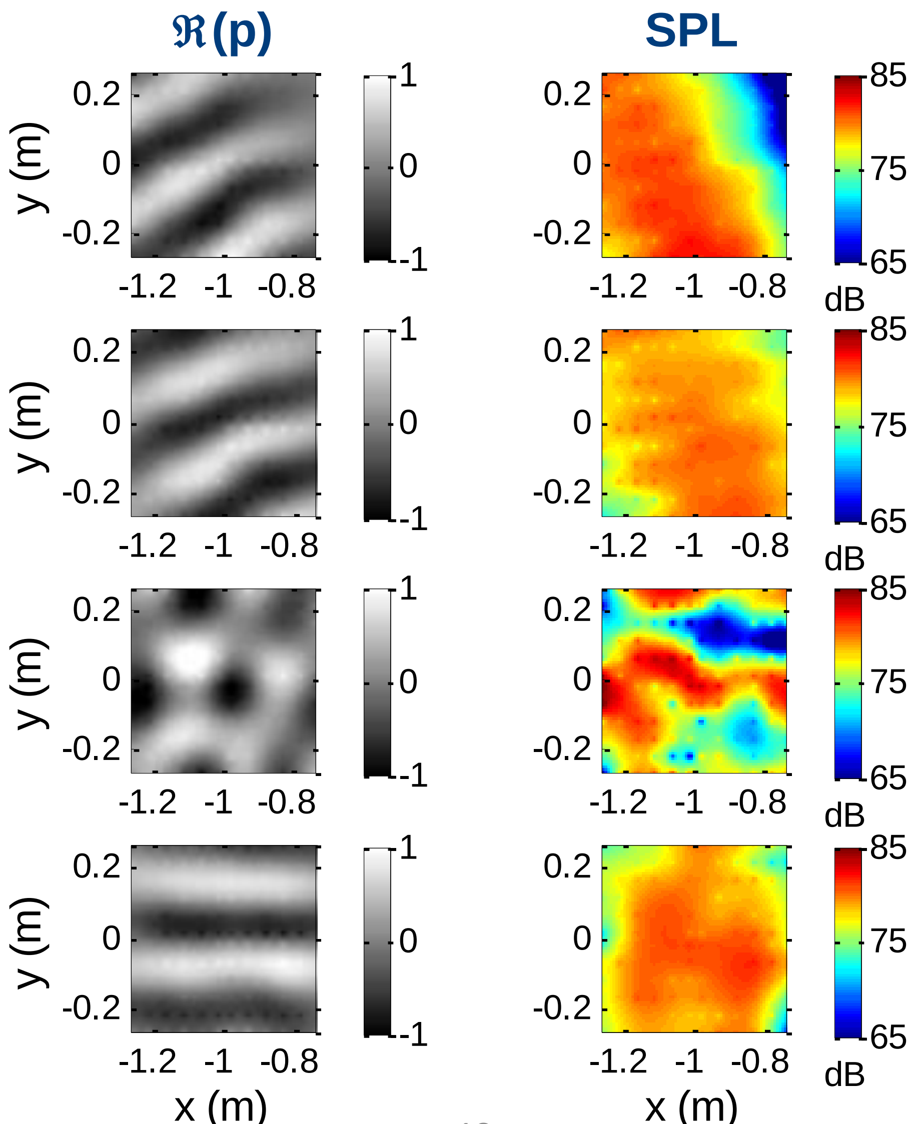

	Planarity (1.5 kHz)
DS (Line)	90%
ACC (Line)	85%
ACC (Circle)	66%
PM (Circle)	89%

