Sound Zone Interaction in Homes

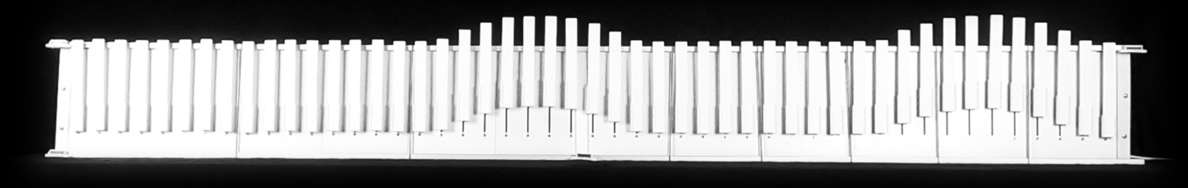
Studying and Designing for Modification of Personal Soundscapes

Johansen, Stine Schmieg

DOI (link to publication from Publisher):
10.54337/aau455013535

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record



SOUND ZONE INTERACTION IN HOMES

STUDYING AND DESIGNING FOR MODIFICATION OF PERSONAL SOUNDSCAPES

BY
STINE SCHMIEG JOHANSEN

DISSERTATION SUBMITTED 2021

AALBORG UNIVERSITY
DENMARK

SOUND ZONE INTERACTION IN HOMES

STUDYING AND DESIGNING FOR MODIFICATION OF PERSONAL SOUNDSCAPES

by Stine Schmieg Johansen

AALBORG UNIVERSITY
DENMARK

Dissertation submitted July 2021

Dissertation submitted: July 31, 2021

PhD supervisor: Professor Peter Axel Nielsen,
Aalborg University

PhD committee: Associate Professor Ivan Aaen (chairman)
Aalborg University

Professor Chris Greenhalgh
University of Nottingham

Associate Professor Eve Hoggan
Aarhus University

PhD Series: Technical Faculty of IT and Design, Aalborg University

Department: Department of Computer Science

ISSN (online): 2446-1628
ISBN (online): 978-87-7210-974-9

Published by:
Aalborg University Press
Kroghstræde 3
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Rosendahls, 2021

AUTHOR CV

Stine Schmieg Johansen achieved a Bachelor of Science, Medialogy, in 2011 and Master of Science, Interactive Digital Media, in 2014. From 2013 to 2017, she worked as a motion graphics designer, video editor, and project manager within the video and gaming industries. She worked as a Research Assistant the following two years until starting her Ph.D. fellowship at the Department of Computer Science, Aalborg University, in August 2018.

Her research interests lie in subjects such as interaction design, soundscape, tangible interaction, HCI theory, and ethnographic methodology. She has published in internationally recognised conferences and journals, such as DIS, INTERACT, and TOCHI. During the past five years, Stine has supervised bachelor and master students at Aalborg University in areas such as design alternatives, participatory design, and system analysis. In this Ph.D. dissertation, Stine investigates interaction with sound zone systems as soundscape modification and explores potentials of light and shape-change for supporting this interaction.

ENGLISH SUMMARY

In this dissertation, I investigate how to design interaction with sound zone systems in homes. Sound zone systems consist of loudspeaker arrays that, together with software filters, can direct sound towards part of a physical environment while minimising it in other parts of that same environment. This means that sound zone systems have spatial properties that contradict users' prior experiences with sound, calling for new interaction design approaches. Technologies for sound zone systems are still emerging. This impacts the research in two ways. First, I rely on methods that enable users to articulate experiences that are entirely new or that they cannot yet have. Second, I build on extant research on the broad topics of personal sound, soundscape, and interaction with physical environments, because research on sound zone systems is conducted within audio engineering. The research is guided by the following research question:

How can interaction with sound zone systems in the home be designed for modifications of soundscapes?

I divide the main research question into two sub-questions that focus on (1) characterising the relation between sound zone systems and soundscapes, and (2) supporting users' understanding and control of sound zone systems with interaction designs. These questions are addressed from a postphenomenological philosophical worldview, with a particular focus on embodied interaction.

The contribution of the dissertation is towards a theory of sound zone configurations from a user experience perspective. On the basis of findings from seven studies, I propose that sound zone systems can be designed in configurations that result in different soundscapes and accommodate different situations. This is unfolded in six full papers. The findings show that sound zone systems can be conceptualised from the way a user relates to their acoustic environment. When physical environments are shared between people, different needs related to sound emerge depending on situations in which users are engaged. Analysing the social characteristics of these situations together with the properties of sound zone systems, the dissertation contributes with a set of interaction design challenges for sound zone systems in homes. Based on the understanding achieved through the initial three of the seven studies, I investigate two different approaches to supporting users' control of sound zone systems: Light and shape-change. Findings show that visual overlays to sound zone systems affect users' experience of how the sound in one sound zone distributes in a physical environment as well as how two sound zones overlap with each other.

Future work includes (1) investigating the relations that emerge in sound zone configurations, (2) further elaborating on using light and shape-change for sound zone systems, and (3) expanding the research into other domains such as hospitals and public spaces.

DANSK RESUMÉ

I denne afhandling undersøger jeg, hvordan der kan designes interaktion med lydzone-systemer i hjem. Lydzone-systemer består af højtalerarrays, der sammen med softwarefiltre kan distribuere lyd ud i bestemte dele af et fysisk miljø og samtidig minimere lyden i andre dele af det samme miljø. Dette betyder, at lydzone-systemer har rumlige egenskaber, der modsiger brugeres tidligere oplevelser med lyd, og det kræver nye tilgange til at designe interaktionen. Teknologier til at skabe lydzone-systemer er stadig under udvikling. Dette har betydning for forskningen på to måder. For det første beror jeg mig på metoder, der sætter brugere i stand til at artikulere oplevelser, der enten er helt nye, eller som de endnu ikke kan have. For det andet bygger jeg på eksisterende forskning i emner som personlig lyd, soundscape og interaktion med fysiske miljøer, fordi forskning specifikt i lydzone-systemer bliver udført af lydingeniører. Forskningen er guidet af følgende forskningsspørgsmål:

Hvordan kan interaktion med lydzone-systemer i hjem designes med det formål at modificere soundscapes?

Jeg opdeler forskningsspørgsmålet i to underspørgsmål, der fokuserer på henholdsvis at (1) karakterisere relationen mellem lydzone-systemer og soundscapes og (2) understøtte brugeres forståelse og kontrol af lydzone-systemer med interaktionsdesigns. Disse spørgsmål bliver adresseret fra et postfænomenologisk verdenssyn med særligt fokus på 'embodied interaction'.

Afhandlingen bidrager mod en teori om konfigurationer af lydzoner fra et perspektiv forankret i brugeroplevelser. På baggrund af resultater fra syv studier foreslår jeg, at lydzone-systemer kan designes i konfigurationer, der resulterer i forskellige soundscapes og akkommoderer forskellige situationer. Dette er udfoldet i seks artikler. Resultaterne viser, at lydzone-systemer kan konceptualiseres med udgangspunkt i den måde, en bruger relaterer sig til deres akustiske miljø. Når mennesker deler fysiske miljøer, opstår forskellige behov relateret til lyd afhængigt af de situationer, menneskene engagerer sig i. Igennem en analyse af de sociale egenskaber af disse situationer sammenholdt med lydzone-systemers egenskaber, bidrager afhandlingen med et sæt af interaktionsdesignudfordringer for lydzone-systemer i hjem. Baseret på en forståelse opnået i de første tre af syv studier, undersøger jeg to forskellige tilgange til at understøtte brugeres kontrol af lydzone-systemer: Lys og 'shape-change'. Resultaterne viser, at visualiseringer af lydzone-systemer har en effekt på brugeres oplevelse af, hvor lyd i en lydzone fordeler sig i et fysisk miljø såvel som, hvordan to lydzoner overlapper med hinanden.

Fremadrettet forskning inkluderer at (1) undersøge de relationer, der opstår i lydzone-konfigurationer, (2) udforske brug af lys og shape-change i lydzone-systemer dybere, og (3) udvide forskningen til andre domæner såsom hospitaler og offentlige rum.

ACKNOWLEDGEMENTS

In 2003, I was sitting in my father's living room, listening to a song that was popular at the time. My father emerged from the kitchen to point out that the chorus of the song had actually been composed four decades earlier by Steven Tyler and recorded by his band, Aerosmith. He was not particularly fond of the songs I listened to at the time, so it was such luck that he was still able to hear the parts of the song he recognised and could then share his knowledge. From then, my path towards an identity closely coupled with music from the 1960s and 1970s began. Had it not been for the ability of sound to travel through air, walls and old furniture, I might not have ended up here. This is to say that, ironically, sound zone systems as envisioned within audio engineering could have hindered a huge part of my identity from forming in this way, and also to acknowledge my father's role in my life. I dedicate this work to you, dad. Thank you to everyone else who has been there for me during these three years:

Peter Axel Nielsen: You have been an insightful, patient, and kind supervisor.

Coauthors of the papers included in this dissertation: Jesper Kjeldskov, Timothy Merritt, Mikael Skov, and Rune Møberg Jacobsen, for letting me tap into your areas of expertise.

Great colleagues at Aalborg University: Maria Kjærup, for being my Ph.D. sister. Rikke Hagensby Jensen and Michael Kvist Svangren for sharing your own experiences as Ph.D. students. The Ph.D. students and RAs in the HCC group, for being up to good times and spontaneous outings. The rest of the HCC group, for always helping with a smile. Claus A. F. Rosenstand, for pulling me back into the academic community and teaching me to be a better student of the world. Thessa Jensen, for listening and offering advice at any odd time. Helle Schroll and the rest of the department secretaries for support at every step of the way.

Collaborators at Bang & Olufsen: Kashmiri Stec, for sharing your insights on UX and life. Lyle Clark, for your exceptional design insights. The entire Audio and UX research groups, for offering constructive advice.

The ISOBEL research team: Søren Bech, Martin Møller, Kim Rishøj, Søren Nielsen, and Anders Kriegbaum, for being excellent mentors. The rest of the team, for great collaboration.

The MRL research group: Steve Benford, Adrian Hazzard, Jocelyn Spence, and the rest of the MRL research team, for welcoming me into the MRL group for my stay abroad. Andriana, Johann, Ed, and Petros for fun hot chocolate meetings in Nottingham and virtually. Gus, Velvet, Hanne, and Rebecca for continuously great collaboration.

Friends and loved ones: Kristina M. Madsen, for (seemingly) endless academic discussions with coffee and wine. Peter Vistisen, for believing that I could do it (I owe you one lightsaber). Heidi, Charlotte, Jonas, and Morten, for making sure my life wasn't all work. My family, for understanding (and sometimes being okay with not understanding).

TABLE OF CONTENTS

1. Introduction **1**

1.1. User Interfaces for Sound Zone Systems 2

1.2. Domestic Soundscapes 3

1.3. Research Questions 4

2. Related Work **7**

2.1. Personal Sound Zones 7

2.2. Personal Sound 8

2.3. Soundscape 10

2.4. Soundscape Interventions 12

2.5. Interaction in Physical Spaces 15

2.6. Key Terms 16

3. Research Design **19**

3.1. Philosophical Worldview and Research Logic 19

3.2. Methods and Techniques 21

4. Paper Contributions **33**

4.1. [P1] Temporal Constraints in HBI 35

4.2. [P2] Personalised Soundscapes in Homes 37

4.3. [P3] Experiences of Personal Sound Technologies 39

4.4. [P4] Designing for Domestic Sound Zone Interaction 41

4.5. [P5] Shedding Light on Sound Zones 43

4.6. [P6] Investigating Potentials of Shape-Changing Interfaces for Sound Zones 45

5. Discussion **47**

5.1. Sound Zones for Soundscape Intervention 47

5.2. Interaction Designs for Sound Zones 50

5.3. Conceptualising Sound Zones 53

6. Conclusion **59**

Reference List **63**

Appendix Overview **77**

LIST OF FIGURES

Figure 2.1: Soundscape, personal sound, and sound zone systems as used in this dissertation.

Figure 3.1: Research design.

Figure 3.2: Overview of data collection (DC) and data analysis (DA) methods according to each study.

Figure 3.3: Design process for the volume controller with light. The process involved different stages of externalisation.

Figure 3.4: Design process for the shape-changing interface. Like the volume controller, this process also involved different stages of externalisation.

Figure 4.1: The relation between the six papers produced throughout the Ph.D. project.

Figure 4.2: The convergence of interaction design and architecture enables interaction on different scales.

Figure 4.3: Different situations are characterised by different soundscapes.

Figure 4.4: Soundscapes can be shared or personal. In some situations, they are both.

Figure 4.5: Three different approaches to addressing challenges for designing interaction with sound zone systems in homes.

Figure 4.6: Light and colour can provide information about sound zone properties as a metaphor and through symbolism.

Figure 4.7: Shape-change can provide information about sound zone position and build users' expectations of sound zone behaviour.

Figure B.1: Lab setup for studies 5 and 6 (regarding light) as well as the start condition for study 7 (regarding shape-change).

Figure B.2: Lab setup for the final condition for study 7 (regarding shape-change).

Figure B.3: Sound in Person A's sound zone. Blue is Person A's personal sound, and red is Person B's personal sound. Corresponds to setup in Figure B.1.

Figure B.4: Sound in Person A's sound zone. Blue is Person A's personal sound, and red is Person B's personal sound. Corresponds to setup in Figure B.2.

PREFACE

This Ph.D. dissertation is based on research conducted from 2018 to 2021 at the Department of Computer Science, Aalborg University, within the Human-Centered Computing research group. The project came about as a result of collaboration between the Departments of Computer Science and Electronic Systems, Aalborg University, and three companies, Bang & Olufsen, Soundfocus, and Wavecare. Together, these partners established the ISOBEL project which is being funded by Innovation Fund Denmark from 2019 to 2023. The general subject of the project is sound zone systems, which are a technological solution to creating limited areas of sound inside a physical environment. The aim of the project is to "(1) Develop new signaling processing technology for making sound zones dynamic, (2) Develop new interaction techniques enabling user control of dynamic sound zones, [and] (3) Test interactive dynamic sound zones in real healthcare and domestic settings" [70]. As a Research Assistant in 2017, I became involved in the ongoing discussions between these partners about the opportunities and challenges posed by sound zone systems. Currently, it is only possible to create sound zones outside a lab using directional speakers. As new methods of constructing sound zones mature, designing the interfaces through which users can modify them becomes increasingly relevant.

When I started my Ph.D. project in 2018, one year before the ISOBEL project officially kicked off, I asked myself two questions. What do I need to know in order to design interaction with sound zones? And how do sound zone systems fit into existing acoustic environments? Beyond interfaces lies an understanding of what sound zone systems can be used for and how exactly they are constructed to modify the acoustic environment. Since that is dependent on the environment, I narrowed my focus to homes. Homes make up a unique domain with particular habits, needs, and desires for aesthetics. The research presented in this dissertation addresses the opportunities for designing interaction with sound zone systems in homes. The contribution spans six full papers.

The dissertation consists of six chapters: 1. Introduction introduces the research area and question, 2. Related Work covers previous research in similar areas and on similar questions, 3. Research Design outlines the philosophical worldview and methods utilised to investigate the research question, 4. Paper Contributions presents the papers and how they relate to each other, 5. Discussion clarifies how the dissertation extends and adds to current research, and 6. Conclusion addresses the main research question by summarising key findings and pointing to future research opportunities.

1. INTRODUCTION

People share physical environments such as office areas, public transportation, and living rooms in homes. In these environments, individual needs for light, temperature, sound, etc., sometimes clash and conflicts might arise. Sometimes, a satisfactory compromise can be reached, balancing individual experiences against each other. Other times, people choose to leave the environment, or they choose to stay and become stressed, because they are not equipped to control it. To prevent this from happening, one direction is to develop technologies for modifying soundscapes to allow people to share a physical environment without disturbing or annoying each other. A soundscape is the acoustic environment experienced by someone [108]. A sound zone system is a potential option for enabling individual soundscapes in shared physical environments without disturbing others. Through my research, I investigate ways in which sound zone systems can be controlled to achieve this.

This Ph.D. dissertation investigates interaction design for sound zone systems. Sound zone systems consist of loudspeakers that create limited areas of sound that allow multiple persons inside a shared physical environment to listen to different sounds without disturbing each other. The experience of being inside a sound zone contradicts typical prior experiences with sound. Using microphone measurements, signal processing filters, and a loudspeaker array, it is possible to maximise a sound in one area while minimising it elsewhere. This area can be widened or narrowed. Since users cannot rely on their experience of sound behaviour, sound zone systems pose challenges for designing interaction that supports an understanding of this new behaviour. Furthermore, sound zone systems are still an emerging technology that users have not had the chance to become familiar with. The technological solution has been refined in parallel to this Ph.D. project, making it a key condition that it did not exist at the outset of the project and only in a lab-based version during the final year. Therefore, the project also entailed addressing the challenge of how to carry out studies that contribute knowledge to this ongoing development.

In this dissertation, I frame sound zone systems as an intervention into a soundscape. Consequently, interaction with sound zone systems is a modification of a soundscape. I have investigated this modification with the aim of making a theoretical and design constructive contribution. Designing for interaction with sound is challenged by the intangible and invisible character of sound. Since users cannot interact directly with sound, an interface is necessarily an overlay to the experience. In this dissertation, I propose a design theory of 'sound zone configurations' that, through an exploration into what sound zones are and through concrete design prototypes, challenges and extends current research into the use and control of sound zones and of personalised sound.

1.1. USER INTERFACES FOR SOUND ZONE SYSTEMS

In this dissertation, my research is oriented towards interaction with a system that outputs sound. But how can interaction with something intangible and invisible be designed? While there is still no research on user interfaces for sound zone systems, a variety of other sound interfaces already exist, primarily for playing music. The physical interfaces of my vinyl record player, radio, and CD player contain similar playback buttons and volume knobs for controlling aspects of the music. Similarly, interaction with music in graphical user interfaces typically involves clicking arrows to switch between music tracks, dragging a slider to adjust the volume, and navigating through a digital library to find specific albums or discover new ones. Generally, the different modalities for sound control interfaces can be summarised as 'graspable', 'touch'-based, or 'freehand' [58]. One focus of this previous research has been to design peripheral interaction, because the activity of listening to sound, for example in the form of music, is typically secondary to another activity.

Controlling a sound zone system is different from these examples. While music or other sounds can be played inside a sound zone, control of a sound zone also involves the spatial properties of the sound in addition to the content. Typical music or sound interfaces can still be useful building blocks for a sound zone interface to be designed from, but in this dissertation, I argue that they are not sufficient. Sound zone systems are not only for playing music. They are also systems for creating multiple soundscapes in the same environment and thereby modifying the acoustic geometry of that environment. The current understanding of sound zone systems described by the audio engineers who construct them does not aid users in interacting with them, because it is limited to the methods of construction and lacks the experience-based perspective of soundscapes. From this perspective, two extensions can aid further research into user interfaces for sound zone systems.

First, in the process of designing interaction with sound zones, use situations can clarify particular challenges and conditions. Currently, sound zone systems are envisioned for a limited range of situations. These situations include people listening to different sounds in shared office spaces [15] and people watching a film together with different language preferences [77]. It is relevant to explore different use situations for sound zones because they can lead to different opportunities for interaction designs.

The second extension is how users can be supported in interaction with sound zones. Currently, there is a lack of investigations of user experiences of sound zones and for that reason, it is unclear how these differ from other listening experiences. There are recent examples of speaker systems which promise spatial sound experiences in different variants, for example the 'Cell Alpha' speaker by Syng [116]. One variant of the interface for this speaker enables users to place different sound sources in specific positions inside a room. This is done with the help of a mobile application utilising circular icons which can be dragged and dropped. Such an interface, however, does not offer control of and support for understanding specific properties of sound zone systems. It is relevant to ask: What is it like to be in or walk through a sound zone? This is a paraphrase of Thomas Nagel's 1974 paper

'What is it like to be a bat' [94] in acknowledgement of the fact that conscious experiences are subjective and consist of sensory stimuli in connection with prior experiences. It is not possible to precisely communicate the experience of sound zones since all representations are necessarily reduced to a descriptive model or translated, e.g., into text or illustrations.

To start off this investigation, it can be useful to consider sound zone systems in relation to a wider problem space. I look at lighting, because sound and light are similar in a number of ways. Can sound zone systems be compared with lighting systems to guide the investigation of how to design interaction with such a system? With this question, sound zone systems are positioned in a problem space emerging from multi-user settings where the output of an interaction affects all users. Sound is one type of output where one user can affect other present users. Light is another type of output with similar qualities, and therefore, it is relevant to consider if solutions for lighting are transferrable to sound zone systems. Previous research has expanded on lighting conflicts arising in homes where users have different preferences [98]. A comparison between sound and lighting conflicts in homes could offer some initial insights into the potential opportunities and challenges posed by sound zones. Both can be reflected off surfaces. It is possible to see light or hear a sound without being in eyesight of the actual light or sound source. Both sound and light can have bright spots and shadows, dependent on the physical environment. Finally, even though they are both physical phenomena, they are also intangible, which means that in order to control them, a user needs a mediating interface. However, it can be concluded that sound and light are also too distinctly different to easily transfer knowledge from one area to another, and here are the reasons why. First, sound and light have different physical qualities. For example, sound requires a medium such as air to travel through, travels slower than light, and does not travel as far. Second, there is the obvious difference that you can see but not hear light and hear but not see sound. This further results in differences between light and sound in multi-user environments. When a user modifies lighting, they can see how they affect the entire space. Sound offers no such feedback. Adding to this, sound zone systems do not behave as previous experiences would have users believe. This means that we cannot immediately transfer solutions for lighting interactions to sound interactions. Furthermore, there can be other challenges that are unique to managing sound in homes that call for specific interaction designs.

1.2. DOMESTIC SOUNDSCAPES

Sound zone systems can be used in various multi-user environments. The scope of this dissertation is homes. Sound is present in homes in many ways. It is produced by the people living there, house appliances, floors creaking, birds outside, and speaker systems. When people listen to music on speaker systems in their homes, these sounds are experienced together with all the other present sounds as a soundscape [108]. In this way, the experience of listening to music is affected by the acoustic environment surrounding a listener. The other way around, music also affects a listener's mood, sense of identity, and social experiences [81]. More broadly, annoying sounds reduce listeners' ability to behave proactively towards adapting their environment to their needs, and they can therefore impede health [8]. Annoying sounds are particularly characterised by constantly demanding a listener's attention [7]. A pleasant acoustic environment, on the other hand, makes the listener feel in control and promotes tranquillity. Aiming for this, homes are places that protect against natural elements and unwanted social interactions [46]. In a good home, there is a diversity of options for adapting both the environment and people's behaviour to accommodate needs as they come and go. Since many people spend most of their time at home, it is especially pertinent to consider ways of enabling control of soundscapes in homes. Sound zone technology is one emerging type of technology that offers new opportunities for doing this.

