Sound Zones with a Cost Function based on Human Hearing

Niels de Koeijer
MSc Thesis Defence

Delft University of Technology, The Netherlands
Bang and Olufsen, Denmark

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Preface: About Me

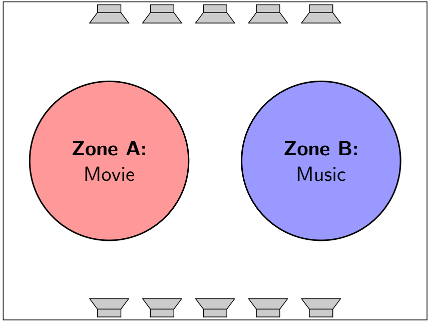
Niels de Koeijer

Master Student at:

- 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

Sound Zone Example

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**

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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.

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[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:

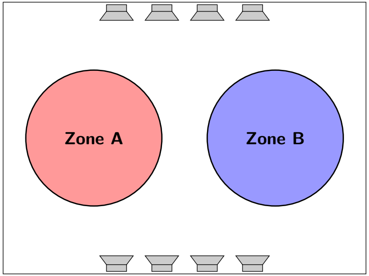
Pressure Matching Sound Zone Algorithm[2]

- 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.



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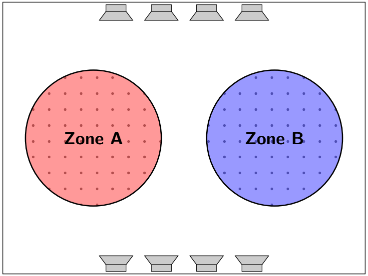


Perceptual Sound Zone Framework: Pressure Matching III

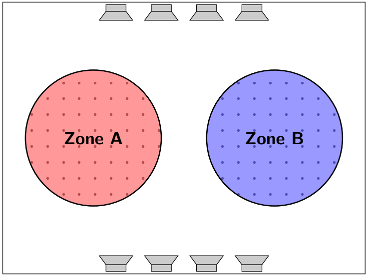
Pressure Matching Quantities

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

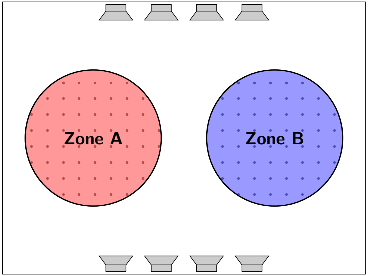
Pressure Matching Errors

- **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:**

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

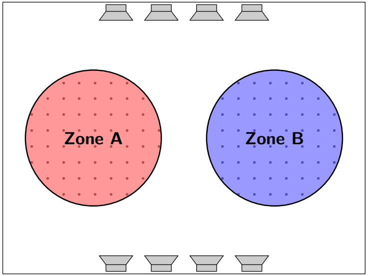


Perceptual Sound Zone Framework: Pressure Matching V

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

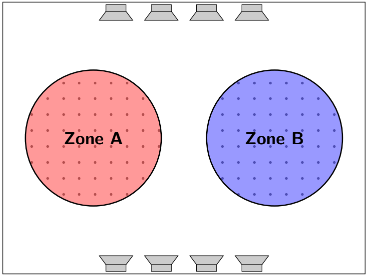
Pressure Matching Errors

- **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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   ✓ Framework of the detectability of sound pressure errors from pressure matching
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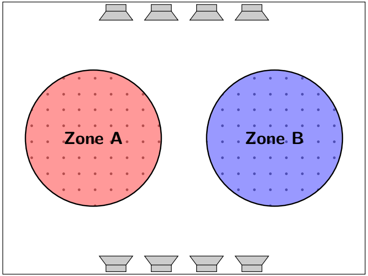
Algorithms: Unconstrained Perceptual Pressure Matching

Unconstrained Perceptual Pressure Matching

Minimize the sum of error detectabilities:

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

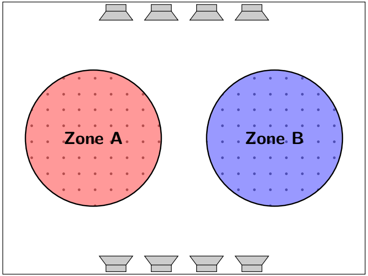


Algorithms: Constrained Perceptual Pressure Matching

Constrained Perceptual Pressure Matching

Minimize the leakage error detectability with constraints:

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



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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**

Structure: Answering Research Question 2

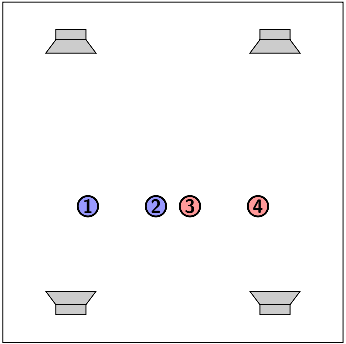
RQ2: What are benefits of including perceptual models in sound zone algorithms?

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

Algorithm Evaluation: Simulation Setup

Simulation Configuration

- Simulations use **speech** signals.
- Simulation of **perceptual** and a **reference** pressure matching algorithms



Algorithm Evaluation: Unconstrained Perceptual Pressure Matching I

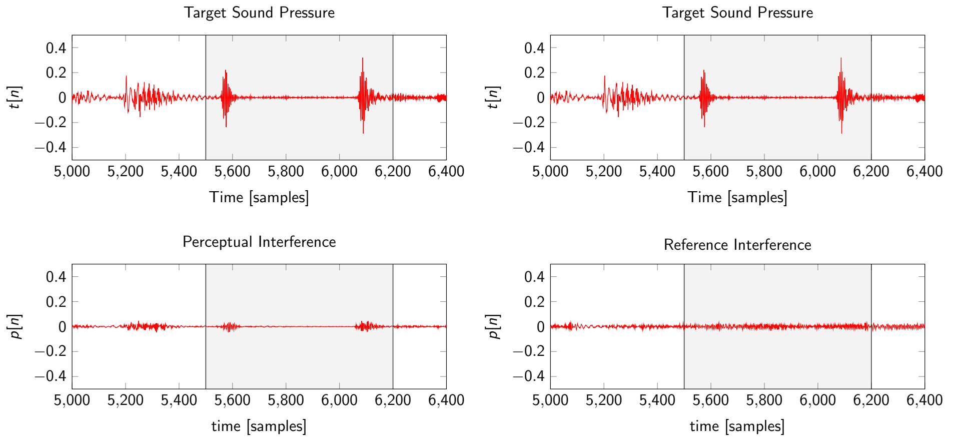
Measure	**Unconstrained Perceptual PM Mean ($\pm$ 95% CI)**	**Reference PM Mean ($\pm$ 95% CI)**
PESQ (No interference)	3.345 ± 0.087	4.107 ± 0.051
PESQ	3.154 ± 0.081	2.609 ± 0.084
Distraction	7.828 ± 1.868	12.693 ± 3.405

Algorithm Evaluation: Unconstrained Perceptual Pressure Matching II

Reference

Unconstrained

Algorithm Evaluation: Unconstrained Perceptual Pressure Matching III



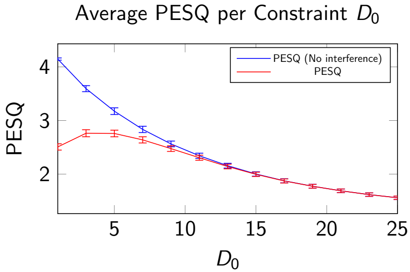
Algorithm Evaluation: Constrained Perceptual Pressure Matching I

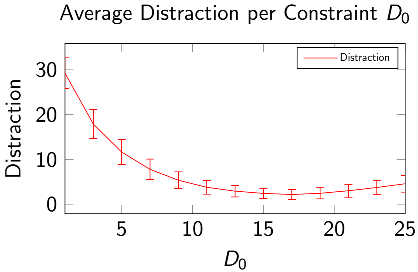
Reference

Unconstrained

Constraining

Algorithm Evaluation: Constrained Perceptual Pressure Matching II





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

Future Work:

- Validation of current results through listening tests.
- Further proposal of new perceptual sound zone algorithms through the proposed framework.
- Current algorithms are very slow, as such it is of interest to speed them up!

Sources:

Betlehem, T., 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.

Par, S. van de, 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.