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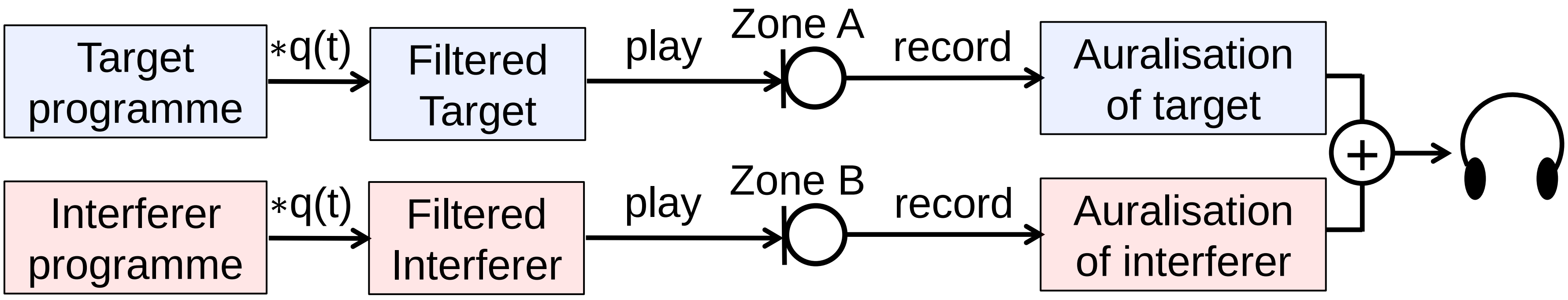
Perceptual Evaluation
Stimulus Creation

- **Listening tests based on recordings in the zones**



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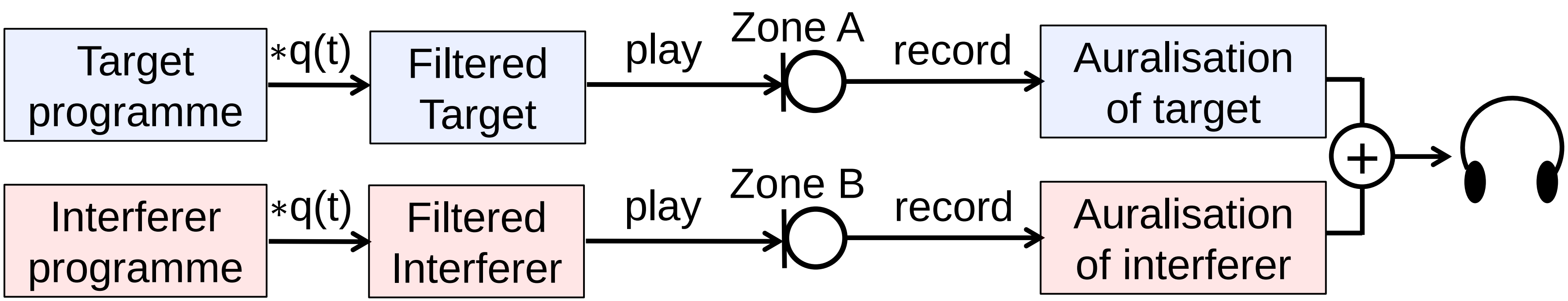

- **Mono stimuli: we can't investigate perceptual effect of spatial variation – but we can begin to observe the perceptual effects of contrast and programme material**

Perceptual Evaluation

Experiment Design

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- **24 stimuli (combination of methods and programme items)**
- **Rate 'distraction'** [Francombe *et al.* 2013]