Homes are places for intimate, mundane activities supported by an infrastructure of technologies [101]. Crabtree and Rodden [35] explicated the value of using ethnographic methods for studying the activities in a home, with a specific focus on how communication is organised between members of a household. Even though the presence of an ethnographer inside a home somewhat disrupts the regular routines of the people living there, participants in a study can overcome that presence and 'get on' with their lives. This leaves the ethnographer with the opportunity to create rich descriptions of everyday life. In such an endeavour, it should be acknowledged that homes are continuously changed by those living in them. This means that new infrastructures of technologies need to be open to dynamic modifications [106].

1.3. RESEARCH QUESTIONS

Based on the research challenges and the introductory framing outlined above, the research question guiding this Ph.D. project is:

How can interaction with sound zone systems in the home be designed for modifications of soundscapes?

This research question has been investigated through studies across homes and laboratory setups, utilising ethnographic, constructive, and experimental methods. To support the investigation, the research question is further elaborated on in two sub-questions. These questions relate to, first, sound zone systems as theoretically framed as a soundscape intervention and, second, the way in which particular interaction designs can support users' understanding and control of sound zones. Therefore, the first sub-question I pursue is the following:

[SQ1] What characterises the relation between sound zone systems and soundscapes?

The relations that can exist between sound zone systems and soundscapes are at the core of the main research question as they call for particular ways of configuring the setup and thereby set the foundation for interaction designs. Through an investigation into this, I extend the existing body of knowledge on sound zone systems with a framing that focuses on the perspective of the listener who experiences sound in a particular way. This forms a foundation for synthesising the knowledge into particular design challenges and investigating how the experience can be configured with particular designs. Therefore, I pursue the following second sub-question:

[SQ2] How can interaction designs support users' understanding and control of sound zones?

Investigating the second sub-question, I synthesise the findings from the first sub-question into an overview of design challenges for sound zones in homes. I then use this overview as a point of departure for experiments with a design constructive approach. With this, I extend existing research with knowledge into the experience of different interaction designs for sound zones. The accumulated findings lead me to the main ambition of the project, which is to offer a theory of sound zone configurations from the perspective of user experiences.

The research is reported in 6 full papers, covering the two research sub-questions:

(Please note that the author of this dissertation was published as Stine S. Lundgaard from 2017 to 2020 – the author is marked in bold for each paper.)

[P1] **Stine S. Lundgaard**, Jesper Kjeldskov, and Mikael B. Skov. 2019. Temporal Constraints in Human--Building Interaction. *ACM Trans. Comput.-Hum. Interact.* 26, 2, Article 8 (April 2019), 29 pages. DOI: https://doi.org/10.1145/3301424

[P2] **Stine S. Lundgaard** and Peter Axel Nielsen. 2019. Personalised Soundscapes in Homes. In *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19)*. Association for Computing Machinery, New York, NY, USA, 813–822. DOI: https://doi.org/10.1145/3322276.3322364

[P3] **Stine S. Johansen**, Peter Axel Nielsen, Kashmiri Stec, and Jesper Kjeldskov. 2021 (accepted for publication). Experiences of Personal Sound Technologies. In *IFIP Conference on Human-Computer Interaction (INTERACT'21)*. Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-85616-8_30

[P4] **Stine S. Lundgaard**, Peter Axel Nielsen, and Jesper Kjeldskov. 2020. Designing for Domestic Sound Zone Interaction. *Personal and Ubiquitous Computing* (March 2020), 1-12. DOI: https://doi.org/10.1007/s00779-020-01387-2

[P5] **Stine S. Johansen**, Kashmiri Stec, Peter A. Nielsen, and Jesper Kjeldskov. (Submitted to CHI'22). Shedding Light on Sound Zones.

[P6] **Stine S. Johansen**, Timothy Merritt, Rune M. Jacobsen, Peter A. Nielsen, and Jesper Kjeldskov. (Submitted to CHI'22). Investigating Potentials of Shape-Changing Interfaces for Sound Zones.

In the following chapters, I outline the research in terms of related research, methods utilised to investigate the research questions and the contributions covered by each paper. Finally, I discuss how the contributions extend current research and offer novel knowledge on designing interaction with sound zones in homes.

2. RELATED WORK

Based on the research question and challenges outlined above, the related research spans the areas of personal sound, interaction with sound, sound zone systems and soundscapes. Expanding the audio engineering view on sound zone systems, I review research in personal sound and soundscape. This further includes research on soundscape interventions. Finally, I use perspectives from architectural interaction where the point of departure is interaction with the built environment.

2.1. PERSONAL SOUND ZONES

This project emerged from the development of sound zones within the discipline of audio engineering. In this discipline, the main concern is transduction, which, in short, means that energy is transformed from an acoustic form into an electrical form [118]. This is also known as signal processing. Sound zones are described within audio engineering as the result of an array of loudspeakers delivering sound to defined areas of a physical room and reducing it in other areas [15]. An approximation of the underlying technical idea was demonstrated in 1967 at the Illinois Institute of Technology where Camras proposed reproducing sound from a preferred listening spot in an auditorium inside a smaller, enclosed area somewhere else [24]. The approach included directional microphones that recorded sound from the listening spot and an array of loudspeakers in the enclosed area to reproduce the recorded sound. In 1997, the concept of 'personal sound zones' was developed by Druyvesteyn and Garas, who proposed a vision where multiple persons in the same room can listen to different sounds without headphones or annoying each other [45]. For constructing sound zones, they included different methods for different frequency ranges. Low frequencies can be controlled with active noise control (ANC), mid-frequencies can be controlled with beamforming, and high frequencies can be controlled with directional loudspeakers.

The paper by Druyvesteyn and Garas has formed a foundation for research on sound zones in the past two decades. During this period, the vision for sound zones has expanded into other domains than homes such as car cabins [30] and outdoor concerts [61]. Depending on the domain, the way multiple sound zones in a space are constructed can differ, but two criteria generally have to be met: (1) the acoustic contrast between sound zones should be maximised, and (2) the sound must be minimally distorted. The acoustic contrast should be at a level where a person inside one sound zone is not distracted by the sound from another sound zone. Betlehem et al. summarise techniques used to achieve this as 'acoustic contrast control' and 'pressure matching' [15]. The technique of acoustic contrast control involves distinguishing between a bright and a dark zone. For each sound that a user wants to listen to, the acoustic energy should be high within the bright zone and reduced in the dark zone [29,32]. To achieve this, microphones positioned throughout the space measure the sound pressure. These measurements can then be used to determine the sound pressure ratio, known as target-to-interferer ratio (TIR), between the bright and the dark zone, and this ratio is subsequently maximised. The pressure matching technique builds on this by focusing on increasing the pressure of the reproduced sound within the bright zone and decreasing it everywhere else. The technique is inspired by the crosstalk-cancellation problem that, for example, emerges when a speaker setup should reproduce specific sounds for the left and right ear. In this case, methods include playing the signal for the right speaker into the left speaker at the correct delay and phase, and vice versa. This cancels the part of the sound that should not be heard by the left and right ear, respectively. The result from using this technique for sound zones is a low level of error in reproducing the sound in the bright zone compared to acoustic contrast control [79]. Essentially, both of these techniques rely on the design of software processing filters to optimise the sound in each sound zone [97].

The acoustic contrast can also be described as sound leakage from one zone to another zone. When sound zones are constructed in a real physical space, the sound from the bright zone leaks into the dark zone to a certain degree. To determine how much leakage is too much, research has taken perceptual attributes into account. In a listening experiment with both speech and music sounds, Rämö et al. [105] asked users to rate how much an interfering sound distracted them from the sound they were listening to. They found that the TIR between the bright and dark zone should be at least 25 dB in order to reach a satisfactory distraction score. In a similar line of thought, other research has included perceptual models for constructing sound zones [78]. The premise behind this work is that the type of sound and the human auditory system matters when assessing the quality of sound zones, thereby potentially reducing the requirement of a TIR of 25 dB.

Relating to sound zones as they are described here are directional sound beams which also offer users physically limited areas of sound without headphones. Pompei proposed the idea of using ultrasound as an acoustic projector in 1999 [103]. Ultrasound contains frequencies that are above the human hearing range. When it travels through air or other non-linear media, however, the shape of the beams is changed so that they are within a new frequency range and become audible. Ultrasound has very small wavelengths, making it possible to create narrow beams of sound. Pompei developed this into a commercial speaker technology called Audio Spotlight [63]. Following this, other variants have been developed, including Soundlazer [54] and Acouspade [120]. However, ultrasound speakers have drawbacks that make other ways of constructing sound zones, such as described above, an attractive alternative. Ultrasound speakers typically lack low range frequencies, and users have reported fatigue when exposed to high levels of lower-frequency ultrasound [104].

2.2. PERSONAL SOUND

Within the field of acoustics and audio engineering, research focuses on sound travelling through different media such as air and water. When the sound reaches an ear, the field of psychoacoustics focuses on how that sound reaches the brain and is processed as a piece of information. This allows a distinction between the physical parameters of sound, such as frequency, and subjective parameters, such as pitch. Building on this, Truax suggests that a sound mediates the relationship between a listener and their environment [118]. The promise of sound zone technology is to deliver sound to a specified area as desired by one or more users. Therefore, sound zone technology should be considered within the wider area of personal sound as an experience that can be obtained using multiple different technologies.

One example is the investigation by Bull centred around the Sony Walkman, referred to as a 'personal stereo', and how this technology fits into users' everyday lives [22]. He emphasises the mobile aspects of the personal stereo which enable "…users to travel through any space accompanied by their own 'individualized' soundworld" [22]. Personal stereos give users the ability to bring personalised sound with them wherever they go, thereby distinguishing it from other headphone technologies. Bull suggests that this changes a user's relationship with the urban environment through a reorientation and re-spatialisation of the experience, i.e., the personal stereo creates a boundary that reshapes the space around them. A similar point is stated by Hagood who investigated marketing material of QuietComfort, a set of noise-cancelling headphones by Bose, aimed at business travellers [55]. Travellers use the headphones to create a personal space inside the public space they are moving through.

Haas et al. refer to this mix of personal and environmental sounds through for example headphones as 'interactive auditory mediated reality' [52]. Headphones offer mediated reality when they are hear-through. Headphones with active noise cancellation, therefore, can be defined as mediated virtuality. One finding in this study relates to user agency and understanding of their acoustic environment. While automation of noise reduction might offer benefits, users in the study by Haas et al. emphasised a scepticism towards alterations that could lead them to missing important auditory information. In order to take control of these alterations, however, users need an understanding of the consequences of making them. When users take control, they engage in a process termed 'personal soundscape curation', which can involve different types of technologies and modification of different sound properties such as volume or frequency spectrum [53]. This is dependent on factors such as the user's capabilities and requirements.

One functionality which enables blending between personal and environment sounds while using headphones is acoustic transparency. Whether or not a user experiences a sound as real or not, though, is another factor. In one study, users listened to birdsong though noise-cancelling headphones while walking outside [87]. Even though they knew the capabilities of the technology, some users experienced the birdsong as real. This prompts questions such as how users' awareness can be steered when they wish to modify their acoustic environment while still retaining a sense of auditory presence as they are walking outdoors. Indoors, headphones can be used together with sound from a TV to create individually adapted experiences [86]. The authors note that this is also relevant for shared experiences by for example adding new elements to repeat views for users watching with first-time viewers. These studies use different technologies for 'personal sound' that are all wearable but can still be differentiated. They include headphones that close off the relation between users and environment through noise cancellation and acoustically transparent headphones such as the Bose Frames.

2.3. SOUNDSCAPE

Taking a step back from technologies that offer personal sound in different ways, the sounds that users listen to intentionally are part of the entirety of hearable sounds surrounding them. This entirety is referred to as the user's soundscape. Similar to seeing, we can choose to focus on a particular sound object, but without active noise cancellation in headphones or a physical barrier, we can still hear all the other sounds in an environment. Soundscape research encompasses multiple branches, the breadth of which cannot be covered fully in this section. Therefore, the following covers soundscape research that is relevant to the specific research question in this Ph.D. project. One point I wish to underline is that the research presented here focuses mostly on urban areas and only in a few cases mention indoor soundscapes in homes. Still, as I outline in the next section, the methods and theory developed for urban areas have been adopted for other domains in HCI research. Several methods have been proposed for exploring and mapping soundscapes, including interviews, recordings, ear cleaning and soundwalks. These empirical methods have in common that they focus on how the acoustic environment is experienced and described by people.

Current research on soundscapes has its roots in the World Soundscape Project (WSP), a research group in Vancouver, Canada, established by Schafer in the late 1960s. Schafer taught a course on noise pollution at Simon Fraser University, and the WSP was built on attempts to steer attention towards the relationship between humans and their acoustic environment. The field of acoustic ecology research emerged from the WSP as "…the study of sounds in relationship to life and society" [108]. This entailed an approach to studying soundscape that emphasised perception of sounds and not just the acoustic environment as an objective phenomenon.

To Schafer, a distinction is to be made between sounds that appear naturally in an environment and sounds that do not. Through his research into noise pollution, he became concerned with developing a framework for determining which sounds to preserve and emphasise. He argued that unnatural sounds, such as traffic noise, make it increasingly difficult to do so, because people learn to ignore those sounds and thereby become worse listeners. One approach to (re)building listening skills is 'ear cleaning', for which Schafer developed the method of 'soundwalking'. In short, this is an active listening exercise performed while walking [108]. Other ear cleaning exercises are stationary and focus on listening for certain sound textures or performing an activity as silently as possible [107]. Becoming better listeners will, according to Schafer, allow a re-evaluation of noise and how it affects quality of life.

Truax, a founding member of the WSP research group, offered a complementary perspective on soundscapes. He uses the term 'acoustic communication' to describe all sound manifestations from a human perspective [118]. Instead of viewing sound as simply energy transfer, he suggests that sound carries information and thereby functions as a mediator between a listener and their environment. Sound can, on the one hand, support shared experiences and, on the other, isolate individuals. In this project, I use the term soundscape as formulated by Truax "…to put emphasis on how that environment is understood by those living within it" [118]. The point of this is to understand functionalities of sound rather than aesthetic qualities. Both Truax and Schafer aim to inform a new research discipline, acoustic design, through a combination of applied and artistic fields of sound studies.

While the approaches described by Schafer and Truax form a foundation for soundscape research that places the listener at the centre, the definition itself is fuzzy. A study was established in 2006 to develop a common language between professionals and encourage the use of empirical data to construct interventions into soundscapes [88]. The study included professionals within acoustics, sound design, and IT. A survey was used to elicit definitions of 'soundscape' and 'noise' as well as classification, notation, and visualisation methods for sound. The findings showed little consensus on definitions and methods between professions. For example, IT participants used the term 'sound event' whereas sound designers preferred 'sound', separating the term from the source. A working group within ISO/TC 43/SC 1 (noise) was established in 2008 with the purpose of establishing standardised methods for assessing the quality of soundscapes [20]. The members came from various backgrounds, such as engineering, architecture, psychology, and geography, and one of the first challenges encountered was the diverse views on what a soundscape is. The outcome was a statement that "…a *soundscape* exists through *human perception* of the *acoustic environment* of a place" [20], based on both Schafer's and Truax's research. Soundscapes have, in contrast with the working group's definition, also been studied as physical phenomena. For such approaches, the working group's recommendation is to restrict such studies to measurements by ear.

Soundwalks were used by Schafer and other members of the WSP research group to identify and document soundscapes in Vancouver and other areas in different countries by, essentially, listening while walking. Soundwalks can be carried out alone or in groups, in a wide area or in a specific place [125]. In some studies, researchers use the method to engage themselves in a soundscape and in other studies, people living within an area are invited to engage with and describe their soundscape [1]. One example is a study conducted in Clerkenwell, London, with 30 residents [2]. Participants marked a walking route close to their homes on a map and were instructed to pay attention to what they heard while walking. A researcher followed each participant and recorded the sounds. This formed the basis for semi-structured interviews about the quality of the acoustic environment to uncover which sounds the residents experienced as unwanted. In this and other similar studies, the soundwalk method has proven valuable for engaging people with no professional background in sound.

Soundscapes can be described in many ways, and it has been a goal in previous research to outline assessment criteria and metrics based on perceptual descriptions to steer policies on built environments and urban development [19]. This is an addition to, for example, the noise guidelines published by the World Health Organization (WHO), which focuses on assessing health risks from noise levels measured physically in dB [132]. Within the field of soundscape, researchers aim at developing tools for characterising acoustic environments in terms beyond wanted and unwanted sounds. One study shows that soundscape perception has three dimensions: pleasantness, eventfulness, and familiarity [10]. The first two dimensions can be used to position different types of soundscapes. For instance, the authors state that a calm soundscape would be highly pleasant and low in terms of eventfulness. These findings were based on having participants listen to binaural recordings of soundscapes inside a listening room. Another approach suggests that visual impressions influence people's assessment of sound quality and, therefore, argues that tools for soundscape assessment should be developed within the same context for which they will be used [14]. Similarly, different activities prompt different responses as to whether or not a particular soundscape is appropriate [96]. For instance, certain sounds carry relevant information for some activities but can be ignored during other activities. This is partly based on prior experiences that set expectations for soundscapes in certain places [21].

2.4. SOUNDSCAPE INTERVENTIONS

When users modify their soundscape, the way that the interaction is designed sets the boundaries for the intervention. From this perspective, a distinction can be made between soundscape intervention and soundscape interaction where interventions can happen without interaction, but interaction always results in an intervention. Studying and assessing the quality of soundscapes is a first step towards modifying them through an intervention. Soundscapes can be modified in different ways by either designers or the people inhabiting them. Hellström [59] identified three strategies for designers to modify soundscapes: defensive, offensive, and creative. Whereas the defensive strategy is directed towards shielding people from unwanted or unhealthy sounds, the offensive strategy is directed towards emphasising wanted sounds. The creative strategy is directed towards adding new sounds into the acoustic environment. These strategies can be used in combination with each other to improve a soundscape [27]. In a similar distinction, Højlund [62] proposes that 'insulation strategies' that focus on general noise reduction can be expanded with a human-centred approach by focusing on subjective experiences of particular sounds.

One challenge when designing interventions into a soundscape is how to represent elements of the soundscape [84]. Representations impact an intervention in two ways. First, representations can be made to enable reflection and discussion throughout a design process. Second, the actual intervention can consist of using representations to allow users to modify or control aspects of their soundscape themselves. As an example of how to enable reflections, McGregor et al. developed a tool for soundscape mapping in workplace environments [89]. Their method included three phases for mapping an open-plan office in one-week intervals: (1) Recording sounds in a two-hour period, (2) Asking participants to note the sounds they heard, and (3) Interviewing participants to clarify any elements that were missing from the notes. The interviews focused on interactive functions of individual sounds to uncover informational properties such as warning, relaxing, confirming, and so on. Using this method, they gained insights into the disparity between the sounds participants noticed and the actual sounds occurring in the environment as well as differences in behaviour between permanent and intermittent staff. Permanent staff adapted the volume of their voice more often to the environment than intermittent staff. McGregor et al. suggest applying this method to other environments for further generalisability and scalability. Another example is Coleman et al. [33] who presented a 'sonic mapping tool' to be used for clarifying opportunities for soundscape interventions through three steps. First, notes in text assist in the process of capturing the acoustic environment. Second, key sounds and their associated meanings are identified. Third, earwitness accounts of the acoustic environment provide narrative context.

As an example of using soundscape mapping to design a soundscape intervention, Alexanderson and Tollmar [6] studied the soundscape inside a chemical factory with the purpose of designing interactions with the soundscape. The approach entailed making recordings inside the working environment and facilitating interpretation sessions with participants. While McGregor et al. suggested a generic classification scheme, Alexanderson and Tollmar derived themes inductively when analysing the sessions. On this basis, they presented three concepts for either emphasising particular existing sounds or adding new sounds. These include SonicProbe, a personal device for recording everyday sounds, SonicRep, a device for sharing and reviewing sounds recorded previously, and finally ScapeNav, a device for enhancing awareness of and mediating far away sounds. These concepts fall under Hellström's offensive and creative strategies. Three takeaways from Alexanderson and Tollmar are that (1) sound offers unique qualities in comparison with other media that require attention, (2) it can effectively carry large amounts of information in dynamic ways, and (3) it supports distributed awareness in space and time. One example of using sound for information is offered in a study on traffic safety [133], where Yoon et al. describe the challenge of how using headphones in public spaces makes it more difficult to detect a potentially dangerous situation through sound. They propose a warning system consisting of a sound sensor that listens for particular sounds in the acoustic environment and forwards a message to a user through the headphones. Other research on sound notifications shows benefits from playing continuous ambient sounds for information compared to binary on/off sounds [31].

The role of the user has also included self-design of soundscapes in previous research on public spaces. Chamberlain et al. suggest an autoethnographical approach to involving a community in designing soundscapes in public spaces [28]. The approach was explored through physical cubes that trigger certain sounds according to how participants position them. This enabled participants to imagine new experiences from connections between sounds, places, and technology. In a follow-up analysis, design opportunities for integrating digital technology into particular public spaces were revealed. While this study focused on personal heritage in soundscapes, tangible interfaces for creating artistic, musical expressions have also shown to be useful for engaging people with a public space [50].

Sound has played different roles within HCI and interaction design. Sonic interaction design is an area within HCI which is focused on mediating user-sound relationships through technology, especially in the form of sound feedback. Franinović and Serafin explain that sonic interaction design considers "…sound as an active medium that can enable novel phenomenological and social experiences with and through interactive technology" [49]. In other words, sonic interaction happens when a user performs an action with an interactive technology that results in a sound. Different action-sound relationships are described by

Caramiaux et al. [25] on the basis of a series of participatory design workshops. The first is 'substituting', which lets the user perform an action as if they were a substitution for the actual source of the sound. For example, one participant imagined being the bell on his bicycle. The second is called 'manipulating', which lets users control the feature of a sound through particular interactions. Finally, 'conducting' relates particular interactions with particular sounds in a semantic way.

