# Sound Zones with a Cost Function based on Human Hearing

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# Preface: About Me

**Niels de Koeijer**

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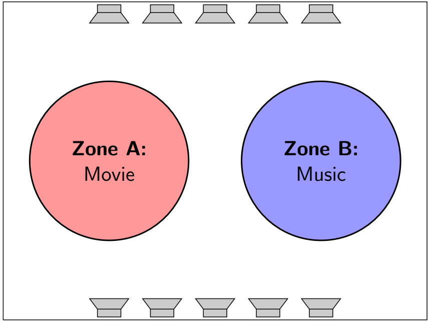
- Delft University of Technology,
- Research Department at Bang & Olufsen.

# **Preface:** The Sound Zone Problem I

"Using an **array of loudspeakers** to create **zones of distinct audio** with **minimal interference** in a room."



# **Preface:** The Sound Zone Problem II

# **Preface:** Introducing Perceptual Sound Zones

**Thesis Approach**

- **Goal of Thesis:**
  Include a model of the human auditory system in sound zone algorithms.
- **Motivation:**
  Optimize what matters to humans perceptually.

# **Preface:** Research Questions

**RQ1:**

**“How can perceptual models be included in sound zone algorithms?”**

**RQ2:**

**“What are benefits of including perceptual models in sound zone algorithms?”**

# **Structure:** Answering Research Question 1

**RQ1:** How can perceptual models be included in sound zone algorithms?

1. **Finding a suitable perceptual model**
2. **Proposal of a perceptual sound zone framework**
3. **Proposal of perceptual sound zone algorithms**

## **Structure:** Answering Research Question 1

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# Finding a Perceptual Model: Par Distortion Detectability Introduction

A perceptual model is found through literature review:

**Par distortion detectability**[1]

- Defines a mathematical function $D(x[n], \varepsilon[n])$.
- Quantifies how easily a **human listener** can **detect disturbance** audio $\varepsilon[n]$ when **also listening to** masking audio $x[n]$.
- It is used in **audio coding** to hide compression artifacts.

[1] S. van de Par, A. Kohlrausch, R. Heusdens, J. Jensen, and S. H. Jensen (2005). "A perceptual model for sinusoidal audio coding based on spectral integration". In: *EURASIP Journal on Advances in Signal Processing* 2005.9, pp. 1–13

# Finding a Perceptual Model: Par Distortion Detectability Workings

## Psycho-Acoustical Principals

- **Threshold of Hearing:**
  The lowest sound pressure level humans can hear.
- **Auditory Masking:**
  The degree to which $x[n]$ "overpowers" disturbance $\varepsilon[n]$.

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# **Perceptual Sound Zone Framework:** Pressure Matching I

A sound zone approach suitable for integration with the Par distortion detectability is found through literature review:

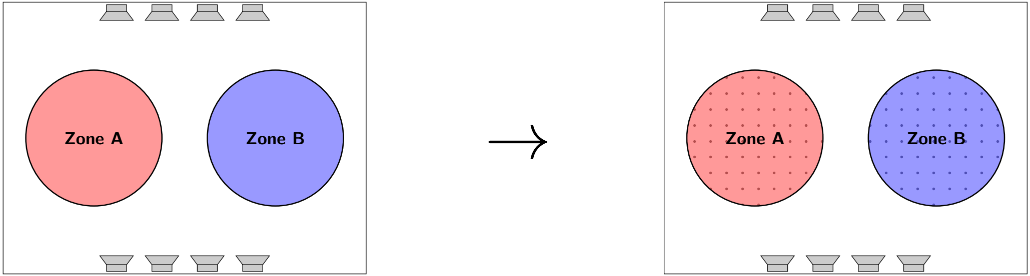
## Pressure Matching Sound Zone Algorithm[2]

- Controls the sound pressure at **discrete points** in the room.
- Minimizes **"sound pressure errors"** to create sound zones.

[2] T. Betlehem, W. Zhang, M. A. Poletti, and T. D. Abhayapala (2015). "Personal sound zones: Delivering interface-free audio to multiple listeners". In: *IEEE Signal Processing Magazine* 32.2, pp. 81–91

# **Perceptual Sound Zone Framework:** Pressure Matching II

The zones are sampled into $M$ **“control points”** where we attempt to control the sound by **controlling the inputs** to the $L$ **loudspeakers** in the room.



# Perceptual Sound Zone Framework: Pressure Matching III

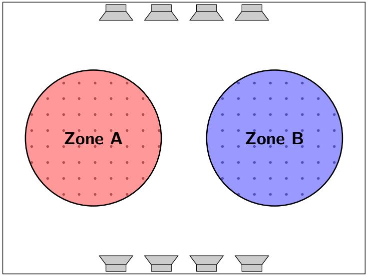
## Pressure Matching Quantities

For each loudspeaker $l$:

- **Input signal** $x_A^{(l)}[n]$ and $x_B^{(l)}[n]$.

For each point $m$:

- **Target sound pressure** $t_A^{(m)}[n]$ and $t_B^{(m)}[n]$.
- **Resulting sound pressure** $p_A^{(m)}[n]$ and $p_B^{(m)}[n]$.