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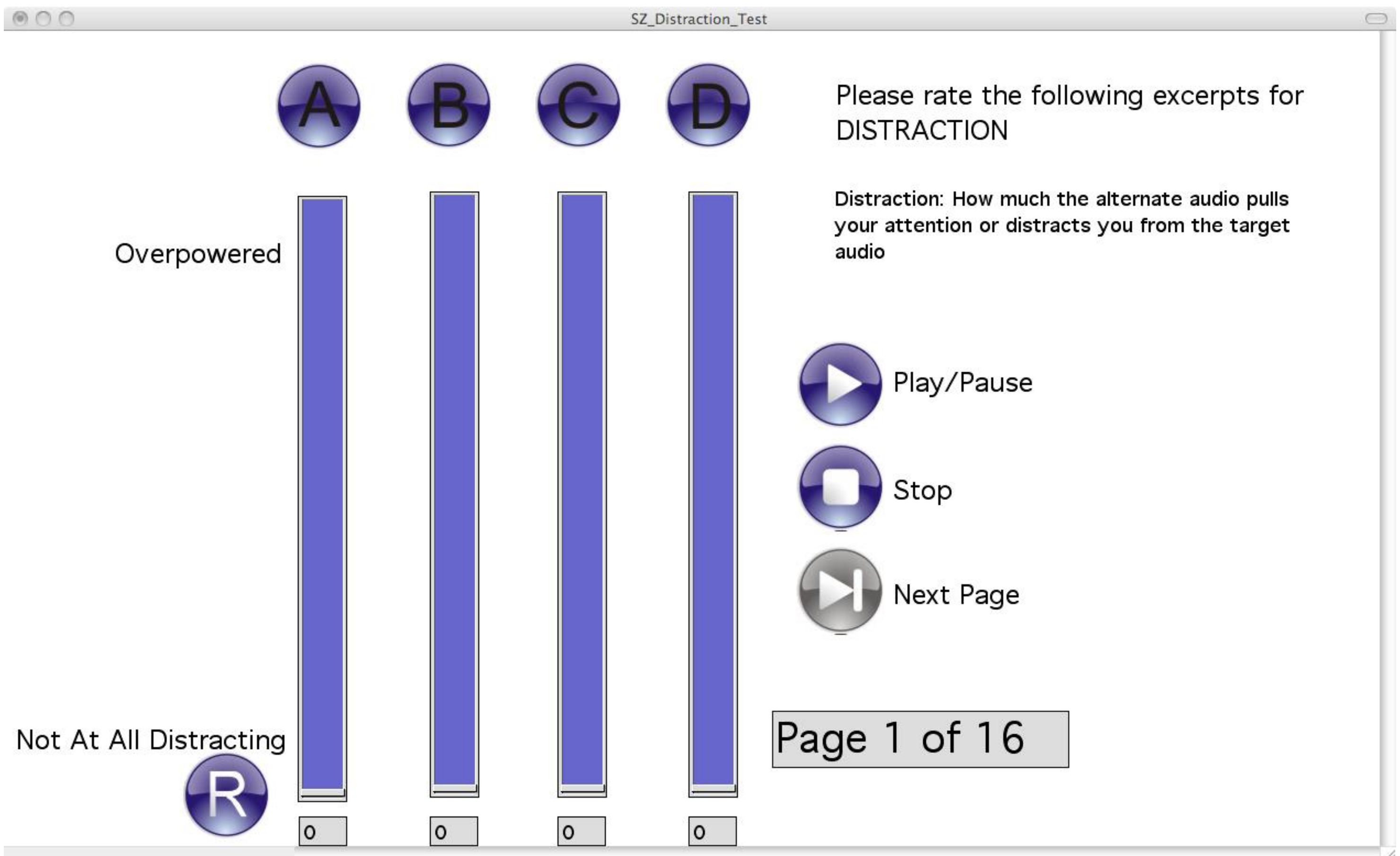
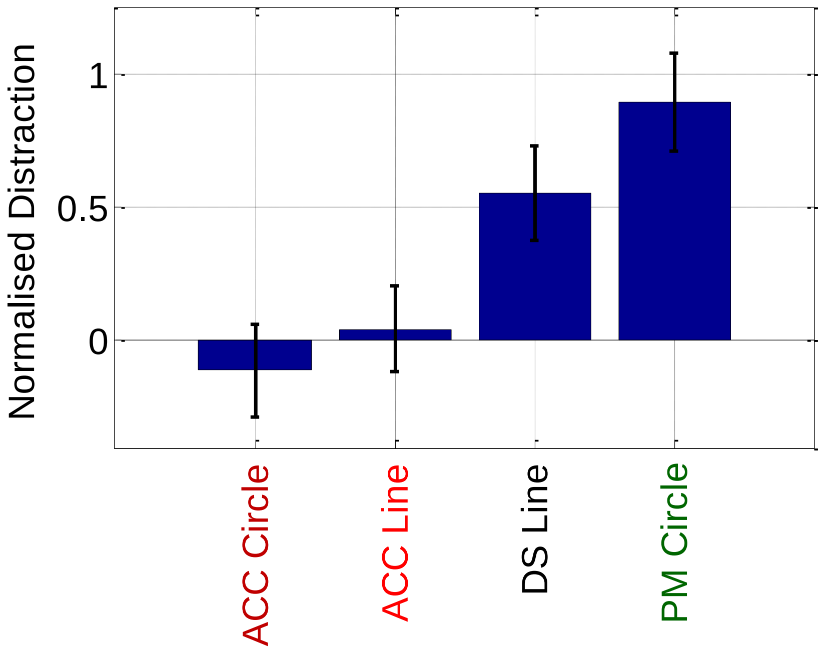