Haas et al. point out in their paper from 2020 [52] that a minority of previous research focuses on interaction with sound and not interaction with sound feedback such as clicking sounds in digital touch interfaces. The latter was discussed in the late 1980s by Gaver [51], who concerned himself with the design of auditory icons. Research on interaction with sound is mainly aimed towards music composition and mixing. One example is the BoomRoom presented by Müller et al. where users manipulate sounds directly in a spatial music mixing room [93]. They found that participants were able to precisely locate sounds in a 3D space without visual feedback, and that tangible objects can be used as physical representations of sounds. Dahl and Wang presented another example in the form of a gesture-based instrument constructed as an application on an iPod Touch [38]. The study showed that using a ball metaphor for sound elicits playful and accessible interactions with sound. The examples have in common that they use metaphors for the sound as a basis for designing interactions. They describe the sound as an object that can be touched and moved by hand. For controlling music as opposed to creating or mixing it, Hausen et al. categorise different modalities for interfaces such as 'graspable', 'touch'-based, and 'freehand' [58]. Graspable interfaces, which might also be called tangible interfaces, include examples such as the Gesture Cube [76] and Musico [117] that allow users to playback, pause, and switch between music tracks. Touch-based sound interfaces have been investigated with the aim of designing control without visual feedback, including for PDAs [102], as an integrated device in car steering wheels [42], and a circular touchpad [134]. Finally, free-hand includes examples such as the BodySpace system [114], where users perform gestures to simulate moving a ball in the air, and the gesture sets investigated by Kim et al. [73] for wearable objects and by Wolf et al. [131] for handheld.

Previous research reveals unique practices around sounds and design opportunities for the 'domestic soundscape'. Leong and Wright [81] conducted a study on social practices around music that emerged within five participating households. Participants were interviewed twice and asked to keep a diary in between interviews. The first interview focused on outlining the existing range of interactions participants have with music in their homes, including routines and preferences, and the second interview focused on experiences over the study period. They found that participants reconfigured technological systems in various ways to enable new social interactions. One participating couple, for example, figured out that while both were wearing wireless headphones, they could tune into each other's music and get a 'peep' into an otherwise personal listening activity.

In a broader study, Oleksik et al. investigated soundscapes in homes and practices for managing them [99]. They recruited seven households and interviewed each household twice. In the intermediate period, participants were asked to keep a sound diary of recorded sounds they liked and disliked as well as sounds that reminded them of home. The findings point to design opportunities for soundscape management based on the role technology can play in (1) connecting remote spaces acoustically, (2) tailoring sound to individual preferences, (3) supporting an understanding of how personal sound affects others nearby, and (4) recording sounds with sentimental value. One of the concepts suggested by Oleksik et al. is to connect different homes with each other to achieve a sense of background presence of, for example, distant family members. Similarly, Baharin et al. [11] use technology probes to explore opportunities for reducing seniors' feelings of isolation from their families and friends. The study showed that relaying activities from one home to another through sound supports social connection between families by, for example, enabling them to develop shared rhythms of daily routines.

2.5. INTERACTION IN PHYSICAL SPACES

Sound travels across a physical space through the air. With sound zone technology, the way that the sound travels is controlled to a certain degree. Even so, a listener is surrounded by the sound in a similar way to being surrounded by light. One way to consider how interaction can then be designed is as Wiberg does; he argues that the fields of interaction design and architecture are increasingly converging [127], opening up opportunities for architectural interactivity [128]. This is a result of increasingly integrating digital technology into the built environment to enable reconfigurations of a physical space. As a consequence, the potential scale of interactions has changed. Whereas interaction design typically revolves around the use of devices small enough to manage by hand, architecture revolves more around people inhabiting a space. It is relevant to consider how structures of physical space are impacted by sounds and subsequently, how this enables new opportunities for interaction designs.

The geometry of a physical space affects how it sounds. This is also referred to as 'aural architecture' [17]. Aural architecture can enhance certain behaviours and feelings. For example, a quiet chapel can enhance a sense of privacy, and footsteps on a hard floor in a lobby can alert service desk assistants of people entering. These examples emphasise that listening is an essential aspect of aural architecture. Blesser and Salter argue that aural architecture is as much a part of a soundscape as individual sound events [17]. Sound events are necessary to 'illuminate' the way that the physical space affects them, and a listener then experiences them as a soundscape. This gives the listener information about the properties of the space, such as physical barriers and size. Spaces with distinct acoustic properties have been shown to be recognisable from recordings of sound events after several weeks [112].

Sound has also been considered in relation to architecture, or the built environment, within HCI. In 1998, Ishii et al. [69] envisioned that the built environment could become a new interface between people and digital information. They presented the ambientROOM as an office 'interface environment' which, among other elements, provides users with information through sound. For example, sounds could include birdsong to represent the number of unread e-mails. This line of research deals with converting data into non-speech sounds as opposed to focusing on sounds naturally emerging from the physical environment; also referred to as 'sonification' [60].

Franinović and Salter propose an extension to sonic interaction design that positions sonic interaction in the physical world as it is experienced by listeners, together and individually. Within the field of sonic interaction design, the model of interaction follows a typical formula of input → mapping → output [48]. Input typically involves a form of sensing, mapping is a data processing step, and output is a form of sound expression. Franinović and Salter argue that designing interaction with sound can be supported by an elaboration of this interaction model. They propose extending the concept in five ways. First, sound is different from other sensory modalities in terms of its spatiotemporal and material properties. Second, they suggest that interacting with sound is a creative process involving touch, listening, and moving. Third, the experience of interacting with sound is embodied and situated, making the experience dependent on each listener's body and position. Fourth, the action itself is performative, because the result is not yet existing and changes over time. And finally, they distance themselves from abstract representations of sound that are unrelated to specific listeners.

2.6. KEY TERMS

In order to align the research with a coherent use of terms, I define key terms according to the previous research presented in this chapter. Figure 2.1 illustrates how these terms differ from each other. Below, I list the key terms 'soundscape', 'personal sound', and 'sound zone system'. These terms are related in different ways, as I will detail.

[A. Soundscape] A soundscape is the acoustic environment as experienced by someone in a particular situation performing a particular activity. The properties of the physical space and sound sources contribute to form a soundscape, but the experience is individual.

[B. Personal sound] Personal sound is when sound is physically centred around one person so that, ideally, other people cannot hear it. This can be achieved with different types of headphone and speaker technologies. Subsequently, the sounds and physical space that contribute to experienced soundscapes can be shared or personal.

[C. Sound zone system] A sound zone system is a technical solution that creates physically limited areas of sound without headphones. These areas can be personal or shared. The system consists of a loudspeaker array in combination with acoustic contrast control and pressure matching techniques through which a sound is controlled using software filters. The properties of the resulting sound zone are volume, size, position, and overlaps.

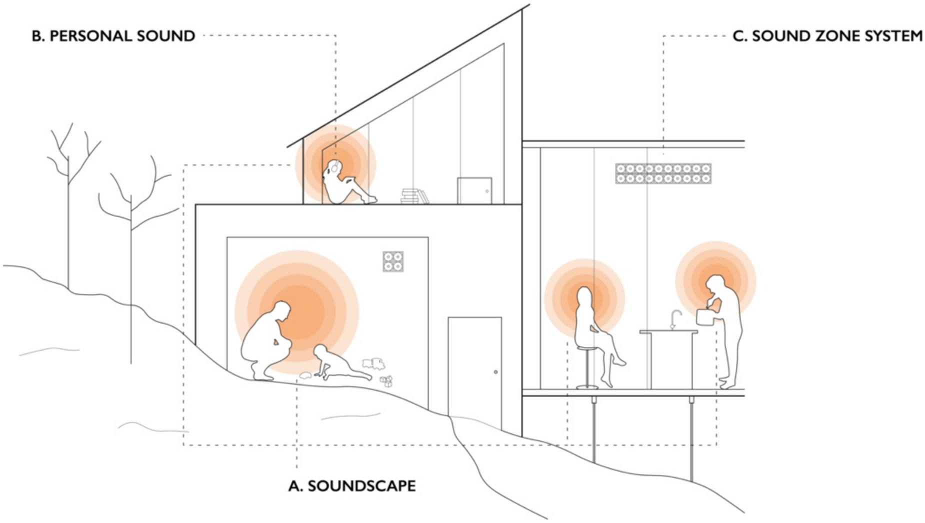


Figure 2.1: Soundscape, personal sound, and sound zone systems as used in this dissertation.

3. RESEARCH DESIGN

This chapter outlines the research design of the dissertation, which sets out to investigate the main research question. The design is dependent on a philosophical worldview and chosen research methods, based on Creswell and Creswell's framework for composing a research project [36]. They illustrate the three elements as a triangular framework in which worldview, methods, and design intersect. To make a research plan, the elements and intersections must be specified. 'Research design' in this dissertation is the combination of a philosophical worldview, research logic, and methods and techniques, see Figure 3.1 for an overview.

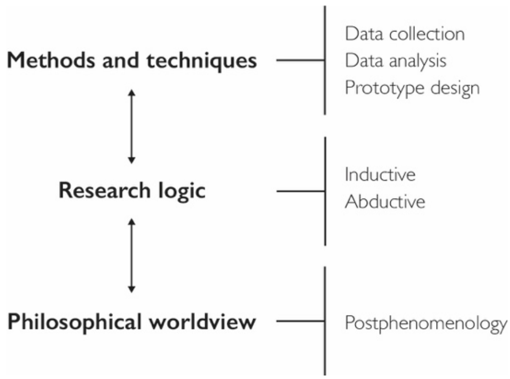


Figure 3.1: Research design.

At the outset of this research, the approach was mainly exploratory. I aimed to generate knowledge to later provide guidance in constructing and evaluating prototypes. Addressing the first sub-question, then, was done through qualitative studies, seeking to structure gathered data in a way that points to the opportunities and constraints involved in designing interaction with sound zone systems in homes. Addressing the second sub-question, I inferred insights from quantitative and qualitative evaluations of prototypes that address specific design challenges.

3.1. PHILOSOPHICAL WORLDVIEW AND RESEARCH LOGIC

I adopted a postphenomenological worldview for this research. A philosophical worldview consists of a set of views that guide my judgement of which activities to engage in. It defines how I address ontological questions about what I determine as true, and it shapes the appropriateness of methods utilised. Postphenomenology is a way to approach the world in terms of what appears to someone [121]. With this worldview, I see a sound zone system, including devices for controlling it, as a mediation between a user and the world.

As the name suggests, postphenomenology developed from research in phenomenology founded by Husserl and further developed by Merleau-Ponty and Heidegger, among others. Husserl's research centred on the notion of intentionality, which describes how a person's thoughts relate to an object in the world [26]. For example, a person does not just see—they see something. A phenomenological study seeks to describe the experiences that different persons have of the same phenomenon and extract "the universal essence" [37]. Heidegger developed this perspective with a focus on technology, the aim being to derive the 'essence' of technology [66]. In postphenomenology, developed initially by Ihde [67], the focus has shifted towards technology as a mediator between a person and the world.

Ihde refers to postphenomenology as "a pragmatic phenomenology" [67]. He draws on Dewey, who posited that if experience and objects in the world are isolated from each other, the result is a reduced view of experience as the mere process of experiencing [41]. On this basis, Ihde proposes two ways in which phenomenology can enrich this pragmatist worldview under the term 'postphenomenology'. First, it is useful to consider an experience by someone or something as nonsubjectivistic, meaning that it exists relative to the experiencer and the objects in the world. Second, phenomena can be said to vary according to the experiencer's previous experiences and structural features of an object. Ihde proposes that such variations can be used to uncover multistable patterns of phenomena, e.g., how the same drawing can look like a duck, a rabbit, or a squid, depending on the perspective of the viewer. In other words, the same technological system can have different use trajectories and be situated in different ways in the world [66].

A key idea within this worldview is relations, of which Ihde defines four: embodiment, hermeneutic, alterity, and background. In this dissertation, I narrow my focus to embodiment, which has received increasing attention in the field of HCI [9,13] as a tool for interpreting users' interactions with digital technologies. The term embodiment is also useful to this research because sound zone systems offer new ways for users to relate to their physical environments and to other people. Embodiment was described by phenomenologist Merleau-Ponty and later put into the context of HCI research by Dourish [43] and Svanæs [115], among others. Dourish defines embodiment as "…the common way in which we encounter physical and social reality in the everyday world" [43]. Embodiment emphasises the fact that sound zone experiences involve users' entire body through which there is already tacit knowledge about the world and, specifically, sound behaviour. Following this, 'embodied interaction' is described by Dourish as "…the creation, manipulation, and sharing of meaning through engaged interaction with artifacts" [43]. This implies that action is needed in order for meaning to develop, based on Merleau-Ponty's philosophy which underlined that perception presupposes action [90]. For hearing, this can be understood as a distinction between hearing, as a passive act, and listening, as an active act [115]. In relation to postphenomenology, Ihde describes embodied relations as a unity between humans and technology, for example speaking through a phone as opposed to speaking directly to it. For sound zone systems, this indicates that a user listens to sound through a speaker as opposed to attending to the speaker itself [121].

The postphenomenological worldview has shaped the research approach by centring around understanding the phenomenon of sound zones and how they are experienced. Based on this understanding, I seek to construct a model of reality that can describe experiences of configurations. This relies on applying inductive and abductive logic to investigate the object of study. Inductive logic has been applied to study particular instances and infer frameworks that structure and thematically describe experiences. Abductive logic has been applied to pair pieces of knowledge that point to further research directions.

Inductive logic is typically used to answer 'what' research questions [16]. The strategy when applying this type of logic is to outline how collected data are related along, e.g., different dimensions. This necessitates establishing ahead of data collection what to look for when conducting a study. To exemplify, the first research sub-question in this Ph.D. project is about the relation between sound zone systems and soundscapes. Therefore, it is relevant to collect data on how people experience personal sound technologies in relation to other sounds around them as well as how they use technologies already to manage soundscapes in their homes. In the application of inductive logic, qualitative depth is emphasised as opposed to quantitative overview. This fits the postphenomenological worldview by focusing on descriptions of how people relate to the physical environment through different technologies. Verbeek states that, from a hermeneutical perspective, experience arises from interactions between sensuous perceptions and the context in which they are made [121]. Following this, inductive logic is appropriate as an approach to uncovering experiences.

Abductive logic can also be used to answer 'what' research questions in addition to addressing 'why' questions [16]. Peirce coined the term abduction, which he describes as "…the only logical operation which introduces any new idea" [100]. As abduction is conceived within his pragmatic philosophy, it is an appropriate research logic within the postphenomenological worldview. This includes a focus on interpretations and the intentions of people in their everyday lives. Whereas I apply inductive logic to explore the phenomenon of study, I apply abductive logic to construct change and develop theory about the phenomenon. In other words, the inductive logic leads me to address the research top-down through related research, while the abductive logic leads me to address the research bottom-up through developing a new understanding of the whole. Developing theory entails a simplification of phenomena in some ways and, for this reason, I do not aim to make a statement about complete truth, but rather to develop a useful lens. In this process, I connect and disconnect with the phenomenon to both gather data and construct a lens from it [92].

3.2. METHODS AND TECHNIQUES

This section covers the choice and appropriateness of the methods and techniques utilised for the Ph.D. project. For each research sub-question, data collection and analysis methods are detailed. Broadly, a mixed-methods approach is applied to the research, investigating the main research question through studies with either a qualitative approach or a combination of qualitative and quantitative approaches. Figure 3.2 provides an overview of the data collection and analysis methods used for each study. The first three studies address research sub-question 1 and aim at understanding the phenomenon in focus. This is followed by a synthesis process which forms the basis for three final studies that address research sub-question 2 through being design oriented and constructive.

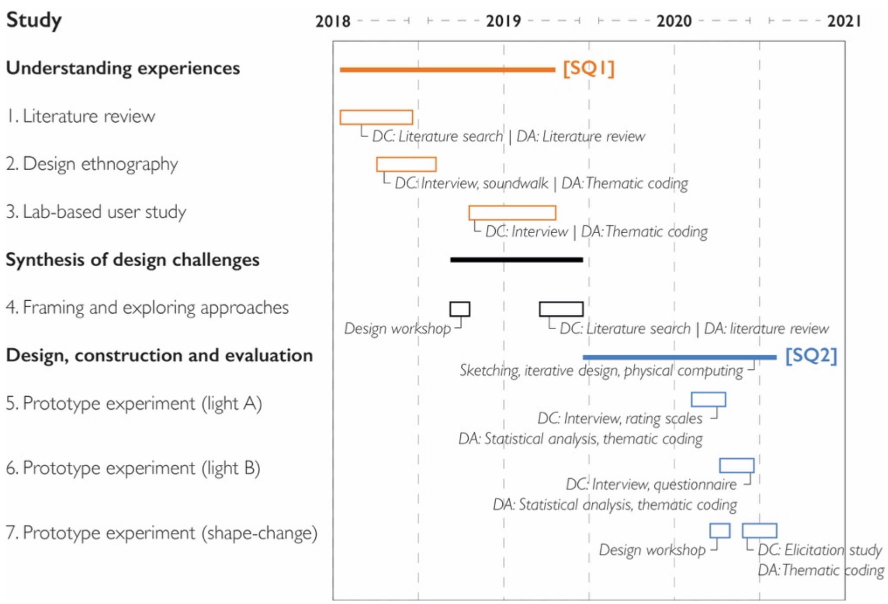


Figure 3.2: Overview of data collection (DC) and data analysis (DA) methods used in each of the seven studies.

UNDERSTANDING EXPERIENCES [SQ1]

Addressing research sub-question 1, I investigate the relation between sound zone systems and soundscapes. The aim is to unfold the characteristics of this relation. At the outset of the research, it was not yet possible to carry out experiments with a functioning sound zone system. Therefore, the investigation necessitated methods to collect data about sound zone systems in relation to soundscapes without an actual system. The pursuit of such methods allowed for going beyond current limitations of sound zone systems, since the investigations were not bound to a particular technical setup. For this reason, I pursued methods that would both offer knowledge into sound zone systems as currently envisioned within audio engineering and also challenge current expectations of use situations and functionality. Three studies addressing the first sub-question were carried out to frame the research theoretically, gain knowledge about the field, and characterise experiences of personal sound technologies.

STUDY 1: LITERATURE REVIEW

The first study entailed conducting a literature review with the aim of identifying challenges and opportunities for designing interaction with a physical environment in contrast to interaction on a small scale. The concept of human-building interaction is one way to frame such interaction, and therefore was the starting point for the literature review. Literature reviews are useful for understanding the status of a research area and outlining further research opportunities. This is especially useful at the start of a project when developing a conceptual model [124]. Within this research, it is an appropriate method, because it points to boundaries of the later design process. This design process can be clarified in terms of 'thinking', 'construction', and 'artefacts', in the words of Dahlbom and Mathiassen [39]. As such, this literature review was intended to shape the philosophical worldview of the research.

Human-building interaction consists of research from both architecture and interaction design, and the review therefore entailed an investigation into both disciplines. Initially, the review followed a snowball searching method to gain an overview of previous research in human-building interaction, smart homes, and interaction with built environments. This search method generally entails using either a reference list of a publication or citations to the publication [130]. The concept of human-building interaction is still new and, therefore, reference lists were used to snowball backwards. The starting point was recent key publications (e.g., [3,95,123,126]). The search was then expanded to include perspectives of 'temporality' from both architecture and interaction design. Publications were included if they contributed knowledge about temporality in one or both of the disciplines, distinct from already included publications.

STUDY 2: DESIGN ETHNOGRAPHY

The second study was carried out in the field, in seven Danish homes, as design ethnography. Design ethnography is a new branch of ethnography, as described by Baskerville and Myers [12]. Pink et al. [101] point out that homes are settings for 'mundane' activities that people are not necessarily consciously aware of, cf. Chapter 1. Therefore, this approach is particularly appropriate, because it enables a researcher to explicate what is typically unnoticed in a setting. In addition, design ethnography seeks to include both descriptive and generative techniques [12]. Ethnographic methods play a prominent role in HCI in informing designers and developers of a field and 'real world' situations of interest. Within systems design, ethnography was initially introduced to investigate social aspects of work [34]. Since then, 'work' has also been expanded to include the activities of ordinary settings as well as the competencies and efforts needed to carry out the activities. To understand how sound zone systems fit into existing activities of managing sound in homes, the second study sought to unpack and elaborate on how these activities are accomplished using ethnographic methods, also referred to as the "interactional what" of activities [23].

Within the postphenomenological worldview, it is appropriate to consider how technology fits into the existing activities of soundscape management in homes. Since a specific aim of design ethnography is to unfold how technologically driven change fits into or alters social aspects of activities, it is a fitting approach within this worldview. Following this, the aim of the study was to explicate the social aspects of situations where soundscapes are currently managed in homes and might be managed using sound zone systems. The structure of the study was inspired by a previous study on soundscape management in homes [99], c.f. section 2.4, where researchers carried out soundwalks to enable participants to reflect upon the soundscapes. Adding to this, the concept of sound zone systems was introduced to the participants to define and unfold opportunities offered by such systems. The study involved three phases: two meetings inside participants' homes and an intermediate period of approximately one month.

Data collection was carried out using semi-structured interviews, soundwalks, and audio recordings. As outlined in section 2.3, soundwalks can be carried out in different ways. For this study, two types of soundwalks were carried out with the purpose of building participants' conscious awareness of sounds in their homes and establishing experiences and activities concerning these sounds. The first consisted of an audio recorded tour of the home with an interviewer during the first meeting, and the second consisted of self-guided listening and recording of sounds in all rooms during the intermediate period. The final phase of the study involved introducing the vision of sound zone systems to participants. Using three strategies during the interview, participants were asked to reflect on how they would use sound zone systems and why. The strategies were based on (1) having participants talk through situations with and without sound zone systems, (2) discussing opportunities and constraints of noise-cancelling technology, and (3) visualising new scenarios on a floor plan of the home using cardboard circles and LEGO figures. During the interview, participants were engaged in an abductive sensemaking process where situations were presented in different ways to allow for reframing and discovering unidentified opportunities [71]. The data were thematically analysed [18] in three iterations. The first iteration entailed printing and physically distributing quotes into different themes. The two second iterations involved arranging the themes into two emerging dimensions.

STUDY 3: LAB-BASED USER STUDY

The third study was designed to enable users to compare different types of personal sound technologies. In order to further address the relation between soundscapes and sound zone systems, it was relevant to investigate how other personal sound technologies related users to their soundscapes as well as other users and, on this basis, outline a frame of reference for sound zone systems. In order to control the basis of such comparisons, this study was carried out in a lab setting. Lab-based user studies have primarily had a place in HCI research for evaluations where variables need to be isolated and controlled. While field studies typically offer a high level of ecological validity, they also have disadvantages, including unknown external validity and a low level of control [74]. Elements to support ecological validity can be brought into a lab study, for example by organising the lab physically to match the real environment [64] and simulating real-world situations [80].

The study follows the postphenomenological worldview by looking at the types of speaker technology as modifications to relations between users and between a user and their environment. Verbeek [121] suggests that people and technologies are not separate entities between which there is interaction, but rather they are both results of that interaction. The relevant aim here, then, was not to review or rate each type of technology, but rather to investigate the differences in how personal and shared soundscapes are experienced with different technologies. Participants took part in the study in pairs where a relation, romantic or other, was already established. Different situations were simulated by having participants engage in three different activities. The activities required participants to interact with each other at different intensity levels. For each type of technology, each pair of participants were engaged in all three activities. Data collection was conducted using semi-structured interviews [72] after each type of technology. The interviews were structured by topics that related to sound zone systems, including awareness of sounds, social interaction, personal sound, and sound quality. An open coding process [91] was then used to thematically analyse the data [18] and investigate how participants described their experiences of the technologies within the topics of discussion.