# **Perceptual Sound Zone Framework:** Pressure Matching IV

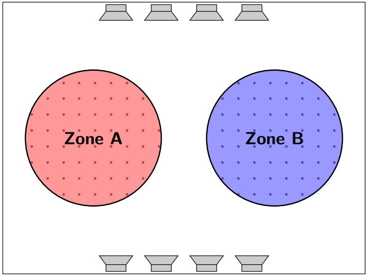
## Pressure Matching Errors

- **Reproduction error for point $m$ in zone A:**

$$\mathrm{RE}^{(m)} = \left|\left| t_A^{(m)} - p_A^{(m)} \right|\right|_2^2 \tag{1}$$

- **Leakage error for point $m$ in zone A:**

$$\mathrm{LE}^{(m)} = \left|\left| p_B^{(m)} \right|\right|_2^2 \tag{2}$$

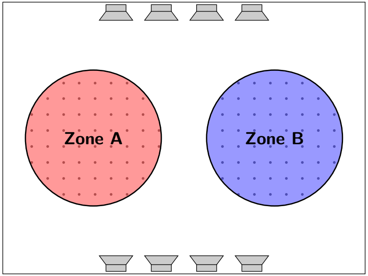


# **Perceptual Sound Zone Framework:** Pressure Matching V

### Pressure Matching

Minimize the sum of reproduction and leakage errors:

$$\underset{x_A^{(l)},\, x_B^{(l)}}{\arg\min} \quad \sum_{m} \mathrm{RE}^{(m)} + \mathrm{LE}^{(m)} \tag{3}$$



# **Perceptual Sound Zone Framework:** Perceptual Pressure Matching I

**Idea: Error Detectability**

- Use of error detectability $D(x[n], \varepsilon[n])$ rather than sound pressure error
- Reproduction error $\rightarrow$ **Reproduction error detectability**:
  How well can humans detect deviations from the target sound pressure?
- Leakage error $\rightarrow$ **Leakage error detectability**:
  How well can humans detect the leakage/interference?

# **Perceptual Sound Zone Framework:** Perceptual Pressure Matching II

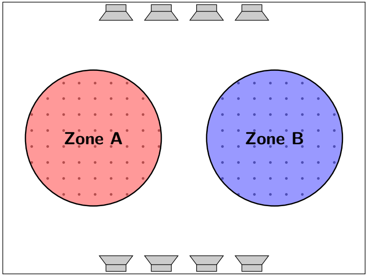
## Pressure Matching Errors

- **Reproduction error for point $m$ in zone A:**

$$\mathrm{RED}^{(m)} = D\left(t_A^{(m)},\, t_A^{(m)} - p_A^{(m)}\right) \tag{4}$$

- **Leakage error for point $m$ in zone A:**

$$\mathrm{LED}^{(m)} = D\left(t_A^{(m)},\, p_B^{(m)}\right) \tag{5}$$



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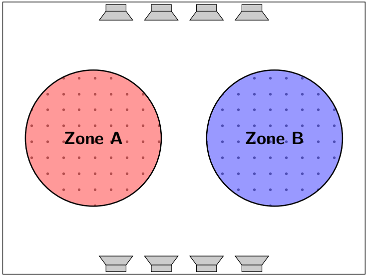
# **Algorithms:** Unconstrained Perceptual Pressure Matching

**Unconstrained Perceptual Pressure Matching**

Minimize the sum of error detectabilities:

$$\underset{x_A^{(l)}, x_B^{(l)}}{\arg\min} \sum_m \mathrm{RED}^{(m)} + \mathrm{LED}^{(m)} \tag{6}$$

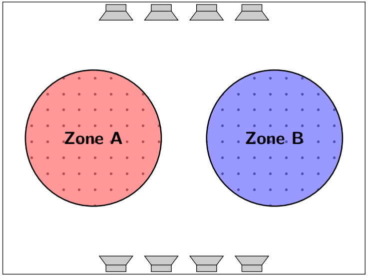


# **Algorithms:** Unconstrained Perceptual Pressure Matching

**Unconstrained Perceptual Pressure Matching**

Minimize the leakage error detectability with constraints:

$$\underset{x_A^{(l)}, x_B^{(l)}}{\arg\min} \quad \sum_m \mathrm{LED}^{(m)} \tag{7}$$
$$\mathrm{RED}^{(m)} \leq D_0 \quad \forall\, m$$



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3. **Proposal of perceptual sound zone algorithms**
   ✓ Proposal of unconstrained and constrained perceptual pressure matching

# **Structure:** Answering Research Question 2

**RQ2:** What are benefits of including perceptual models in sound zone algorithms?

1. **Simulation of proposed perceptual sound zone algorithms**

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## **Structure:** Answering Research Question 2

**RQ2:** What are benefits of including perceptual models in sound zone algorithms?

1. **Simulation of proposed perceptual sound zone algorithms**

   ✓ Unconstrained perceptual approach outperforms and constrained perceptual approach allows for control over the perceived quality of reproduced content