Perceptual Evaluation

Results

- **ANOVA model – most significant factor: sound zone method**



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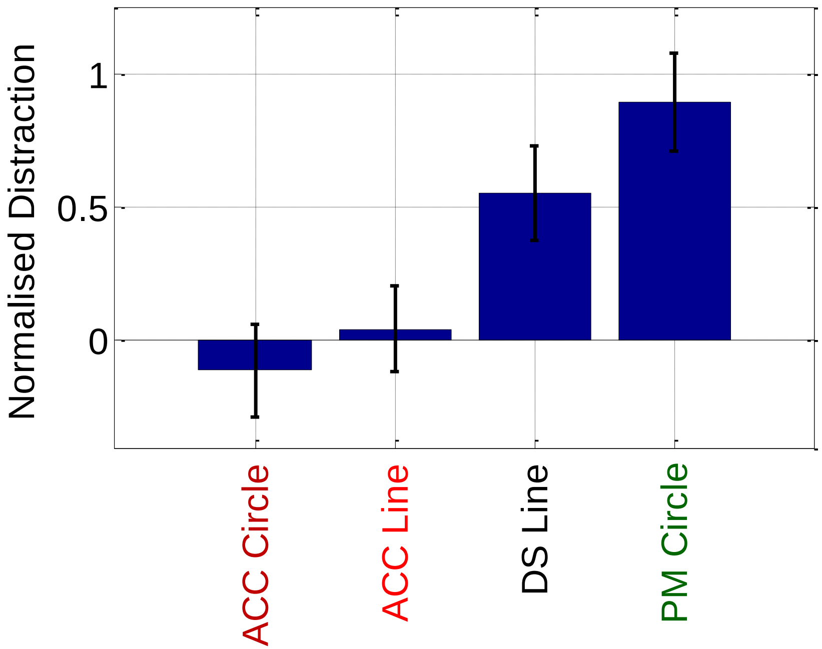