STUDY 4: SYNTHESIS OF DESIGN CHALLENGES

The focus after addressing the first research sub-question was to structure a process that would allow me to move from understanding experiences to designing for new experiences. To begin the design process, it was necessary to outline interaction design challenges and possible design approaches to address them. For this reason, this part of the research consisted of synthesising the gathered knowledge about sub-question 1 and a workshop to explore the space of possible solutions. Whereas the first part of the research resulted in knowledge about the opportunities and constraints for sound zone systems in homes, this part of the research involved making reductions and clarifying to create continuity between use situations and concrete designs. This necessitated a synthesis process [75], narrowed to a specific use situation and a theoretical framing of sound zone systems as soundscape interventions. Synthesis involves, according to Kolko [75], an abductive process where data are organised and reorganised to forge arguments for why certain patterns occur. Such a process can also be designed to point to yet untried design opportunities. This study used the method of insight combination, as described by Kolko, by articulating insights from the first studies and what was gained from a literature search and theoretical framing. The insights were articulated in the form of design challenges that were paired with specific design approaches in a design workshop. This insight combination aimed to yield new conceptual ideas. In the workshop, 6 HCI and IS researchers used their knowledge to address a set of interaction design challenges posed by sound zone systems.

This approach was pursued in order to define the theoretical outset of each prototype experiment upfront. The design workshop aided in defining conceptual approaches to designing interaction with sound zone systems. While the previous studies had provided knowledge about soundscape experiences, it was not possible to empirically study specific problems that might arise from having sound zone systems installed in homes. For this reason, the theoretical framing and open design prompts were relevant to include as techniques for exploring possible solutions that did not immediately appear from the previously collected data. Stolterman and Wiberg refer to theorising as "…a matter of sensemaking" [113] when the object of study is constantly changing; as is currently the case with sound zone systems. They propose that interaction design research can be concept-driven where the goal is theoretical development as opposed to addressing real-world issues. Stolterman and Wiberg make a hard distinction between concept-driven and situation-driven research, where the research presented here draws on aspects of both. Possible future situations are grounded in existing ones (studies 2 and 3). Still, this study was structured to form a basis for designing prototypes that would enable exploration of theoretical concepts and support the development of a theory of sound zone configurations.

DESIGN AND CONSTRUCTION OF PROTOTYPES [SQ2]

Addressing the second research sub-question, I investigate how users can be supported in understanding and controlling sound zone systems through concrete designs. During this part of the research, a sound zone system was set up in a lab. This enabled experiments that could address experiences of sound zones. To carry out such experiments, I pursued methods that would enable me to articulate what the designs should do, and gain knowledge about how they were experienced. Three studies addressing the second sub-question were carried out to frame the design process and gain knowledge about the experience of concrete designs.

This part of this Ph.D. project consisted of designing, constructing, and experimenting with prototypes. As illustrated in Figure 3.2, the process of design and construction spanned across several months. The empirical studies and theoretical framing clarified a set of constraints for prototype designs and construction. From these, a basis was formed in the synthesis process for identifying conceptual approaches to designing interaction with sound zone systems in homes. Zimmerman and Forlizzi [135] point out that the goal of theory development clashes with the goal of design practice, because theories should be unifying wholes, and design outcomes are particular instances. However, in the process of creating each instance, e.g., through sketching, propositions about the object of study can be explored and evaluated, potentially leading to a theoretical contribution. In relation to theory development in HCI, an ongoing discussion includes different terms for intermediary knowledge that resides between theory and particular instances. For example, Höök and Löwgren [65] coined the term 'strong concepts' which, in contrast to Stolterman and Wiberg's concept-driven approach, was developed inductively for design practice. Dalsgaard and Dindler [40] propose an alternative, termed 'bridging concepts', which can support both theory and practice development and emerges from both. I primarily draw on Dalsgaard and Dindler for designing and constructing prototypes by aiming at both types of development.

For this Ph.D. project, my aim with all prototype experiments was to investigate how to support users' understanding of sound zone systems through different ways of visualising information about the system. The point of departure was the concept of 'seamfulness' [68], i.e., revealing aspects of the system that are otherwise invisible to users. Two approaches were explored: one concerning light and another concerning shape-change. These approaches were chosen based on the results from the design workshop on visualising sound zones. The role and nature of prototypes have been discussed widely, including what constitutes a prototype and how they aid researchers in testing hypotheses and developing theory. Here, I chose to limit the perspective to Lim et al.'s description of the anatomy of prototypes [82]. They suggest that prototypes are designed for exploring a design space and, in this exploration, are constructed purposefully to manifest an idea. In this way, prototypes are 'filters', because they enable designers to identify aspects that work and aspects that do not by being incomplete. On the basis of this, the design and construction of prototypes for this research consisted of a set of activities which explored dimensions of shape and functionality, first in paper, foam, and 3D printing, and later through physical computing. In these iterative activities, ideas are externalised. Schön describes that such externalisation lets a situation "talk back" to identify weak and strong aspects of a design [109]. Figures 3.3 and 3.4 on the following pages show different stages for both light and shape-change prototypes. Throughout the stages, the externalisation led to changes in both dimensions explored.

STUDIES 5 AND 6: PROTOTYPE EXPERIMENT (LIGHT A AND LIGHT B)

The first approach taken to address concrete ways of supporting users in understanding and controlling sound zones was to use light to represent sound zone properties. For this, I pursued methods that could provide knowledge about two aspects of participants' experiences: (1) how different light properties relate to sound zone properties as experienced by participants, and (2) how light properties affect participants' experiences and expectations of the sound zone system. In terms of the relation between light and sound zone properties, quantitative methods including scales and Likert-item ratings were utilised for data collection. This enabled an investigation of whether general patterns of experiences emerged. In terms of participants' experiences of the sound zone system with different lights, semi-structured interviews were utilised throughout different experiment conditions.

Within the postphenomenological worldview, this mixed methods approach is appropriate in order to study the same phenomenon from different perspectives. The aim is to unfold the structures of participants' experiences which arise under each condition. I did this with a mixed-methods approach under the constraints of not reducing participants' experiences to objective descriptions. The two studies were conducted as lab-based experiments with a sound zone system, two active sound zones, and a volume controller for each sound zone. They were designed to investigate light in relation to size, volume and overlaps of sound zones. This relied on participants experiencing light with different brightness and colour properties together with active sound zones. In the case of overlapping sound zones, it was furthermore appropriate to invite participants in pairs already familiar with each other to investigate social aspects of the experience resulting from different light conditions and sound zone settings. The quantitative data were analysed with statistical techniques, and the data collected in the interviews were analysed using an open coding thematic analysis. Appendix B includes measurements of the lab setup to show what participants could hear inside their own sound zone as the two zones were activated.

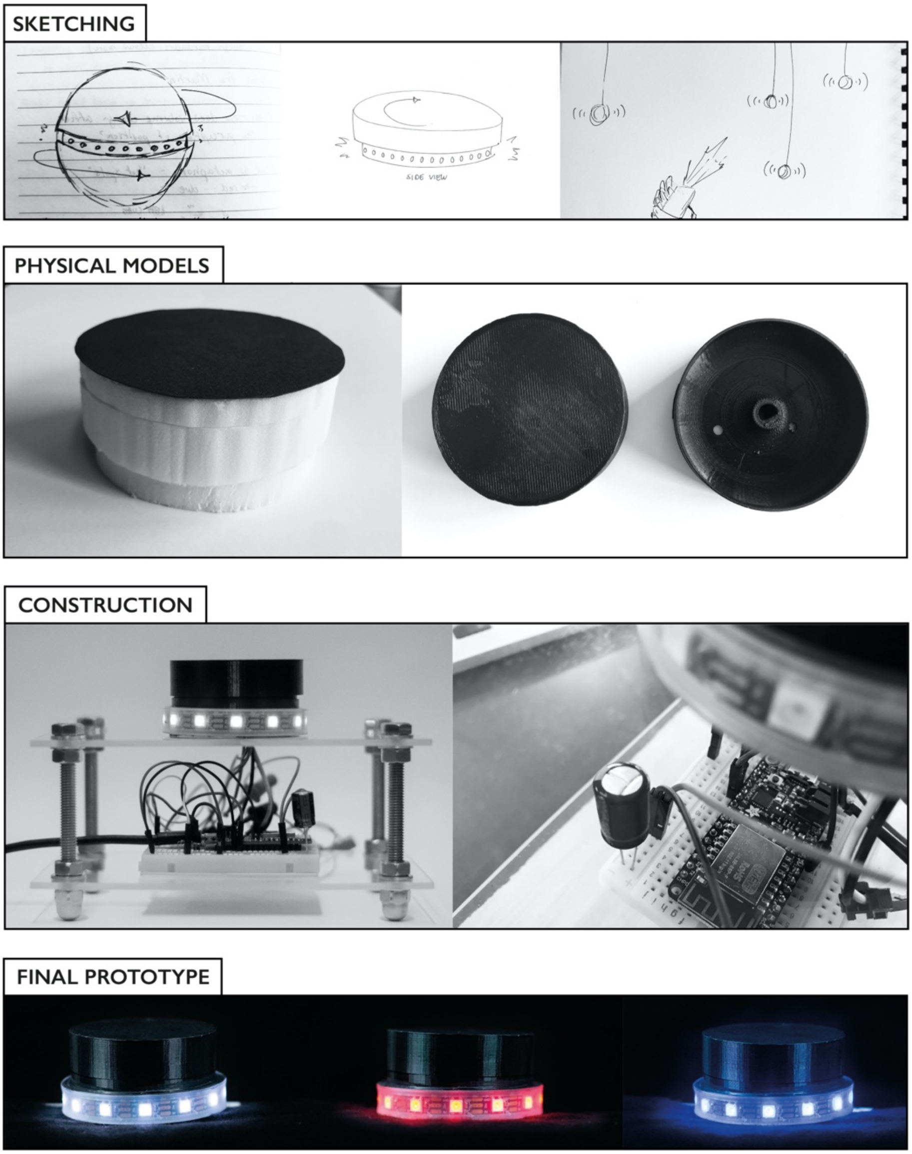


Figure 3.3: Design process for the volume controller with light. The process involved different stages of externalisation.

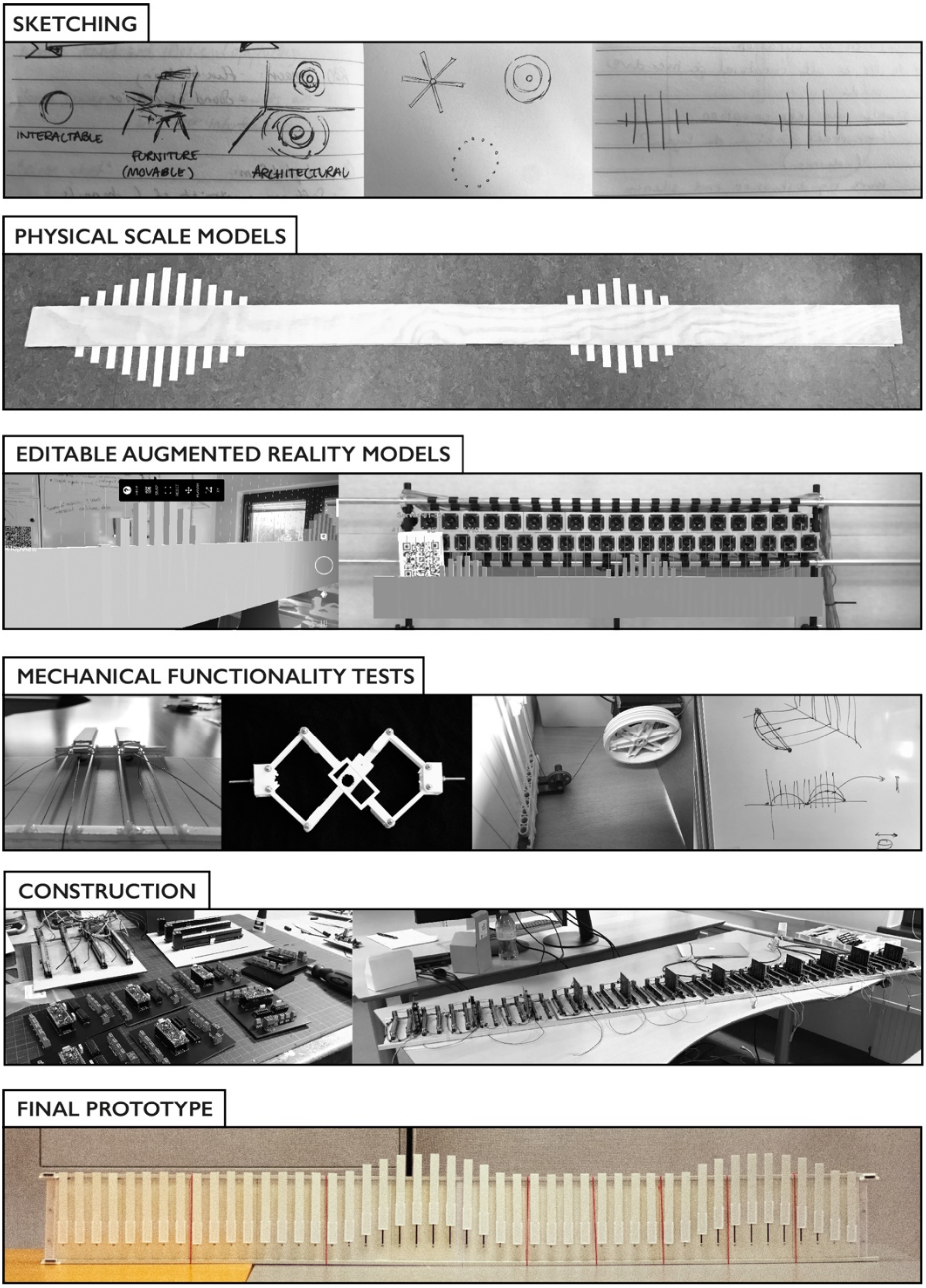


Figure 3.4: Design process for the shape-changing interface. Like the volume controller, this process also involved different stages of externalisation.

STUDY 7: PROTOTYPE EXPERIMENT (SHAPE-CHANGE)

The second approach to investigating ways of supporting users was to use physical, shape-changing visualisations to provide feedback about the sound zone system. The methods used in this study were qualitative in contrast to studies 5 and 6. Whereas light has been investigated in various studies for its ability to carry information about objects and spaces, shape-change is still a comparably new area of research [5]. Therefore, it was appropriate to utilise methods described here to explore possible design directions. This included two phases: (1) exploring possible shapes and functionality, and (2) eliciting participants' experiences of shapes and movements. The first phase was carried out through sketching and construction as well as a design workshop with professional audio engineers and UX researchers at Bang & Olufsen. The second phase was a lab-based elicitation study, inspired by Wobbrock et al. [129], with a sound zone system, two active sound zones, and a shape-changing interface that could be controlled using a volume controller and a position tracking device. Appendix B also includes documentation of the sound zones used for this experiment.

The interpretation of shapes can vary depending on participants' previous experiences. In this study, experiences of meaning are prompted using a set of shapes that can be compared and interpreted, following the postphenomenological worldview. The elicitation study was designed to gather knowledge through interviews while participants interacted with the sound zone system and by observing participants' choices for certain tasks. Participants were shown an effect of an interaction on the shape-changing interface and then asked to perform the cause of that effect by interacting with the sound zone system. During the study, they were asked continuously to reflect upon their interactions with and experiences of shapes. Data collection included audio and video recordings. These were analysed by comparing participants' interactions and movements for each shape and identifying common ways of relating to the shapes. Finally, participants' descriptions of experiences were thematically analysed.

4. PAPER CONTRIBUTIONS

In this chapter, I provide an overview of the contributions made through the six papers produced throughout this Ph.D. project. With the studies reported in these papers, the aim was to unfold the design space for interaction with sound zone systems in homes and investigate how particular interaction designs support users in interacting with a sound zone. The study numbers presented in Chapter 3 are not transferrable to paper numbers, e.g., studies 5 and 6 are reported in P5 together. Figure 4.1 illustrates how the papers relate to each other and form a foundation for addressing the main research question.

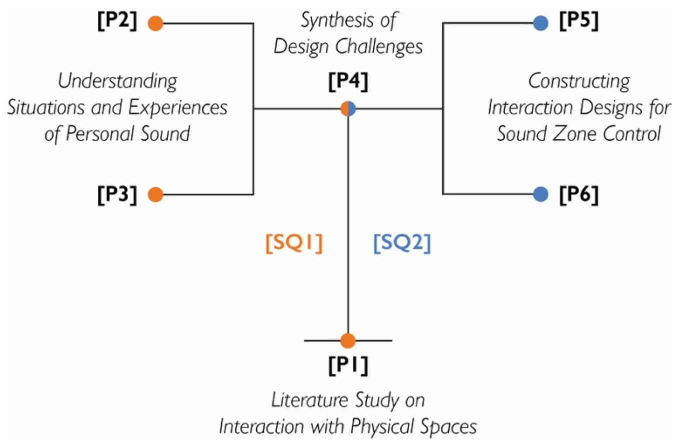


Figure 4.1: The relation between the six papers produced throughout the Ph.D. project.

P1, P2, and P3 are concerned with understanding a phenomenon, and P4, P5, and P6 are concerned with defining and addressing design challenges. To clarify in the words of Aristotle [47], the first papers give insights of 'episteme' by focusing on asserting what currently is. The last papers give insights of 'techne' by deliberating what could be through the design and construction of prototypes.

As such, the first three papers address sub-question 1. This was done through a literature study on interaction with physical spaces and empirical studies in the field and in a lab study on situations and experiences of personal sound. P4 synthesises the collective understanding from P1, P2, and P3 to form the foundation for P5 and P6. As such, P4 provides a connection between the two sub-questions. The following sections outline the contributions presented in the six papers. This is necessarily a condensed version, and I encourage readers to dive into the specific papers for full details about the methods, findings, and discussions. Publication details can be found in Appendix A. For each paper, I specify the research question and methods utilised to investigate it. Following this, I describe the insights gained that relate to the main research question of this Ph.D. project. The research questions and their answers are at the same time apparent and complex, as shown by unfolding them in the papers.

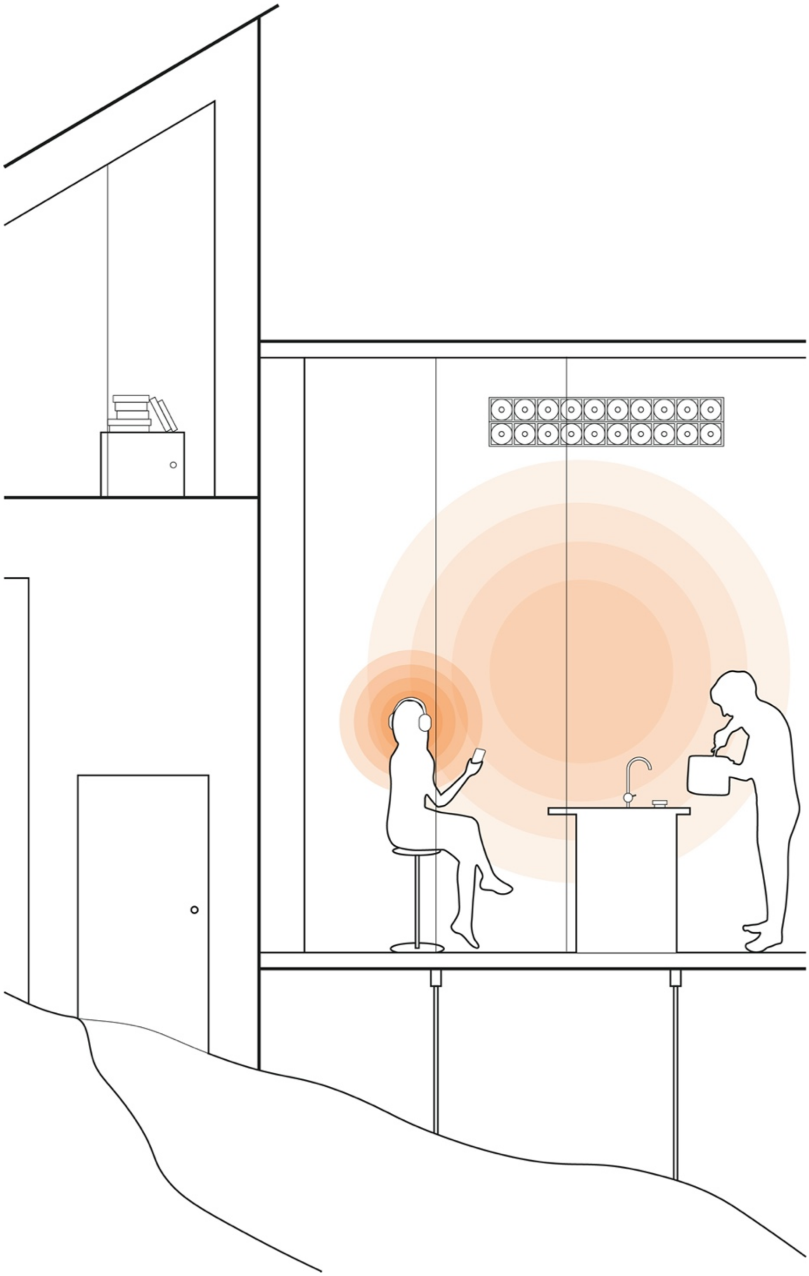


Figure 4.2: The convergence of interaction design and architecture enables interaction on different scales.

4.1. [P1] TEMPORAL CONSTRAINTS IN HBI

[RQ] How can human-building interaction designers meaningfully combine perspectives and approaches?

[Method] Literature review, data collection using snowball literature search

This paper was motivated by wondering about the implications for interaction design on the levels of rationale, methods, and final design outcomes when digital technologies are integrated into built environments, such as homes. This motivation was founded in the acknowledgement that sound zones cannot be touched or seen, but they can form a part of our buildings, and the technology used to construct them is integrated into the built structures of our homes. I investigated how temporality constrains the design process within architecture and interaction design, respectively, based on the notion that buildings offer user experiences that are "spatio-temporally immersive" [4] and on the changing nature of buildings [106]. I did so to underline differences between these disciplines, which are converging within the new research area of human-building interaction. Based on these differences, a foundation for the temporality of design rationale, methods, and outcomes is outlined and discussed. The particular structure of the study was inspired by Dahlbom and Mathiassen's division of 'thinking', 'construction', and 'artefacts' in systems design philosophy and practice [39]. Thus, this first step of the research positions the work as interaction with an environment surrounding the user rather than with an isolated artefact.