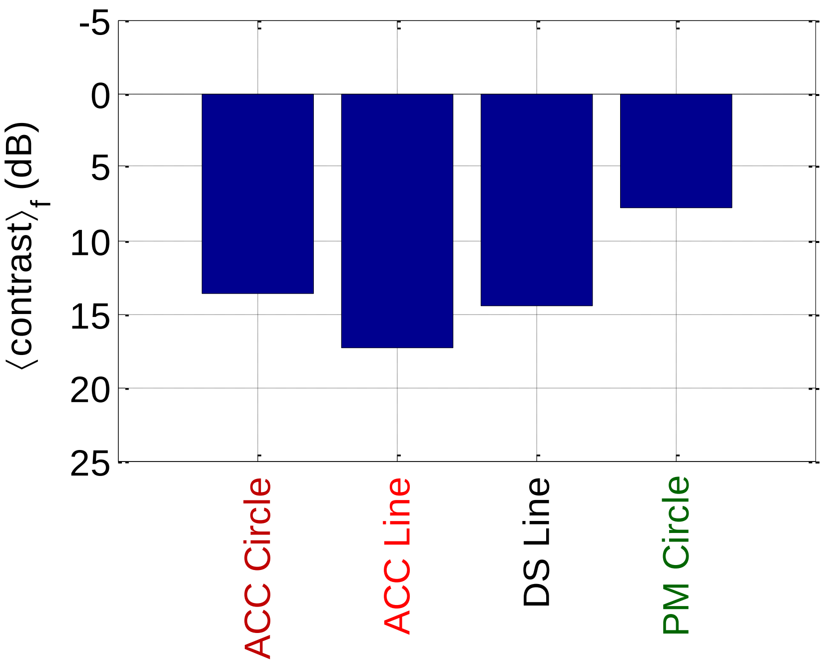

- **Other significant factors influenced distraction: programme material and interactions**

Summary and Further Work

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- **A comparative study of sound zone methods implemented in a room**
- **Methods: Delay and Sum, Acoustic Contrast and Pressure Matching**
- **Arrays: linear and circular (each 24 elements)**

Summary and Further Work

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- **A comparative study of sound zone methods implemented in a room**
- **Methods: Delay and Sum, Acoustic Contrast and Pressure Matching**
- **Arrays: linear and circular (each 24 elements)**

- **Contrast: highest overall contrast from ACC; DS and PM were more sensitive to limitations of the array geometries**
- **Planarity: line array - high planarity; PM improved planarity at low frequencies; ACC circle – inhomogeneous bright zone, lowest planarity score**

- **Listening tests indicated that contrast may be perceptually important**

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Further work:

- **In situ listening tests – to evaluate effect of spatial differences**
- **Evaluation of sound quality in the bright zone (signal to distortion ratio, basic audio quality)**