The paper points to new opportunities and challenges that are specific to designing human-building interaction that involves digital technologies. In terms of rationale, designers' visions need to be flexible to different time scales. Within the discipline of interaction design, solutions are typically evolved continuously, and technologies quickly substitute each other. Human-building interaction necessitates considerations of new ways in which digital technologies can extend a built environment such as a home. In terms of methods, the paper proposes 'tuning' environments in incremental stages, because a built environment evolves through time. Finally, in terms of outcome, I point to scale, materials, and context as areas which require different approaches compared to interaction design for interactable devices. For example, how can materials adapt on different scales, physically and temporally?

This paper highlights an inherent challenge when designing interactions with built environments such as homes based on their temporality. Using Brand's model of buildings as layers, some layers are built to last, and some can be adapted or changed within short periods of time. Digital technologies can be incorporated into different layers, but each layer requires individual considerations on materials and scale as well as varying design rationales. A sound zone system in a home similarly consists of technologies that can be integrated into different layers, e.g., speakers can be embedded into a wall or ceiling, or they can be placed on the floor and moved around according to the changing layouts of the room. Another aspect of this is how these infrastructural layers of the system are exposed to users. Exposing elements invites users to make modifications, but only to the extent that they understand them.

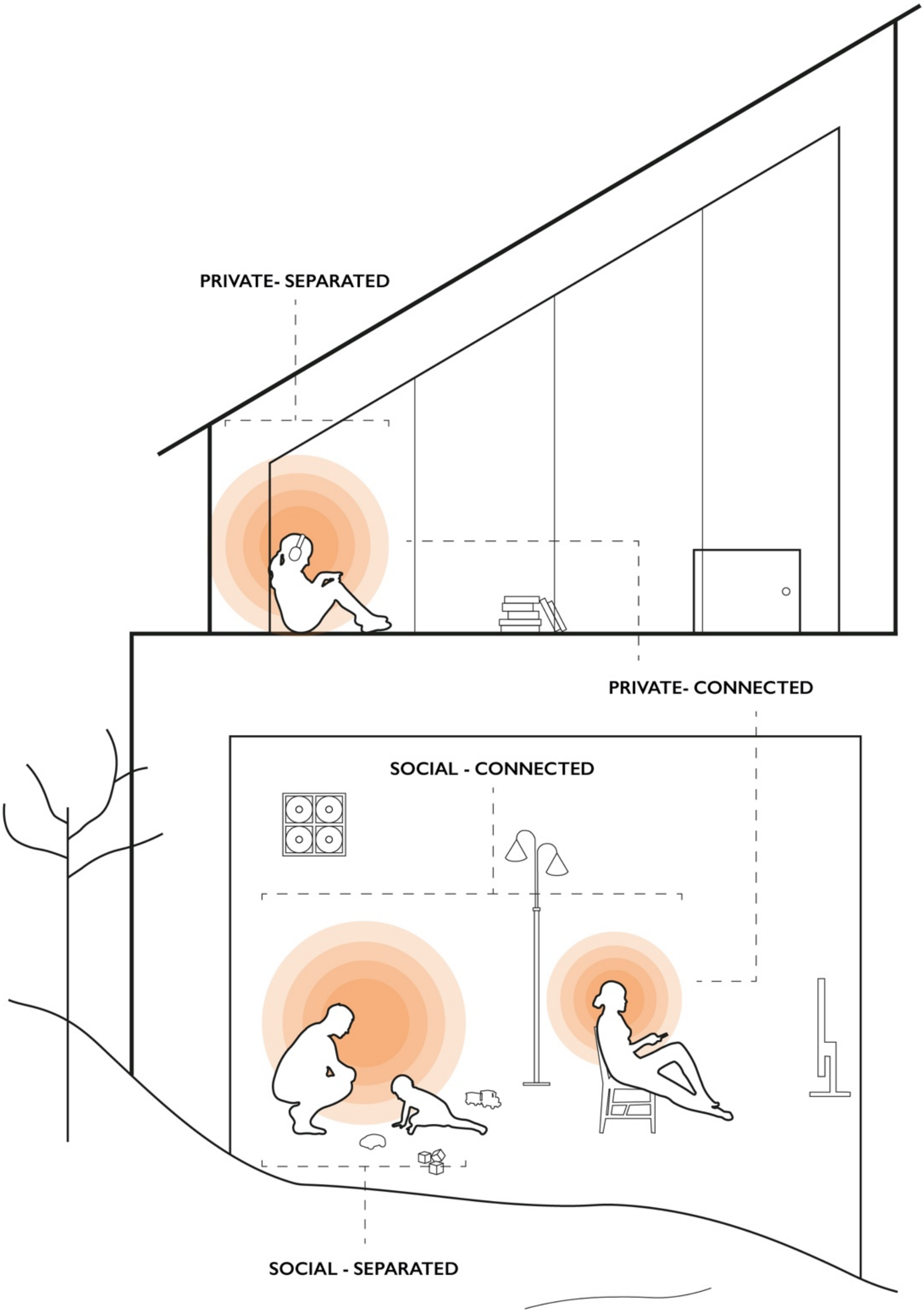


Figure 4.3: Different situations are characterised by different soundscapes.

4.2. [P2] PERSONALISED SOUNDSCAPES IN HOMES

[RQ] How can key experiences of soundscapes in homes be used to inform interaction design for sound zone systems?

[Method] Design ethnography, data collection using interviews and soundwalks

With the study presented in this paper, the aim was to clarify types of domestic situations in which sound zone systems could apply and the subsequent conditions for design. The study was motivated by research sub-question 1 regarding the relation between sound zone systems and soundscapes in homes. Insights from the domestic domain itself were gathered to better understand the conditions for sound zone systems. To investigate soundscapes in homes and potential applications for sound zones, a design ethnographical approach was used. The approach was inspired by Oleksik et al. [99], who used the soundwalk method to map the domestic soundscape. The method was extended by integrating it with design ethnography, mapping domestic soundscapes and introducing the concept of sound zone systems to participants [71]. Seven households varying in types of dwelling, household composition, and areas participated in two interviews. The purpose was to increase participants' awareness of sounds in their homes, gain an overview of sounds in different situations and then engage participants in reflecting on how sound zone systems could be applied to these situations. The collected data were thematically analysed using an open-coding process.

A framework of two dimensions, social-private and separated-connected, was derived. The resulting four quadrants each represent a type of situation with a particular application of sound zone systems. The situations offer insights into different configurations of people sharing a home using sound zone systems. Social-connected situations match the typical envisioned situation within sound zone research where multiple people share a room, listen to their own sound, and still want to be able to communicate with each other. Private-connected situations were characterised by one or more people only wanting certain sounds, termed 'signals', outside the sound zone to reach them. Private-separated situations occurred when one person wanted to control all sounds inside and coming from outside the sound zone. Finally, social-separated situations happened when two or more people listened to the same sound but had different preferences for the characteristics of the sound.

Two types of insights further progressed the research. First, the framework of situations gave insights into the conditions for interaction design such as which activities users are engaged in while they are modifying their soundscape and what causes them to seek modifications in the first place. Typically, the cause emerges from social or technological conflicts between subjective attitudes and needs. Second, the approach allowed me to explore strategies for enabling reflections about sound zone systems while no participants had the opportunity to experience it. The paper forms part of the foundation for P4.

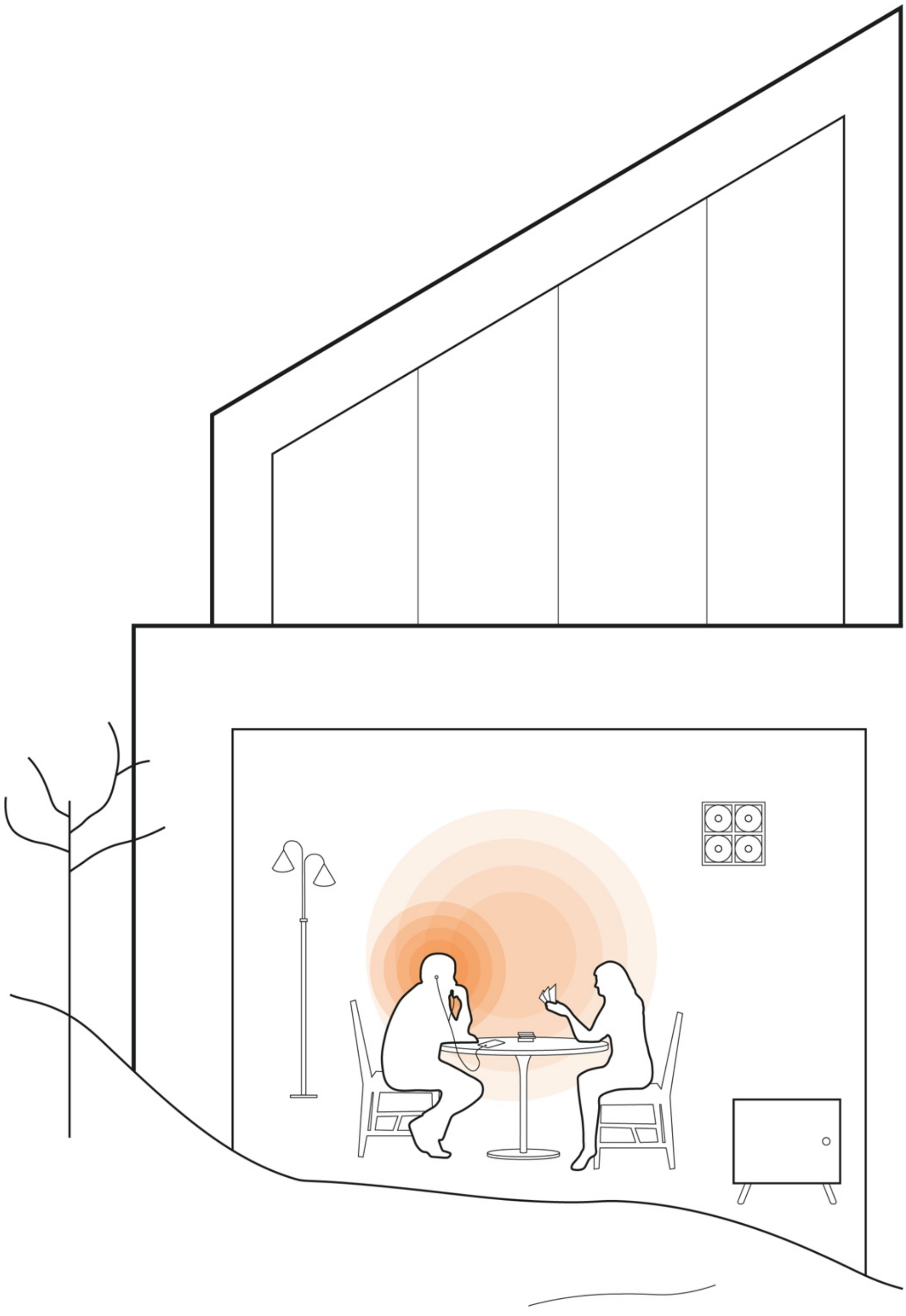


Figure 4.4: Soundscapes can be shared or personal. In some situations, they are both.

4.3. [P3] EXPERIENCES OF PERSONAL SOUND TECHNOLOGIES

[RQ] How are personal sound technologies experienced in various social situations with mixed personal and shared soundscapes?

[Methods] Lab-based user study, data collection using interviews

With the study presented in this paper, I sought to identify elements of the experience of personal sound technologies in different situations. As detailed in Chapter 2, there are tools for assessing the quality of soundscapes, but few for comparing experiences of the same soundscape as mediated by different types of personal sound technologies [52]. The study was motivated by research sub-question 1 and by wondering how to assess the quality of a soundscape modified by sound zone systems – especially when these systems are not yet commercially available. I chose to conduct the study in a lab to control the situations, sounds, and acoustic environment. Three types of personal sound technologies were chosen, each allowing for more or less sound from the environment: (1) a wearable speaker, (2) open earbuds, and (3) ANC headphones. Each technology functioned as a proxy for sound zone systems in the study. The aim was not to investigate the artefacts themselves but rather the experience of different personal sound technologies in various situations. These situations varied in the intensity of social interaction participants had with each other. The study was designed to enable six participating pairs to reflect verbally on their experiences of the technologies in each situation within four themes identified prior to the study. The themes were: (1) Social interaction, (2) Awareness of background sounds, (3) Disturbances, and (4) Sound quality. The audio recordings were thematically analysed.

Findings showed that participants were able to compare experiences within the same themes across technologies. For example, ANC headphones enable immersion in the personal sound whereas personal sound from wearable speakers is used to drown out unwanted environment sounds. Participants' communication strategies also changed between technologies. For open earbuds, participants chose non-verbal communication, e.g., eye contact, even though the technology enabled them to hear each other. This made them focus more on the personal sound compared to when wearing the wearable speaker. Finally, participants' ability to modify their soundscape affected their expectations of a situation on the one hand and on the other, the situation affected the level of tolerance towards certain sounds.

Sound zone systems are one option for personal listening out of many, but it was not yet clear how different options related to each other in terms of the user experience. Clarifying this provided knowledge in two ways: first, the findings show how different personal sound technologies can be used as representative of sound zone systems in further research. Second, shared and personal soundscapes were composed in different ways by participants based on the situation and characteristics of the personal sounds. The relevance of sound zone systems is highly based on a premise that some personal sounds can be disturbing to others in a physical space. The findings show that this is dependent on the technology delivering personal sound to the user and on users' subsequent behaviour.

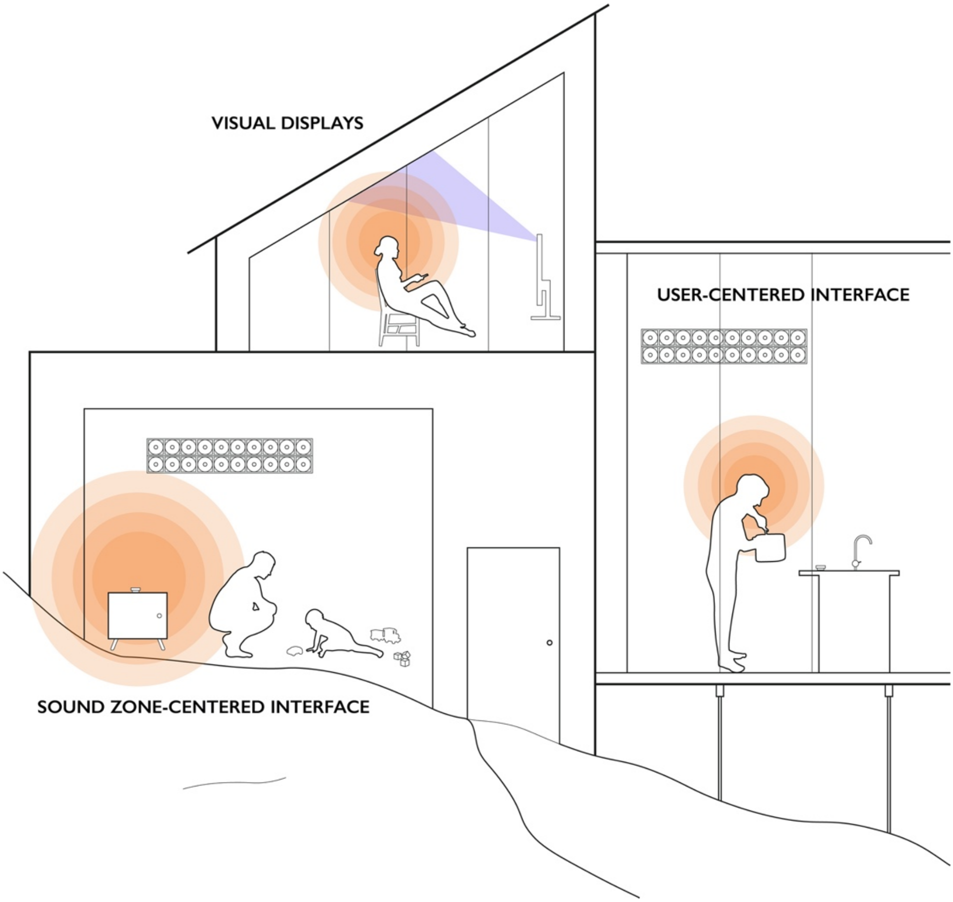


Figure 4.5: Three different approaches to addressing challenges for designing interaction with sound zone systems in homes.

4.4. [P4] DESIGNING FOR DOMESTIC SOUND ZONE INTERACTION

[RQ] Which new interaction design challenges arise from modifying soundscapes with sound zone systems, and how can they be addressed?

[Method, Study 1] Theoretical analysis, data collection using desk research

[Method, Study 2] Design workshop with HCI and IS researchers

This paper was motivated by a need to synthesise the findings from the first part of the Ph.D. project into concrete design challenges and point to directions for addressing them before beginning to design and construct prototypes. As such, the paper addresses research sub-question 1 initially and then provides a first step towards addressing research sub-question 2. Based on findings about interaction with physical spaces, situations in homes for sound zone systems, and experiences of personal sound technologies as a proxy for sound zone systems, I conducted a theoretical analysis of the relation between sound zone systems and soundscapes. This included outlining the implications of framing sound zone systems as soundscape modifications. Based on the results of the analysis, I conducted a design workshop in which solutions to concrete design challenges were explored based on a use situation of the type social-connected as defined in P2. The sketches were categorised according to different interaction design approaches which were then analysed according to each design challenge.

The paper proposes a view that soundscapes precede sound zone systems. Soundscapes are experienced continuously by users who utilise different tools for modifying them. Sound zone systems are one option for this that enables users to create localised, individual soundscapes. Eight interaction design challenges are outlined for sound zone systems in homes based on the analysis. The identified interaction design challenges have to do with (1) the invisible and intangible nature of sound combined with new spatial properties of sound zone systems, (2) potentials for social conflicts, and (3) sound behaviour in a physical space that contradicts previous experiences users might have with sound. The first set of challenges have to do with enabling users to control the position and width of a sound zone, knowing the initial settings of a sound zone when activating it, and determining how sound zones should behave when they overlap. The second set of challenges have to do with signalling the need for privacy, sharing sound between sound zones, and enabling non-user interaction. Finally, the third set of challenges have to do with users' understanding of the shape and functionality of sound zones. Drawing on the subsequent workshop, I described three interaction design approaches to addressing the challenges: (1) Sound zone-centred interfaces, (2) User-centred interfaces, and (3) Visual displays.

Designing interaction with sound zone systems in homes requires clarity about how sound zone systems are different from other sound technologies. The synthesis of knowledge from the three first studies offers a foundation on which research sub-question 2 can be addressed.

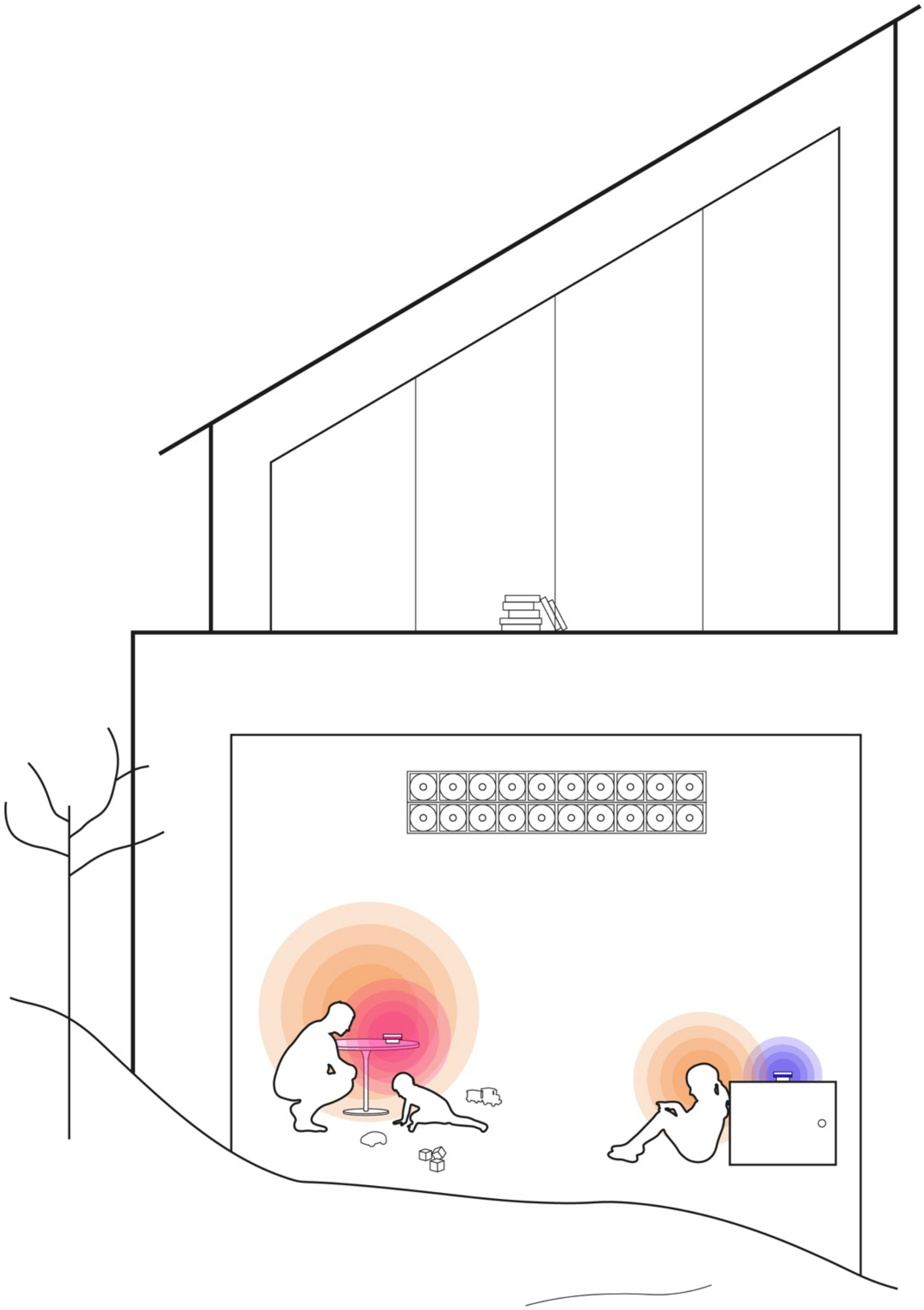


Figure 4.6: Light and colour can provide information about sound zone properties as a metaphor and through symbolism.

4.5. [P5] SHEDDING LIGHT ON SOUND ZONES

[RQ] How can feedback about zone volume, size, and overlaps be provided using light?

[Method, Study 1] Lab-based prototype experiment, data collection using ratings and semi-structured interviews

[Method, Study 2] Lab-based prototype experiment, data collection using questionnaires and semi-structured interviews

In this paper, two experiments are presented. Both experiments were designed to investigate the use of light on a volume controller to provide users with feedback about different sound zone properties. This was based on a hypothesis that the information light typically carries about physical objects could be transferred to sound zones, for example that bright is big. For displaying light, I chose to modify the standard design of a volume knob, because the position of a sound zone can be determined using the position of a mobile volume knob. I attached an LED strip around the volume knob to allow for light in all directions of a horisontal plane. The first study aimed to answer the question: How can colour and brightness be used as feedback about the volume and size of one sound zone? For this, 27 participants were recruited and exposed to different colours and brightness settings on the volume knob. They were then asked to rate the expected loudness of a sound zone and draw the expected size of a sound zone according to each setting. The second study aimed to answer the questions: How can animated light patterns be used as feedback for overlapping sound zones? And how do patterns compare with each other in terms of supporting users' understanding of sound zone overlaps and for notification? 36 participants were recruited, and each brought a friend, co-worker, or relative to the lab. They were exposed to 12 different light animations, occurring when the volume of one sound zone was turned up to a level of overlapping zones.

The findings showed that the participants related high brightness to high volume and large sound zone size. Colours, on the other hand, carry symbolic information that can vary based on participants' prior experiences. For the second experiment, this meant that some participants saw gradual colour transformations as the two sound zones mixing while others interpreted the colours as different types of notification, e.g., red is dangerously high volume. In terms of controlling the sound zones, participants tended to forget the effect their interactions with one sound zone had on the other sound zone. This showed that light can reinforce a 'bubble' understanding through instant changes in colour and light where the participant is not thinking about the other participant's sound zone.

The findings provided insights into sub-question 2 in terms of how sound zones are experienced when light is overlayed on that experience. In terms of the main research question, the findings point to a specific way in which this overlay affects users' understanding of the limits and functionalities of sound zone systems. Light as feedback about sound zone properties can be designed both from a metaphorical perspective regarding sound zone size and volume, and from a symbolic perspective when notifying users about overlapping zones.

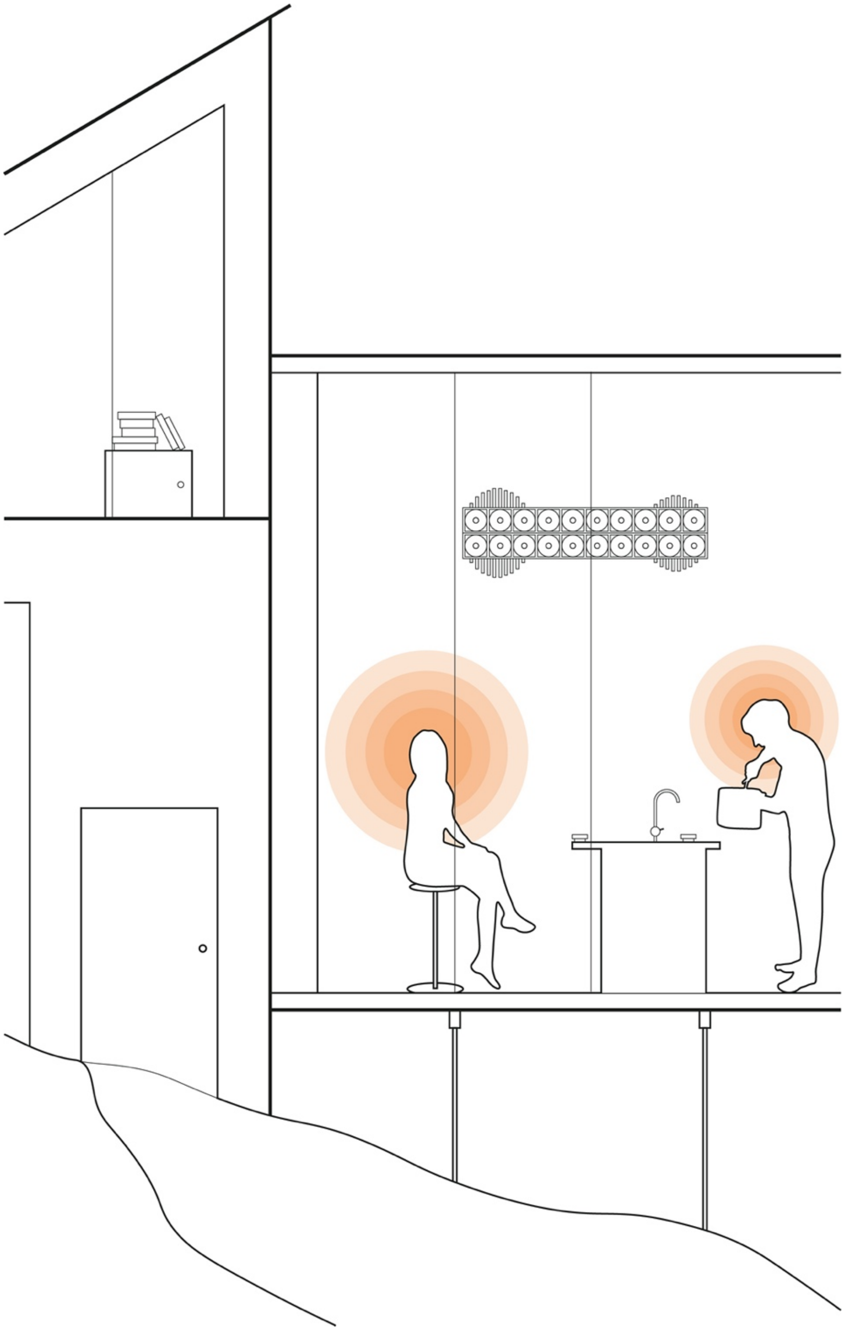


Figure 4.7: Shape-change can provide information about sound zone position and build users' expectations of sound zone behaviour.

4.6. [P6] INVESTIGATING POTENTIALS OF SHAPE-CHANGING INTERFACES FOR SOUND ZONES

[RQ] How can physical shape-changing visualisations support users' experience of sound zones?

[Method, Study 1] Iterative design exploration and design workshop with audio engineers and UX researchers

[Method, Study 2] Lab-based prototype experiment, data collection using an elicitation study and semi-structured interviews

This paper presents an investigation of using shape-change to support users' interactions with a sound zone system. The investigation was designed to explore users' experiences of different physical shapes as visual overlays to sound zones. The motivation came from a hypothesis that physical manifestations of sound zones could support users in understanding the constraints of a sound zone system. The investigation consisted of three subsequent phases. First, a formative exploration of physical shapes and functionalities of a shape-changing interface was conducted. The conceptual result was a wall-mounted solution that could display information in a 2-dimensional vertical plane. Second, a design workshop was conducted with 10 audio engineers and 2 UX researchers, all with experience with sound zone systems. The purpose of the workshop was to explore different shapes that could be visualised within the constraints of the previously defined functionality. On the basis of this, a prototype that could display the shapes was constructed. The prototype was installed in a sound zone lab, with a volume and position controller to modify the prototype and sound zone system simultaneously. Finally, a qualitative lab-based study was conducted with 17 participants. The study involved (1) eliciting interactions based on the movement of shapes and (2) interviewing participants about their experience of the shapes according to the sound.

The findings showed that the participants related vertical movement to volume and horisontal movement to position changes. Furthermore, different shapes resulted in different expectations of the sound zone system. For curved shapes, participants expected a steady drop-off in volume from the centre of a sound zone, whereas for block shapes, they expected an immediate drop in volume at the edge of the sound zone. Furthermore, participants anticipated sound bleeding between two sound zones for curved shapes, whereas they expected silence between two sound zones from block shapes. A 2 by 2 matrix was derived from the findings, describing different types of shapes. On one side, the shapes can either be information rich or poor, and on the other side, they can either be concrete or abstract.

The findings provide further insights into sub-question 2. Similarly to P5, this study shows that different experiences of sound zones can be reinforced with different visual overlays. In addition, it shows that the participants were able to develop their reflections about their experiences by continuously interacting with the system. In other words, the embodied interaction with the system expanded participants' vocabulary for describing their experiences.

5. DISCUSSION

In this dissertation, I have presented an investigation into the research question: "How can interaction with sound zone systems in the home be designed to enable user modifications of soundscapes?" The research contributions, reported in six papers, were produced through a structured process of inquiry into two sub-questions, allowing me to now step back and revisit the main research question. In this chapter, I seek to explain how the contributions extend and add to existing research. I do so by summarising the collection of findings from the studies and relating the contributions to the extant research outlined in Chapter 2.

The studies and papers presented in Chapters 3 and 4 took a point of departure in the physical space, then addressed situations inside specific spaces, homes. This led me to investigate shared and individual soundscapes, before moving on to studies involving concrete prototypes in a functional sound zone setup. With this discussion, I turn the perspective outwards again by first addressing the two research sub-questions and finally the main research question.

5.1. SOUND ZONES FOR SOUNDSCAPE INTERVENTION

The first part of the research seeks to answer research sub-question 1: What characterises the relation between sound zone systems and soundscapes? Soundscapes exist through being experienced by someone, as defined in section 2.6 on the basis of research by Schafer [108] and Truax [118]. Subsequently, the relation between sound zones and soundscapes is a relation characterised by a user's experience. A first step towards investigating that experience entailed a framing of the type of interaction that users have with sound zone systems as an interaction with a physical space. P1 presented the perspective of temporality on technologies that are integrated into built environments and have a physical manifestation, such as a sound zone system. The findings were organised in a framework of three levels, rationale, methods, and outcome, where human-building interaction design can be characterised from the perspective of temporality. At the level of outcome, sound zone systems as well as other speaker technologies can have different physical manifestations, but they have in common that the system cannot be immediately updated or changed, in comparison with software-based solutions. Furthermore, the properties of a sound zone system can be exposed more or less to users depending, for example, on what it is possible for users to modify in day-to-day situations. This is one example of how interaction design at the scale of buildings is different from interaction design at the scale of, e.g., handheld devices, when viewed through the lens of temporality. As such, this paper extends and formalises parts of extant research concerned with the convergence of architecture and interaction design by, e.g., Wiberg [127].

The first study, reported in P1, showed that when framed by temporality, there are opportunities for extending interaction design with perspectives from architecture on the levels of rationale, methods, and design outcomes. One takeaway from the paper is the fact that the built environment is designed to form certain experiences, leading to new opportunities for interaction design. This is especially the case when digital technologies are integrated into the built environment. When framing sound zone systems in relation to soundscapes, it is also a framing of the interaction with a sound zone system as an interaction with a physical space, as existing research shows that sound experiences are embodied [48], as detailed in section 2.5. Subsequently, in order to study and understand current experiences for the purpose of eventually designing interactions with sound zone systems, it is essential to understand how users interact with their environments and not limit the scope to the devices they use for that interaction. Research in aural architecture provides important information about the ways in which the physical features of a space affects how it sounds [17]. The resulting sound impacts people's experiences emotionally and intellectually, and it affects them when determining how to act in a physical space.

On this basis, I took a postphenomenological worldview with a specific focus on embodied interaction. This has shaped the research design, which included soundwalks in homes and letting participants explore the physical space inside labs. The next step of the research was to unfold experiences of soundscapes when they are anchored in homes and when they are shared between people. The study reported in P2 applied a design ethnographical approach to investigating situations in homes where soundscapes can be modified using sound zone systems. The approach helped participants conceive of the conceptual idea of sound zones and reflect on how they fit into their daily lives. This methodological finding supports Crabtree et al.'s [34] position on design ethnography as the study of "naturally accountable" phenomena. Crabtree et al. suggest that in order to make experiences accountable to people who have not experienced them, there should be ways to explicate those experiences. To use the terms described by Harrison and Dourish [57], the 'space', or physical properties of an environment, has an impact on fostering participants' abilities to articulate their experiences about the 'place', or the values embedded inside those physical frames, in which certain behaviours are appropriate and expected. When people are asked to articulate sound experiences, they can focus on either the sound source or the way the sound affects their experience of the physical space. The methods used here focused on the relations between people and their environment, for example by relating the music from a record player to situations that occur within a particular living room setting. This concurs with and adds to the methodological findings of Baharin et al. [11] with a focus on sound zone systems.

From the analysis in P2, four different types of situations were uncovered, each calling for different designs of sound zone systems. As outlined in this paragraph, this extends the research presented in section 2.1 with additional experience-based knowledge on how sound zone systems can be used to modify soundscapes. Typically, sound zone systems are illustrated as being useful in situations where people in a physical environment listen to different sounds and do not want to disturb each other. P2 contributes with a perspective that, conceptually, sound zone systems can also be used when people are listening to the same sound, but have different preferences, when one person wants complete control of their soundscape, or when one person wants to stay connected to other people in the environment while excluding annoying sounds. The study was conducted and framed in alignment with Dourish's point on ethnographic studies in HCI as framing users as people who create the circumstances and consequences of technology in use [44]. As reported in P2, existing situations in homes included examples of using technologies in ways that signify specific social meaning, such as signalling the need for privacy by wearing headphones. Designing for future sound zone systems necessitates a form which allows people to configure the systems to these various social situations. This concurs with McCollough's statement that "The very configuration of people, places, and things has significance" [85]. He suggested that situational awareness can be supported to enable people to shape their everyday activities through spatial configurations. For sound zone systems, situations carry intrinsic information in the ways people inhabit a space when engaged with different sounds. If one person reads a book in an armchair, another person who cooks dinner in the kitchen might already try to be careful not to disturb them without any additional information being displayed. This intrinsic information is embodied through their being in the physical space.

Continuing the investigation on the relation between sound zone systems and soundscapes, the next study, reported in P3, contributes with a characterisation of personal sound technologies as proxies for sound zone systems. A sound zone system modifies the experience of soundscapes through the dimensions of social interaction, the sounds one or more users want to hear, and their relation to the physical space, including their awareness of other present sounds and how they inhabit the space. The study showed that, more broadly, personal sound technologies can be characterised by these dimensions when used as a proxy for sound zone technologies. This is an exemplification of what was referred to as 'personal soundscape curation' by Haas et al. [53], cf. section 2.2. As such, the contribution extends research by Haas et al., showing that soundscape modifications with personal sound technologies can be understood on a continuum of how connected a user is to the surrounding acoustic environment.

The findings from P2 and P3 concur with previous research by Oleksik et al. [99] by showing that people already employ different strategies for modifying their soundscapes, using existing technologies or altering the physical space, e.g., by closing a door. From a perspective beyond extant research presented in Chapter 2, this also supports and adds to Brown and Duguid's point that "Context, not simply content, underwrites interpretation" [111] with a specific focus on sound zone systems. They pose a theory of 'borders' in design that can be both physical and social, e.g., the sound of typing on a keyboard both provides feedback to a typist and lets nearby people know that the typist is working. Borders appear where the centre and periphery of the use of an artefact meet. The findings reported in P2 and P3 show that the centre and periphery changed according to types of situations and technologies, leading to the emergence of different borders. For example, volume control might be central in some situations but peripheral in others. Thus, the findings provide knowledge about how these changes are experienced and how the experiences can be described within the same continuum of user-environment relations.

In addition to adding knowledge about experiences of sound in relation to sound zone systems, P2 and P4 add to research on soundscapes with a design-oriented understanding targeted towards sound zone systems. In these studies, I relied on the definitions by Schafer [108] and Truax [118], similar to Oleksik et al. [99], who also developed design concepts for sound modifications in homes. The studies reported in P2 and P4, however, differ from and add to the study by Oleksik et al. and previous soundscape research in two ways. First, participants took part in initial design concept development in P2 and thereby reflected forwards in addition to backwards. Second, both P2 and P4 focused on a particular type of speaker technology for modifying soundscapes. P4 synthesises the results of this and offers the perspective that when sound zone systems are used as tools for soundscape interventions, a set of interaction design challenges emerge that relate to users' understanding of sound behaviour and social interaction with other users.

In Chapter 1, I wondered how compatible light and sound could be considered to be in an effort to clarify directions for the research. Concluding that light and sound are different in how they can be conceived by users, I stepped away from the thought experiment. However, with the new knowledge, similarities can be identified. Niemantsverdriet et al. [98] uncovered three types of lighting conflicts that emerged between couples sharing single-room apartments. First, preference conflicts have to do with the intensity and colour of the light. Second, activity conflicts emerge when people are engaged in different activities with different lighting requirements. Third, attitude conflicts can arise from for example one person having environmental concerns about energy consumption. My findings show that similar conflicts can emerge for sound and be addressed with sound zone systems and as such adds this perspective to previous research on sound zone systems and personal sound as outlined in sections 2.1 and 2.2.

To summarise the contributions made in relation to research sub-question 1, the relation between sound zone systems and soundscapes can be characterised as follows. Soundscapes are experienced, and sound zone systems can be used to support and modify that experience. Soundscapes are experienced in relation to different situations, each calling for particular functionalities of sound zone systems. This is particularly true when it comes to modifying awareness of background sounds and either enhancing or minimising social relations between people sharing a physical environment. On this basis, I suggest the following first proposition:

[Proposition 1] Sound zone systems should be designed to enable users to modify soundscapes in different ways depending on the type of situation.

5.2. INTERACTION DESIGNS FOR SOUND ZONES

The second part of the research seeks to answer research sub-question 2: How can interaction designs support users' understanding and control of sound zones? This entailed an investigation of how two concrete prototypes were experienced in relation to a sound zone system. The steps involved an exploration of design approaches, and then designing and evaluating two prototypes on the basis of the first studies. The contributions are founded in an exploration of interaction design approaches, followed by qualitative and quantitative lab studies with concrete prototypes.

As reported in P4, a broad exploration of interaction design approaches was conducted to address a set of challenges. These approaches were categorised and analysed according to each challenge, contributing with an overview of the advantages and disadvantages of each approach. In other words, the exploration resulted in opening up a design space of alternative approaches. Typically, a design space does not have clearly defined boundaries other than creative constraints emerging from the context of the final design. In the case of the design process in this research, constraints were synthesised from the results of addressing research sub-question 1. The constraints, however, did not point to a specific design approach, calling for a way to gather information about approaches that would be beneficial to pursue. As such, the research moved towards a lower level of abstraction in order to answer research sub-question 2.

This process can be viewed from the recent perspective put forward by Halskov and Lundqvist [56] on design spaces as they evolve dynamically. They propose an extension to Lim et al.'s [82] paper on prototypes as filters by suggesting that not only prototypes but several design artefacts, such as sketches 'filter' and 'inform' a design space. As described in Chapter 3, Lim et al.'s paper framed the design process in this research. Therefore, it is relevant to include this more recent perspective from Halskov and Lundqvist to further explicate how the final designs came to be. While the terms informing and filtering are interconnected, they are also distinct. The distinction describes how the exploration in P4 differs from the experiments in P5 and P6. It was necessary to first expand the design space, using informing and filtering tools, in order to then investigate selected areas, using filtering tools. Halskov and Lundqvist describe that one way to represent a design space is through conceptual alternatives when searching for a direction to pursue. In P4, this was done by describing and comparing different interaction design approaches. As such, participants in the design workshop reported on in P4 used their existing repertoire to inform the design space and performed an initial, collective filtering of concepts.

Designing and constructing prototypes for this research was done with considerations about which questions were interesting to ask. Rather than asking whether or not the designs were good or bad, I considered the epistemological question of how the prototype would support the production of new knowledge. Through an exploratory design process, two prototypes were designed and constructed with the purpose of addressing research sub-question 2 in experiments with novice users. The experiments focused on light and shape-change, respectively. Both used a physical controller which allowed participants to directly control an active sound zone in the lab setup. P5 and P6 report findings on the prototype experiments. The discussion in each paper relates to areas of research using light and shape-change, respectively, in interaction design. In this discussion, I will focus on how the findings from these experiments offer answers to research sub-question 2 as well as the main research question. First, the findings are summarised. Second, they are discussed according to their cumulative contribution to the research.

The two experiments regarding light, reported in P5, evaluated how light is experienced in relation to one and two active sound zones. The first experiment showed that brightness is useful for information about sound zone size and volume. Colours, however, have previously been used in various ways for displaying information about sound, making it less useful to explore colours as representative of individual sound zones. However, adding to this, the second experiment also showed that, for overlapping sound zones, it is easier for participants to distinguish coloured light transitions compared to transitions in white. Participants preferred instant transitions for displaying overlapping sound zones. When the participants were interviewed, an understanding of sound zones as having distinct borders emerged which emphasised the preference for instant light transitions in comparison to gradual transitions. The approach of using light for sound zone interaction and the resulting findings of the experiments are novel and do not build directly on extant research. The findings offer initial knowledge about how light can be used to support users' control of sound zone systems, and this forms a foundation on which further studies can be conducted. For instance, the relation between brightness and sound zone volume and size concurs with previous research on using light as a metaphor for object properties [83], where users rely on prior experiences relating to physical objects. This was also true for findings that showed that participants related light animations on a controller to the sound zone of that particular controller and not to the other or both sound zones. Other findings show various interpretations of colours mixing or alternating as either warnings or sound zone overlaps, pointing to potential modifications of the same previous research. In this case, the metaphor of object properties was confused with colour symbolism, which can result in a variety of experiences based on participants' prior knowledge. Widening the perspective to using light more generally for information about sound, these findings are also useful for the expanding area of spatial audio for which interfaces are still limited, as described in Chapter 1. As speaker systems are increasingly modified to offer sound with new spatial properties, ways of representing how sound is directed and distributed within physical environments become more relevant.

The experiment on shape-change, reported in P6, unfolded different experiences of sound zones together with different physical shapes. The findings showed that participants relied on prior knowledge about sound behaviour to describe their experiences. While these differed from person to person, similarities emerged, including how movements on the interface related to modifications to the sound zone system and how shapes resulted in particular expectations for the behaviour of the system, e.g., that a curved shape would result in more sound bleeding from one sound zone to another compared to a block shape. Similarly to the experiments on light, the findings on shape-change do not build directly on extant research, because the experiment is a first step towards using shape-change to support users' control of sound zone systems. As such, the findings expand the area of research on sound zone systems, as outlined in section 2.1, with knowledge about how different shapes are experienced together with sound zones. Also similar to the experiments on light, the findings reported in P6 can be useful in the broader area of spatial audio, since participants experienced a relation between a shape and the position towards which sound was directed. In relation to research on shape-changing interfaces, e.g., [5], the findings offer knowledge on a specific area of application.