References

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Appendix A

Pre-Processing: Impulse Smoothing

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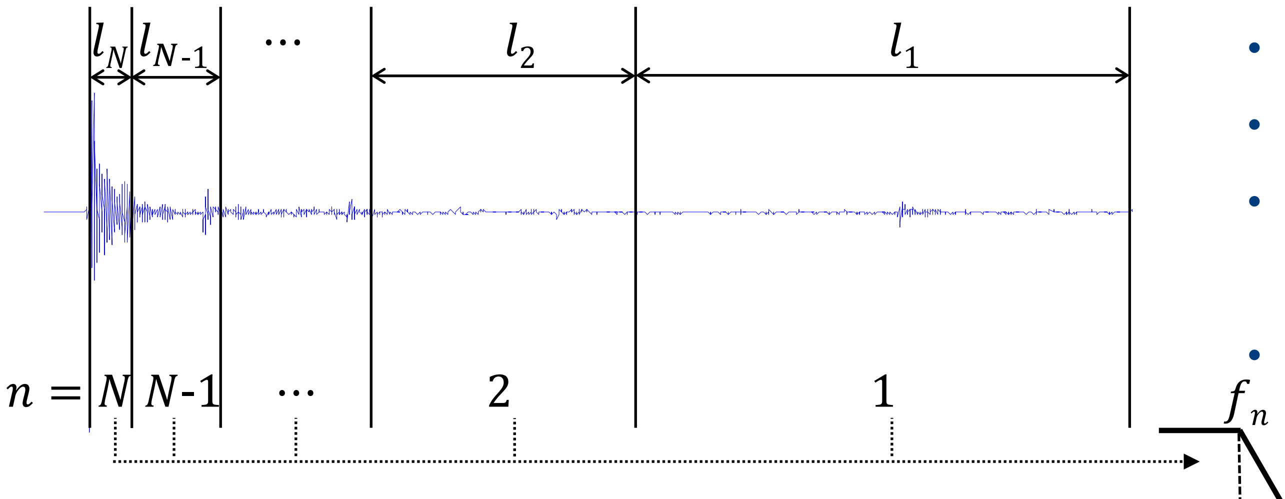
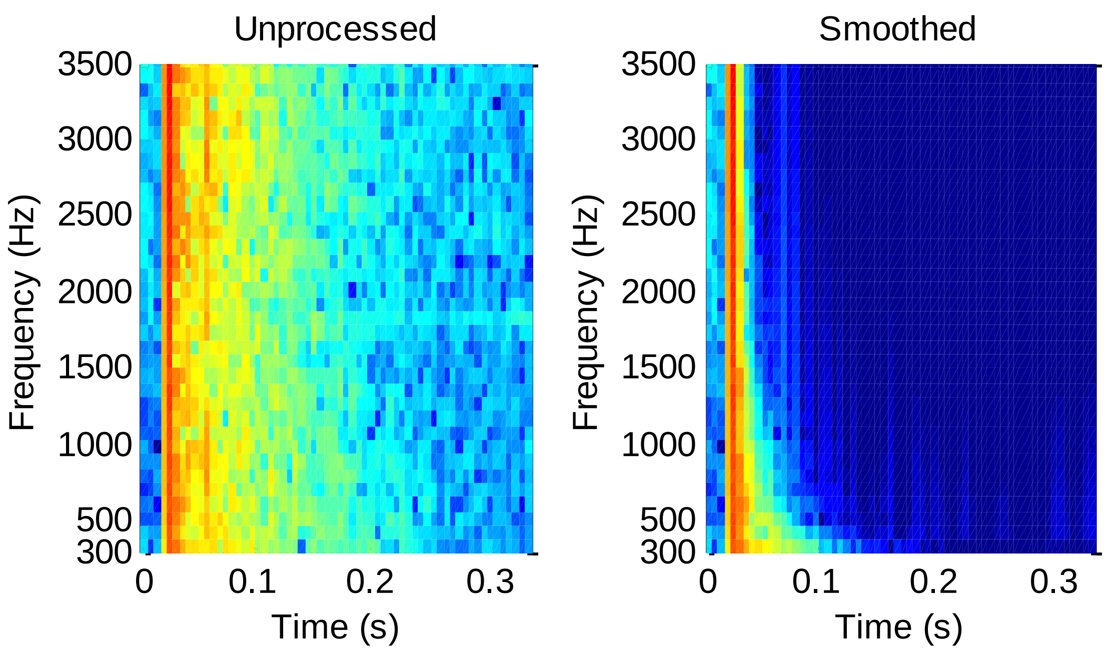


- $l_n = f_s i / f_n$
- i - number of bins before f_n
- f_n- cut-off freq. of LPF in n-th band
- f_s - sampling frequency



Parameter	Value
i	10
f_s	48 kHz
N	141
f_1	8 Hz
f_N	2.376 kHz
Freq. spacing	1/12 Oct.
Slope	80 dB/Dec.