The collection of findings in both P5 and P6 contributes with concrete approaches to supporting users' control of a sound zone system. The approaches involve presenting users with continuous information as they modify the system. The findings showed that users experienced the information as concrete or abstract, and that both physical shapes and light were useful in representing sound zones. Furthermore, the experiences and expectations of how the sound behaved in the experiment room changed between representations. This can be related to Schön's concept of 'generative metaphors' [110], which means seeing one thing as something else, leading to a new understanding of that thing. In section 2.4, I outlined existing research on interaction with sound, which typically involves interaction modalities that are 'graspable', 'touch'-based, or 'free-hand' [58]. Sounds can be thought of as finite objects, but at the same time sound distributes in physical space with no distinct border. Studies such as Müller et al.'s BoomRoom [93] focus on, e.g., moving a sound object from one place to another. This implies that the sound object has a form which can be grabbed (like a sphere or cube) and moved. In reality, sound acts more like a fog. It can be helpful to conceive of sounds as objects with a defined shape when designing an interface for moving them, but the contributions of this research show that this impacts how users understand the sound behaviour in a physical space modified with a sound zone system. Since users' understanding builds on their existing experiences with sound, they expect sound to spread evenly. When they experience that it does not when a sound zone is active, they try to build a new understanding. The new understanding is developed through a process of moving around but at the same time also affected by any visual overlays that designers put on top. These visual overlays can enforce different conceptions such as being inside an area from which sound cannot escape. Drawing on this discussion, I suggest the following second proposition:

[Proposition 2] Users' understanding and control of sound zone systems can be supported with visual overlays of information, resulting in different perceptions of sound zone behaviour.

5.3. CONCEPTUALISING SOUND ZONES

The problems that I initially set out to investigate in this Ph.D. project emerged together with sound zone systems. As a result, the process was initially structured in a top-down fashion where my questions were founded in a potential solution, and I sought to uncover which problems sound zone systems could solve. In this chapter, I have approached the subject the other way around. Based on findings from the studies presented in the previous chapters, a conceptualisation of sound zones can be made in this section, grounded in theory and elaborated through the collection of findings. This approach is inspired by Dalsgaard and Dindler, who proposed the notion of 'bridging concepts' [40] as a form of intermediary knowledge between theory and practice in HCI research, also referred to in Chapter 3. The collection of findings discussed in this chapter point to the concept of configurations as central to designing interaction with sound zone systems in homes. As cited in section 5.1, McCollough [85] uses the term 'configurations' to describe spatial arrangements made by people in attempts to accommodate and modify various situations. His focus lies on people's awareness of information and how to present information ambiently using digital technologies. My understanding of configurations builds on McCollough's description. I summarise the term in this way: configurations consist of different components that relate to each other in different ways. Different configurations result in different relations between components. In this dissertation, the findings contribute with knowledge about relations that can exist in configurations of different situations, types of personal sound technologies, and interaction designs.

Within audio engineering research, sound zone systems are viewed as a particular type of technology that can be constructed using speaker arrays. In the papers presented here, I expand on this view by describing a number of configurations that can be viewed as 'personal sound zones' beyond the current notion in audio engineering. One example is based on a situation where two users wish to listen to the same sound but have different preferences for volume levels. This calls for a configuration where users are in control of the same sound source but still experience a separation in the acoustic environment. This goes beyond current conceptualisations within audio engineering where each sound zone contains a unique sound. The different configurations enable a deeper investigation into the questions: How can the concept of a personal sound zone be described? And then, what is personal sound zone interaction? Conceptualising personal sound zones entails a bottom-up approach based on the empirical investigations and theoretical discussions conducted throughout the Ph.D. project. In other words, what do these findings tell us about what a sound zone is, and how can we articulate a resulting design space that forms the foundation for future research in designing interaction with personal sound zones?

An understanding of sound zone systems emerges and develops from interacting with them. Conceptualising sound zone systems through this lens has enabled me to analyse the relationship that emerges between a person and the surrounding environment through a sound zone system. As shown through the studies in this research, this is dependent on how the setup is configured. For example, findings reported in P3 show that users use different strategies for communicating with each other when personal sound is delivered through different types of speaker technology. Another example is the prototype experiments on light which showed that light animations can enforce particular experiences of the constraints of the system. This supports Truax's [118] model of the mediating relationship between a listener and the environment through sound, similar to the postphenomenological worldview presented in Chapter 3. This view emphasises that sound experiences establish, influence, and shape a listener's relationship with their environment. Like Merleau-Ponty's [90] example of a musician who learns to play on an unfamiliar instrument not through a structured, intellectual learning process but through explorative interaction, users can become acquainted with sound zones by interacting with them and building on prior experiences. This requires movement and therefore puts the body at the centre of the act, supporting Schafer's description of listening as "touching on a distance" [108]. The findings reported in this dissertation, e.g., situations in P2 and experiences of shapes in P6, suggest that different configurations can lead to different ways of moving and acting in a situation, thereby modifying the embodied experience of sound zones. And vice versa, the relationship between people, soundscapes, and situations is mediated through sound zone configurations.

Sound zone systems are developed from the perspective of solving a technological challenge of limiting sound to a specific area within a physical environment. As described in Chapter 1 and section 2.1, this is useful when people experience conflicts related to listening to sound. With the research presented in this dissertation, I have sought to not view sound zone systems as a solution to a specific problem, however. Instead, I view them as part of configurations with people in particular situations. This supports the postphenomenological worldview where Verbeek [122] suggests that we should be careful not to reduce the relation between people and technology to instrumentality. In some cases, technology emerges which offers people new ways of relating to the world as opposed to fixing an identified problem. On this background, it was useful to apply a worldview that emphasises embodied experiences to explore the conceptual breadth of sound zone systems. Other than providing a focus on users' bodily presence in the world, embodied interaction helped emphasise the fact that their personal experiences and habits shape the way they experience the world. As such, I have utilised the perspective developed by Merleau-Ponty [90], as described in Chapter 3, that experiences exist only through actions. As a result of this perspective, findings reported in this dissertation also concur with existing research on soundwalking methods as described in section 2.3. For example, one point made on using recording technology for soundwalking is made by Uimonen [119], who compares the relation between microphones and ears to Le Corbusier's relation between photography and drawing, meaning that if you consciously engage in recording sound, you listen rather than passively hear. The first is analytical, and the second is reactive. In the studies reported in this dissertation, participants engaged analytically with sound as opposed to staying passive.

Sound zone systems can be designed to modify soundscapes in different ways by, for example, isolating sound or connecting soundscapes as shown with the framework of situations in P2. Furthermore, individual sound zones have adjustable properties such as diameter and position which are inherently hidden from users. Designing interaction with sound zone systems includes the integration of these properties into a user interface, thereby supporting users in making sense of a physical environment. In the prototype experiments for this research, each prototype established a configuration, thereby modifying the experience through visual overlays. Using light or shape-change, a sound zone has a particular manifestation, resulting in a unique experience. Within each configuration, participants were aware of different aspects of the sound behaviour and social situation in the experiments. This is a result of the whole setup of prototypes, speaker technology, and the situations in which participants were engaged. As a result, the type of speaker technology would alter how the rest of the elements of each configuration would relate to each other, and thus also how the prototypes would be experienced. If participants listened to personal sound through headphones, the embodied experience would be different, and the relation to other people in the same physical environment would change.

Configurations were embodied in different ways throughout the studies conducted for this dissertation. The design ethnographical field study uncovered situations in which personal sound was either stationary or was sometimes experienced when moving around inside the home. Furthermore, it showed that personal sound affects other people inside the same physical environment. Personal sound can be experienced and wanted in different ways, resulting from a need for not being disturbed or for not disturbing others. The study reported in P3 required participants to wear different speakers on their shoulders, over their ears, and inside their ears while interacting with each other. In some cases, the speakers did not fit and in others, the limitations of the technology became the focus of participants' attention when it performed in unexpected ways. Finally, in the prototype experiments, the embodied experience of personal sound, in this case sound zones, changed over time as participants became familiar with the system through interacting with it.

With these results, the dissertation has contributed to existing research on soundscape interventions, c.f. section 2.4, with findings showing that when users interact with one sound, e.g., music or television, they do so inside a soundscape that can be modified with sound zone systems in configurations. The particular properties of sound zone systems offer ways of modifying soundscapes that are different from using headphones. At the same time, the experience can be compared to using headphones in a continuum of how aware users are of their acoustic environment and people inside of it. The findings of the studies reported in this dissertation show that parameters such as social interaction, physical organisation of an environment and the content of a sound are all experienced in different ways through different sound zone configurations. When designing for control of sound zone systems in homes, these parameters are key components whose relations change with different interaction designs. On this basis, I make the third and final proposition:

[Proposition 3] Soundscape interaction through sound zone systems in homes can be designed for in configurations as embodied interaction.

6. CONCLUSION

In this dissertation, I propose that sound zone systems in homes can be configured to modify soundscapes through interaction design that emphasises embodied interaction. I make this proposition on the basis of seven studies addressing the research question: How can interaction with sound zone systems in the home be designed for modifications of soundscapes? The studies explore relations between people, soundscapes, and speaker technology in the field and in lab setups with active sound zone systems. The research was divided into two research sub-questions. The first asked: What characterises the relation between sound zone systems and soundscapes? The second asked: How can interaction designs support users' understanding and control of sound zones? I have engaged with the research questions in parallel to the development of sound zone systems and explored approaches to (1) articulating experiences of sound zones in different situations and (2) designing interaction with sound zones. These approaches were essential elements of all seven studies, by enabling participants, myself, audio engineers, or HCI researchers to reflect on and imagine future configurations of sound zone systems. The result is a set of three propositions that point towards a theory of sound zone configurations:

[Proposition 1] Sound zone systems should be designed to enable users to modify soundscapes in different ways depending on the type of situation.

[Proposition 2] Users' understanding and control of sound zone systems can be supported with visual overlays of information, resulting in different perceptions of sound zone behaviour.

[Proposition 3] Soundscape interaction through sound zone systems in homes can be designed for in configurations as embodied interaction.

Addressing the first sub-question, I unfolded and characterised the relation between sound zone systems and soundscapes. This was done through the first three studies in which I investigated (1) the convergence between architecture and interaction, (2) situations for sound zone systems in homes, and (3) experiences of personal sound technologies. The first paper contributes with an analysis of how rationale, methods, and outcomes change when the scale of interaction changes from devices to physical environments. This led me to adopt a postphenomenological worldview focused on embodied interaction. With this worldview, the next paper contributes with a framework of two dimensions that describes situations in which sound zone systems can be useful. This framework shows that, conceptually, sound zone systems are broader than what is currently envisioned within audio engineering. It also emphasises users' experiences as opposed to technical capabilities. Further addressing users' experiences, the third paper offers a characterisation of personal sound technologies as experienced in different isolated and social situations. The findings from the first three papers are synthesised in the fourth paper where I frame sound zone systems as forms of soundscape intervention, leading to particular interaction design challenges.

Articulating the design challenges led me to the second sub-question where I explored two approaches to designing interaction with sound zone systems. These involved light and shape-change, respectively, in three studies. The fifth paper contributes with concrete ways in which light is useful for interaction with sound zone systems, including using brightness to provide information about sound zone volume and size as well as how different light animations promote different experiences of the sound. The sixth and final paper contributes with a structured approach to designing a shape-changing interface for sound zone systems and knowledge about how different shapes are experienced together with sound zones.

The collection of findings reported in the six papers lead me to the main contribution of this dissertation: sound zone systems can be experienced in configurations designed for embodied interaction, leading to different ways of supporting people's understanding of sound behaviour and social situations. Sound zone systems as a combination of speaker arrays and software filters have been developed for more than two decades within the field of audio engineering. The perspective on sound zone systems as user experiences had not yet been pursued. With this dissertation, I have expanded this body of knowledge on sound zone systems with a theoretical framing and empirically grounded descriptions of situations and experiences. Furthermore, I have shown how light and shape-change can be used for interaction with sound zone systems as well as providing knowledge about how these approaches shape users' experiences and expectations of sound zone systems.

At this point in the dissertation, it is fair to ask to what extent the research has answered the main research question posed in Chapter 1. I have applied a systematic research approach in order to offer an answer to the research question. This includes a literature review, a design ethnography, a qualitative lab-based user study, a synthesis of knowledge, and three lab-based prototype experiments. The findings reported in the six papers provide overviews of experiences of personal sound in relation to sound zones, and they offer first steps towards addressing concrete interaction design challenges. As such, the dissertation provides a coupling between understanding how sound zone systems fit into people's daily lives and how interaction designs can support this. With this coupling, I have mapped out an experience-based extension to an existing research area within audio engineering through relating it to other areas of research in soundscape, personal sound, and interaction with physical environments and applying these perspectives to the studies described in Chapters 3 and 4. Within the area of sonic interaction design research, phenomenological perspectives have already been proposed, but I have shown how this is particularly useful to investigate interaction with sound zone systems. I thereby argue that I leave this research area more stable and with a clearer set of directions to go in compared to the state of the research in 2018.

With the concept of configurations, it is now possible to ask more far-reaching questions. These pertain to particular configurations and the domains in which they are deployed. In every type of configuration, the individual relations between components are unique with each organisation. Moving forward with the research presented here, investigating these relations and how they change can be further pursued.

Going further than the concept of configuration, the research presented in this dissertation leaves other directions for future research. First, other philosophical worldviews could be applied to broaden the types of knowledge about designing interaction with sound zone systems. The postphenomenological worldview provided one perspective, leading to insights on embodied interaction with sound zone systems. Future research can both build on this and diverge from it to explore the perspective of another philosophical worldview. For example, with a postpositivist worldview, studies could include establishing hypotheses about which interaction designs would better support interaction with sound zone systems. The research here offers a foundation on which such hypotheses can be established.

Second, future research could further investigate the range of experiences of personal sound technologies in the home, particularly with a focus on how these technologies fit with social activities as a unique quality of sound zone systems is the opportunity to stay aware of other sounds in an environment than the personal sound. Furthermore, the framework in P2 shows four different types of situations of which I have focused on one for exploring interaction designs. All four situations could be further investigated ethnographically through, e.g., self-documentation using diaries focused more directly on the social aspects of sound experiences as opposed to individual participants' feelings towards specific sounds. Future studies could also include probes that explore the different types of sound zone systems that arise from each type of situation. This would further support findings with a level of realism that could not be achieved in the lab-based study reported in P3.

Third, the findings show that both light and shape-change can be useful interaction design approaches for sound zone systems. Building on these findings, future research could investigate how to integrate light and shape-change in different ways to sound zone systems. The findings in P5 and P6 offer initial knowledge about how light settings and physical shapes build certain expectations to a sound zone system. This can be extended and challenged by applying the designs to other domains or by integrating them at different scales, for example a small-scale shape-changing volume controller or a large-scale light panel on a soundbar.

Finally, the knowledge uncovered here could be used to investigate other domains than homes in future research and investigate how it can be expanded, confirmed, or contradicted in domains such as hospitals, car cabins, and public spaces. Within these domains, users inhabit the physical environment in different ways, opening for new opportunities and needs.

ARE THERE ANY QUESTIONS?

Completing this dissertation, questions accumulate but also crystallise in a clearer way than when I started the project in August 2018. The final word has not been written on designing interaction with sound zones in homes, and the journey will continue.

Stine Schmieg Johansen, 2021

REFERENCE LIST

[1] Mags D. Adams, Neil S. Bruce, William Davies, Rebecca Cain, Paul Jennings, Angus Carlyle, Peter Cusack, Ken I. Hume, and Christopher J. Plack. 2008. Soundwalking as a Methodology for Understanding Soundscapes. In *Proceedings of the Institute of Acoustics*, Reading, UK.

[2] Mags D. Adams, Trevor Cox, Gemma Moore, Ben Croxford, Mohamed Refaee, and Steve Sharples. 2006. Sustainable Soundscapes: Noise Policy and the Urban Experience. *Urban Stud.* 43, 13 (December 2006), 2385–2398.

[3] Hamed S. Alavi, Elizabeth Churchill, David Kirk, Julien Nembrini, and Denis Lalanne. 2016. Deconstructing Human-Building Interaction. *Interactions* 23, 6 (2016), 60–62.

[4] Hamed S. Alavi, Elizabeth Churchill, and Denis Lalanne. 2017. The Evolution of Human-Building Interaction: An HCI Perspective. *Interact. Des. Archit.* (2017), 3–6.

[5] Jason Alexander, Anne Roudaut, Jürgen Steimle, Kasper Hornbaek, Miguel Bruns, Alonso Sean Follmer, and Timothy Merritt. 2018. Grand Challenges in Shape-Changing Interface Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, ACM, 1–14. DOI:https://doi.org/10.1145/3173574.3173873

[6] Petter Alexanderson and Konrad Tollmar. 2006. Being and Mixing: Designing Interactive Soundscapes. In *Proceedings of the 4th Nordic Conference on Human-Computer Interaction: Changing Roles*, ACM, 252–261.

[7] Tjeerd C. Andringa and Jolie J. L. Lanser. 2011. Towards Causality in Sound Annoyance. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, Institute of Noise Control Engineering, 4415–4422.

[8] Tjeerd Andringa and Jolie J. L. Lanser. 2013. How Pleasant Sounds Promote and Annoying Sounds Impede Health: A Cognitive Approach. *Int. J. Environ. Res. Public Health* 10, 4 (April 2013), 1439–1461. DOI:https://doi.org/10.3390/ijerph10041439

[9] Alissa N. Antle, Paul Marshall, and Elise Van Den Hoven. 2011. Workshop on Embodied Interaction: Theory and Practice in HCI. In *Proceedings of the 2011 Annual Conference Extended Abstracts on Human Factors in Computing Systems*, ACM, New York, New York, USA, 5–8.

[10] Östen Axelsson, Mats E. Nilsson, and Birgitta Berglund. 2010. A Principal Components Model of Soundscape Perception. *J. Acoust. Soc. Am.* 128, 5 (November 2010), 2836–2846. DOI:https://doi.org/10.1121/1.3493436

[11] Hanif Baharin, Stephen Viller, and Sean Rintel. 2015. SonicAIR: Supporting Independent Living with Reciprocal Ambient Audio Awareness. *ACM Trans. Comput. Interact.* 22, (2015). DOI:https://doi.org/10.1145/2754165

[12] Richard L. Baskerville and Michael D. Myers. 2015. Design Ethnography in Information Systems. *Inf. Syst. J.* 25, 1 (January 2015), 23–46. DOI:https://doi.org/10.1111/isj.12055

[13] Steve Benford, Richard Ramchurn, Joe Marshall, Max L. Wilson, Matthew Pike, Sarah Martindale, Adrian Hazzard, Chris Greenhalgh, Maria Kallionpää, Paul Tennent, and Brendan Walker. 2020. Contesting Control: Journeys through Surrender, Self-Awareness and Looseness of Control in Embodied Interaction. *Human–Computer Interact.* (2020). DOI:https://doi.org/10.1080/07370024.2020.1754214

[14] Birgitta Berglund and Mats E. Nilsson. 2006. On a Tool for Measuring Soundscape Quality in Urban Residential Areas. *Acta Acust. united with Acust.* 92, 6 (November 2006), 938–944.

[15] Terence Betlehem, Wen Zhang, Mark A. Poletti, and Thushara D. Abhayapala. 2015. Personal Sound Zones: Delivering Interface-Free Audio to Multiple Listeners. *IEEE Signal Processing Magazine*, 81–91.

[16] Norman Blaikie. 2010. *Designing Social Research* (2nd ed.). Polity Press, Cambridge, UK.

[17] Barry Blesser and Linda-Ruth Salter. 2007. *Spaces Speak, Are You Listening? Experiencing Aural Architecture.* MIT Press, Cambridge, Massachusetts, US.

[18] Virginia Braun and Victoria Clarke. 2006. Using Thematic Analysis in Psychology. *Qual. Res. Psychol.* 3, (2006), 77–101.

[19] Bennett M. Brooks, Brigitte Schulte-Fortkamp, Kay S. Voigt, and Alex U. Case. 2014. Exploring Our Sonic Environment through Soundscape Research & Theory. *Acoustics Today*, 30–40.

[20] A. L. Brown, Jian Kang, and Truls Gjestland. 2011. Towards Standardization in Soundscape Preference Assessment. *Appl. Acoust.* 72, 6 (May 2011), 387–392. DOI:https://doi.org/10.1016/j.apacoust.2011.01.001

[21] Neil S. Bruce and William J. Davies. 2014. The Effects of Expectation on the Perception of Soundscapes. *Appl. Acoust.* 85, (April 2014). DOI:https://doi.org/10.1016/j.apacoust.2014.03.016

[22] Michael Bull. 2000. *Sounding Out the City: Personal Stereos and the Management of Everyday Life.* Berg, Oxford, UK.

[23] Graham Button. 2000. The Ethnographic Tradition and Design. *Des. Stud.* 21, 4 (July 2000), 319–332. DOI:https://doi.org/10.1016/s0142-694x(00)00005-3

[24] Marvin Camras. 1968. Approach to Recreating a Sound Field. *J. Acoust. Soc. Am.* 43, (1968), 1425. DOI:https://doi.org/10.1121/1.1911002

[25] Baptiste Caramiaux, Alessandro Altavilla, Scott G. Pobiner, and Atau Tanaka. 2015. Form Follows Sound: Designing Interactions from Sonic Memories. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, ACM, 3943–3952. DOI:https://doi.org/10.1145/2702123.2702515

[26] David Carr. 1987. Intentionality: Husserl and the Analytic Approach. In *Husserl, Intentionality and Cognitive Science.* Martinus Nijhoff Publishers, 117–136.

[27] Gunnar Cerwén. 2016. Urban Soundscapes: A Quasi-Experiment in Landscape Architecture. *Landsc. Res.* 41, 5 (July 2016), 481–494. DOI:https://doi.org/10.1080/01426397.2015.1117062

[28] Alan Chamberlain, Mads Bødker, and Konstantinos Papangelis. 2018. Sounding Out Ethnography and Design: Developing Metadata Frameworks for Designing Personal Heritage Soundscapes. *J. Audio Eng. Soc.* 66, 6 (May 2018), 1–10. DOI:https://doi.org/10.17743/jaes.2018.0025

[29] Ji-Ho Chang, Chan-Hui Lee, Jin-Young Park, and Yang-Hann Kim. 2009. A Realization of Sound Focused Personal Audio System Using Acoustic Contrast Control. *J. Acoust. Soc. Am.* 125, 4 (April 2009), 2091–2097. DOI:https://doi.org/10.1121/1.3082114

[30] Jordan Cheer, Stephen J. Elliott, and Marcos F. Simón Gálvez. 2013. Design and Implementation of a Car Cabin Personal Audio System. *J. Audio Eng. Soc.* 61, 6 (July 2013), 412–424.