Appendix B

Contrast: Two Recording Points

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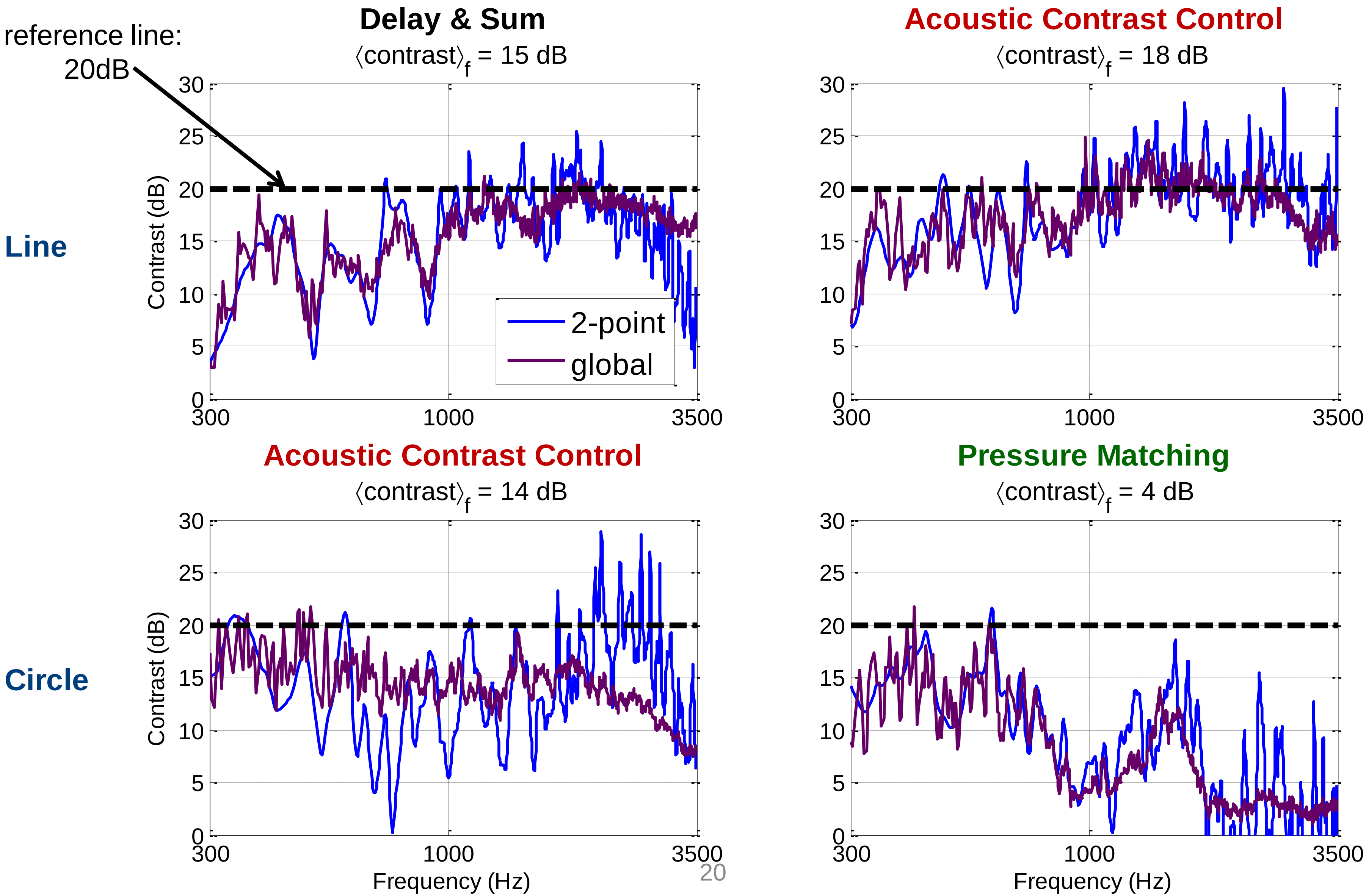

Appendix C

Perceptual Evaluation: Details of Experiment Design

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- **24 stimuli**
  - 2 target programmes: sports commentary, pop music
  - 3 interferer programmes: male speech, pop music, classical music
  - 4 sound zone methods (DS Line, ACC Line & Circle, PM Circle)
- **Rate 'distraction'** [Francombe *et al.* 2013]
  - How much the alternate audio pulls your attention or distracts you from the target audio
- **Multiple stimulus presentation**
  - 3 test items per page (target programme and SZ method held constant)
- **Each page also had a reference**
  - Just the target audio with no interference
  - Hidden reference included should be scored at 0

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