[31] George Chernyshov, Jiajun Chen, Yenchin Lai, Vontin Noriyasu, and Kai Kunze. 2016. Ambient Rhythm - Melodic Sonification of Status Information for IoT-enabled Devices. In *Proceedings of the 6th International Conference on the Internet of Things*, ACM. DOI:https://doi.org/10.1145/2991561.2991564

[32] Joung-Woo Choi and Yang-Hann Kim. 2002. Generation of an Acoustically Bright Zone with an Illuminated Region Using Multiple Sources. *J. Acoust. Soc. Am.* 111, 4 (2002), 1695–1700. DOI:https://doi.org/10.1121/1.1456926

[33] Graeme W. Coleman, Catriona Macaulay, and Alan F. Newell. 2008. Sonic Mapping: Towards Engaging the User in the Design of Sound for Computerized Artifacts. In *Proceedings of the 5th Nordic Conference on Human-Computer Interaction*, ACM, New York, New York, USA, 83–92. DOI:https://doi.org/10.1145/1463160.1463170

[34] Andrew Crabtree, Mark Rouncefield, and Peter Tolmie. 2012. *Doing Design Ethnography*. Springer-Verlag, London, UK.

[35] Andy Crabtree and Tom Rodden. 2004. Domestic Routines and Design for the Home. *Comput. Support. Coop. Work* 13, 2 (2004), 191–220.

[36] John W. Creswell and J. David Creswell. 2017. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches* (5th ed.). SAGE Publications, Newbury Park, California, US.

[37] John W. Creswell and Cheryl N. Poth. 2018. *Qualitative Inquiry & Research Design: Choosing among Five Approaches* (4th ed.). SAGE Publications, Newbury Park, California, US.

[38] Luke Dahl and Ge Wang. 2010. Sound Bounce: Physical Metaphors in Designing Mobile Music Performance. In *Proceedings of the 2010 Conference on New Interfaces for Musical Expression*, ACM, 178–181.

[39] Bo Dahlbom and Lars Mathiassen. 1993. *Computers in Context: The Philosophy and Practice of System Design*. John Wiley & Sons, Hoboken, New Jersey, US.

[40] Peter Dalsgaard and Christian Dindler. 2014. Between Theory and Practice: Bridging Concepts in HCI Research. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, ACM, 1635–1644. DOI:https://doi.org/10.1145/2556288.2557342

[41] John Dewey. 1958. Experience and Philosophic Method. In *Experience and Nature*. Dover Publications, 1a – 39.

[42] Tanja Döring, Dagmar Kern, Paul Marshall, Max Pfeiffer, Johannes Schöning, Volker Gruhn, and Albrecht Schmidt. 2011. Gestural Interaction on the Steering Wheel-Reducing the Visual Demand. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, 483–492. DOI:https://doi.org/10.1145/1978942.1979010

[43] Paul Dourish. 2004. *Where the Action Is: The Foundations of Embodied Interaction*. MIT Press, Cambridge, Massachusetts, US.

[44] Paul Dourish. 2006. Implications for Design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, 541–550. DOI:https://doi.org/10.1145/1124772.1124855

[45] W. F. Druyvesteyn and John Garas. 1997. Personal Sound. *J. Audio Eng. Soc.* 45, 9 (1997), 685–701.

[46] Gary W. Evans, Nancy M. Wells, and Annie Moch. 2003. Housing and Mental Health: A Review of the Evidence and a Methodological and Conceptual Critique. *J. Soc. Issues* 59, 3 (2003), 475–500.

[47] Bent Flyvbjerg. 2008. Aristotle, Foucault and Progressive Phronesis: Outline of an Applied Ethics of Sustainable Development. In *Critical Essays in Planning Theory*, Jean Hillier and Patsy Healey (eds.). Ashgate, London, 65–83. DOI:https://doi.org/10.2139/ssrn.2717697

[48] Karmen Franinovic and Christopher Salter. 2013. The Experience of Sonic Interaction. In *Sonic Interaction Design*, Karmen Franinovic and Stefania Serafin (eds.). MIT Press, Cambridge, Massachusetts, US.

[49] Karmen Franinovic and Stefania Serafin. 2013. *Sonic Interaction Design*. MIT Press, Cambridge, Massachusetts, US.

[50] Karmen Franinovic and Yon Visell. 2007. New Musical Interfaces in Context: Sonic Interaction Design in the Urban Setting. In *Proceedings of the 7th International Conference on New Interfaces for Musical Expression*, ACM, New York, New York, USA, 191–196. DOI:https://doi.org/10.1145/1279740.1279776

[51] William W. Gaver. 1989. The SonicFinder: An Interface That Uses Auditory Icons. *J. Human-Computer Interact.* 4, (1989), 67–94.

[52] Gabriel Haas, Evgeny Stemasov, Michael Rietzler, and Enrico Rukzio. 2020. Interactive Auditory Mediated Reality: Towards User-defined Personal Soundscapes. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*, ACM, 2035–2050. DOI:https://doi.org/10.1145/3357236.3395493

[53] Gabriel Haas, Evgeny Stemasov, and Enrico Rukzio. 2018. Can't You Hear Me? Investigating Personal Soundscape Curation. In *Proceedings of the 17th International Conference on Mobile and Ubiquitous Multimedia*, ACM, 59–69. DOI:https://doi.org/10.1145/3282894.3282897

[54] Richard Haberkern. Soundlazer. Retrieved March 17, 2021 from https://www.soundlazer.com

[55] Mack Hagood. 2011. Quiet Comfort: Noise, Otherness, and the Mobile Production of Personal Space. *Am. Q.* 63, 3 (2011), 573–589.

[56] Kim Halskov and Caroline Lundqvist. 2021. Filtering and Informing the Design Space: Towards Design-Space Thinking. *ACM Trans. Comput. Interact* 28, 8 (2021). DOI:https://doi.org/10.1145/3434462

[57] Steve Harrison and Paul Dourish. 1996. Re-Place-ing Space: The Roles of Place and Space in Collaborative Systems. In *Proceedings of the 1996 ACM Conference on Computer Supported Cooperative Work*, ACM, 67–76.

[58] Doris Hausen, Hendrik Richter, Adalie Hemme, and Andreas Butz. 2013. Comparing Input Modalities for Peripheral Interaction: A Case Study on Peripheral Music Control. In *IFIP Conference on Human-Computer Interaction*, Springer, Berlin, Heidelberg, 162–179.

[59] Björn Hellström. 2003. Noise Design: Architectural Modelling and the Aesthetics of Urban Acoustic Space. KTH Royal Institute of Technology.

[60] Thomas Hermann. 2008. Taxonomy and Definitions for Sonification and Auditory Display. In *Proceedings of the 14th International Conference on Auditory Display*.

[61] Franz M. Heuchel, Diego Caviedes Nozal, Finn T. Agerkvist, and Jonas Brunskog. 2019. Sound Field Control for Reduction of Noise from Outdoor Concerts. In *Proceedings of 145th Audio Engineering Society Convention*, Journal of the Audio Engineering Society.

[62] Marie Koldkjær Højlund. 2017. Overhearing: An Attuning Approach to Noise in Danish Hospitals. Aarhus University. DOI:https://doi.org/10.7146/aul.211.151

[63] Holosonics. Audio Spotlight. Retrieved March 17, 2021 from https://www.holosonics.com

[64] Andreas Holzinger, Martin Schlögl, Bernhard Peischl, and Matjaz Debevc. 2010. Optimization of a Handwriting Recognition Algorithm for a Mobile Enterprise Health Information System on the Basis of Real-Life Usability Research. In *International Conference on E-Business and Telecommunications*, Springer, Berlin, Heidelberg, 97–111.

[65] Kristina Höök and Jonas Löwgren. 2012. Strong Concepts: Intermediate-Level Knowledge in Interaction Design Research. *ACM Trans. Comput. Interact* 19, 23 (2012). DOI:https://doi.org/10.1145/2362364.2362371

[66] Don Ihde. 2010. Heidegger on Technology: One Size Fits All. *Philos. Today* 54, Supplement (2010), 101–105.

[67] Don Ihde. 2016. Adding Pragmatism to Phenomenology. In *Husserl's Missing Technologies*. Fordham University Press, New York, New York, USA, 103–121.

[68] Sarah Inman and David Ribes. 2019. "Beautiful Seams": Strategic Revelations and Concealments. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, ACM, 1–14. DOI:https://doi.org/10.1145/3290607

[69] Hiroshi Ishii, Craig Wisneski, Scott Brave, Andrew Dahley, Matt Gorbet, Brygg Ullmer, and Paul Yarin. 1998. ambientROOM: Integrating Ambient Media with Architectural Space. In *Proceedings of the 1998 Conference on Human Factors in Computing Systems*, ACM, 173–174. DOI:https://doi.org/10.1145/286498.286652

[70] ISOBEL. Interactive Sound Zones for Better Living. Retrieved from https://isobel.dk

[71] Stine S. Johansen and Peter Axel Nielsen. 2021. Soundwalking Homes in Design Ethnography. *J. Sonic Stud.* (2021).

[72] Hanna Kallio, Anna Maija Pietilä, Martin Johnson, and Mari Kangasniemi. 2016. Systematic Methodological Review: Developing a Framework for a Qualitative Semi-Structured Interview Guide. *J. Adv. Nurs.* 72, 12 (December 2016), 2954–2965. DOI:https://doi.org/10.1111/jan.13031

[73] KwanMyung Kim, Dongwoo Joo, and Kun-Pyo Lee. 2010. Wearable-Object-Based Interaction for a Mobile Audio Device. In *CHI'10 Extended Abstracts on Human Factors in Computing Systems*, ACM, 3865–3870. DOI:https://doi.org/10.1145/1753846.1754070

[74] Jesper Kjeldskov and Mikael B Skov. 2014. Was it Worth the Hassle? Ten Years of Mobile HCI Research Discussions on Lab and Field Evaluations. In *Proceedings of the 16th International Conference on Human-Computer Interaction with Mobile Devices & Services*, ACM, 43–52. DOI:https://doi.org/10.1145/2628363.2628398

[75] Jon Kolko. 2010. Abductive Thinking and Sensemaking: The Drivers of Design Synthesis. *Des. Issues* 26, 1 (2010), 15–28.

[76] Matthias Kranz, Stefan Freund, Paul Holleis, and Albrecht Schmidt. 2006. Developing Gestural Input. In *Proceedings of the 26th IEEE International Conference on Distributed Computing Systems Workshops*, IEEE. DOI:https://doi.org/10.1109/ICDCSW.2006.41

[77] Taewoong Lee. 2020. Taewoong Lee - User tuneable sound zones. *YouTube*. Retrieved April 27, 2021 from https://www.youtube.com/watch?v=W8KRMjEU1AE

[78] Taewoong Lee, Jesper Kjær Nielsen, and Mads Græsbøll Christensen. 2019. Towards Perceptually Optimized Sound Zones: A Proof-of-Concept Study. In *Proceedings of the 2019 IEEE International Conference on Acoustics, Speech, and Signal Processing, ICASSP 2019*, IEEE, 136–140. DOI:https://doi.org/10.1109/ICASSP.2019.8682902

[79] Taewoong Lee, Jesper Kjær Nielsen, Jesper Rindom Jensen, and Mads Græsbøll Christensen. 2018. A Unified Approach to Generating Sound Zones Using Variable Span Linear Filters. In *2018 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, IEEE, Calgary, AB, Canada, 491–495. DOI:https://doi.org/10.1109/ICASSP.2018.8462477

[80] Gerhard Leitner, David Ahlström, and Martin Hitz. 2007. Usability of Mobile Computing in Emergency Response Systems – Lessons Learned and Future Directions. In *Symposium of the Austrian HCI and Usability Engineering Group*, Springer, Berlin, Heidelberg, 241–254.

[81] Tuck W. Leong and Peter Wright. 2013. Revisiting Social Practices Surrounding Music. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, 951–960. DOI:https://doi.org/https://doi.org/10.1145/2470654.2466122

[82] Youn-Kyung Lim, Erik Stolterman, and Josh Tenenberg. 2008. The Anatomy of Prototypes: Prototypes as Filters, Prototypes as Manifestations of Design Ideas. *ACM Trans. Comput. Interact.* 15, 2 (July 2008). DOI:https://doi.org/10.1145/1375761.1375762

[83] Diana Löffler, Lennart Arlt, Takashi Toriizuka, Robert Tscharn, and Jörn Hurtienne. 2016. Substituting Color for Haptic Attributes in Conceptual Metaphors for Tangible Interaction Design. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, ACM, 118–125. DOI:https://doi.org/10.1145/2839462.2839485

[84] Catriona Macaulay and Alison Crerar. 1998. "Observing" the Workplace Soundscape: Ethnography and Auditory Interface Design. In *Proceedings of the 1998 International Conference on Auditory Display*, ACM.

[85] Malcolm McCollough. 2015. *Ambient Commons: Attention in the Age of Embodied Information*. MIT Press, Cambridge, Massachusetts, US.

[86] Mark McGill, Florian Mathis, Mohamed Khamis, and Julie Williamson. 2020. Augmenting TV Viewing using Acoustically Transparent Auditory Headsets. In *ACM International Conference on Interactive Media Experiences*, ACM, 34–44. DOI:https://doi.org/10.1145/3391614.3393650

[87] Mark McGill, David McGookin, Graham Wilson, and Stephen Brewster. 2020. Acoustic Transparency and the Changing Soundscape of Auditory Mixed Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, ACM, 1–16. DOI:https://doi.org/10.1145/3313831.3376702

[88] Iain McGregor, Alison Crerar, David Benyon, and Grégory Leplâtre. 2007. Establishing Key Dimensions for Reifying Soundfields and Soundscapes from Auditory Professionals. In *Proceedings of the 13th International Conference on Auditory Display*, Montréal, Canada, 364–371.

[89] Iain McGregor, Alison Crerar, David Benyon, and Catriona Macaulay. 2002. Soundfields and Soundscapes: Reifying Auditory Communities. In *Proceedings of the 2002 International Conference on Auditory Display*, Georgia Institute of Technology, Kyoto, Japan.

[90] Maurice Merleau-Ponty. 2012. *Phenomenology of Perception*. Routledge, Oxfordshire, England, UK.

[91] Matthew B. Miles and A. Michael Huberman. 1994. Early Steps in Analysis. In *Qualitative Data Analysis*. SAGE Publications, Newbury Park, California, US, 50–88.

[92] Henry Mintzberg. 2017. Developing Theory about the Development of Theory. In *Handbook of Middle Management Strategy Process Research*, Steven W. Floyd and Bill Wooldridge (eds.). Edward Elgar Publishing Ltd., 177–196. DOI:https://doi.org/10.4337/9781783473250.00017

[93] Jörg Müller, Matthias Geier, Christina Dicke, and Sascha Spors. 2014. The BoomRoom: Mid-Air Direct Interaction with Virtual Sound Sources. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, 247–256. DOI:https://doi.org/10.1145/2556288.2557000

[94] Thomas Nagel. 1974. What Is It Like to Be a Bat? *Philos. Rev.* 83, 4 (1974), 435–450.

[95] Julien Nembrini and Denis Lalanne. 2017. Human-Building Interaction: When the Machine Becomes a Building. In *16th IFIP Conference on Human-Computer Interaction*, Springer, Bombay, India, 348–369. DOI:https://doi.org/10.1007/978-3-319-67684-5_21ï

[96] Frederik L. Nielbo, Daniel Steele, and Catherine Guastavino. 2013. Investigating Soundscape Affordances through Activity Appropriateness. *Proc. Meet. Acoust. ICA2013* 19, 1 (2013). DOI:https://doi.org/10.1121/1.4800502

[97] Jesper Kjær Nielsen, Taewoong Lee, Jesper Rindom Jensen, and Mads Græsbøll Christensen. 2018. Sound Zones as an Optimal Filtering Problem. In *2018 52nd Asilomar Conference on Signals, Systems, and Computers*, IEEE, Pacific Grove, CA, USA, 1075–1079.

[98] Karin Niemantsverdriet, Harm Van Essen, and Berry Eggen. 2017. A Perspective on Multi-User Interaction Design Based on an Understanding of Domestic Lighting Conflicts. *Pers. Ubiquitous Comput.* 21, 2 (2017), 371–389. DOI:https://doi.org/10.1007/s00779-016-0998-5

[99] Gerard Oleksik, David Frohlich, Lorna M. Brown, and Abigail Sellen. 2008. Sonic Interventions: Understanding and Extending the Domestic Soundscape. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, 1419–1428. DOI:https://doi.org/10.1145/1357054.1357277

[100] Charles Sanders Peirce. 1935. Three Types of Reasoning. In *Collected Papers of Charles Sanders Peirce* (4th ed.), Charles Hartshorne and Paul Weiss (eds.). The Belknap Press of Harvard University Press, 94–112.

[101] Sarah Pink, Kerstin Leder Mackley, Roxana Morosanu, Val Mitchel, and Tracy Bhamra. 2017. *Making Homes: Ethnography and Design*. Bloomsbury Academic.

[102] Antti Pirhonen, Stephen Brewster, and Christopher Holguin. 2002. Gestural and Audio Metaphors as a Means of Control for Mobile Devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, 291–298. DOI:https://doi.org/10.1145/503376.503428

[103] F. Joseph Pompei. 1999. The Use of Airborne Ultrasonics for Generating Audible Sound Beams. *J. Audio Eng. Soc.* 47, 9 (1999), 726–731.

[104] F. Joseph Pompei. 2002. Sound from Ultrasound: The Parametric Array as an Audible Sound Source. Massachusetts Institute of Technology.

[105] Jussi Rämö, Lasse Christensen, Søren Bech, and Søren Jensen. 2017. Validating a Perceptual Distraction Model Using a Personal Two-Zone Sound System. *Proc. Meet. Acoust.* 30, 1 (2017). DOI:https://doi.org/10.1121/2.0000534

[106] Tom Rodden and Steve Benford. 2003. The Evolution of Buildings and Implications for the Design of Ubiquitous Domestic Environments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, 9–16. DOI:https://doi.org/10.1145/642611.642615

[107] R. Murray Schafer. 1967. *Ear Cleaning: Notes for an Experimental Music Course*. Clark & Cruickshank, Toronto, Canada.

[108] R. Murray Schafer. 1993. *The Soundscape: Our Sonic Environment and the Tuning of the World.* Destiny Books, Vancouver, BC.

[109] Donald A. Schön. 1983. *The Reflective Practitioner.* Routledge, Oxfordshire, England, UK.

[110] Donald A. Schön. 1993. Generative Metaphor: A Perspective on Problem-Setting in Social Policy. In *Metaphor and Thought* (2nd ed.), Andrew Ortony (ed.). Cambridge University Press, 137–163.

[111] John Seely Brown and Paul Duguid. 1994. Borderline Issues: Social And Material Aspects Of Design. *Human-Computer Interact.* 9, (1994), 3–36.

[112] Ted Sheridan and Karen Van Lengen. 2013. Hearing Architecture: Exploring and Designing the Aural Environment. *J. Archit. Educ.* 57, 2 (November 2013), 37–44. DOI:https://doi.org/10.1162/104648803770558978

[113] Erik Stolterman and Mikael Wiberg. 2010. Concept-Driven Interaction Design Research. *Human-Computer Interact.* 25, 2 (2010), 95–118. DOI:https://doi.org/10.1080/07370020903586696

[114] Steven Strachan, Roderick Murray-Smith, and Sile O'Modhrain. 2007. BodySpace: Inferring Body Pose for Natural Control of a Music Player. In *CHI'07 Extended Abstracts on Human Factors in Computing Systems*, ACM, 2001–2006. DOI:https://doi.org/10.1145/1240866.1240939

[115] Dag Svanæs. 2013. Interaction Design for and with the Lived Body: Some Implications of Merleau-Ponty's Phenomenology. *ACM Trans. Comput. Interact* 20, 8 (2013). DOI:https://doi.org/10.1145/2442106.2442114

[116] Syng. Cell Alpha. Retrieved June 15, 2021 from https://syngspace.com/

[117] Petek Tezcan, Saskia Bakker, and Berry Eggen. 2017. Musico: Personal Playlists through Peripheral and Implicit Interaction. In *DIS'17 Companion*, ACM, 121–126. DOI:https://doi.org/10.1145/3064857.3079131

[118] Barry Truax. 2001. *Acoustic Communication* (2nd ed.). Ablex Publishing, Westport.

[119] Heikki Uimonen. 2011. Everyday Sounds Revealed: Acoustic Communication and Environmental Recordings. *Organised Sound* 16, 3 (December 2011), 256–263. DOI:https://doi.org/10.1017/S1355771811000264

[120] Ultrasonic Audio Technologies. Acouspade. Retrieved March 17, 2021 from https://ultrasonic-audio.com

[121] Peter-Paul Verbeek. 2005. *What Things Do: Philosophical Reflections on Technology, Agency, and Design*. The Pennsylvania State University Press.

[122] Peter-Paul Verbeek. 2015. Beyond Interaction: A Short Introduction to Mediation Theory. *Interactions* 22, 3 (2015), 26–31.

[123] Himanshu Verma, Hamed S. Alavi, and Denis Lalanne. 2017. Studying Space Use: Bringing HCI Tools to Architectural Projects. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, ACM, 3856–3866. DOI:https://doi.org/10.1145/3025453.3026055

[124] Jane Webster and Richard T. Watson. 2002. Analyzing the Past to Prepare for the Future: Writing a Literature Review. *MIS Q.* 26, 2 (June 2002), xiii–xxiii.

[125] Hildegard Westerkamp. 1974. Soundwalking. *Sound Herit.* 3, 4 (1974).

[126] Mikael Wiberg. 2015. Interaction Design Meets Architectural Thinking. *Interactions* 22, 2 (2015), 60–63. DOI:https://doi.org/10.1145/2732936

[127] Mikael Wiberg. 2017. From Interactables to Architectonic Interaction. *Interactions* 24, 2 (2017), 62–65. DOI:https://doi.org/10.1145/3036203

[128] Mikael Wiberg. 2020. Interaction and Architecture Is Dead. Long Live Architectural Interactivity. *Interactions 27*, 72–75. DOI:https://doi.org/10.1145/3378567

[129] Jacob O. Wobbrock, Meredith Ringel Morris, and Andrew D. Wilson. 2009. User-Defined Gestures for Surface Computing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, 1083–1092. DOI:https://doi.org/https://doi.org/10.1145/1518701.1518866

[130] Claes Wohlin. 2014. Guidelines for Snowballing in Systematic Literature Studies and a Replication in Software Engineering. In *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering*, ACM, 1–10. DOI:https://doi.org/10.1145/2601248.2601268

[131] Katrin Wolf, Christina Dicke, and Raphael Grasset. 2011. Touching the Void: Gestures for Auditory Interfaces. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction*, ACM, 305–308. DOI:https://doi.org/10.1145/1935701.1935772

[132] World Health Organization. 2018. Environmental Noise Guidelines for the European Region. Retrieved March 23, 2021 from http://www.euro.who.int/pubrequest

[133] Sungwook Yoon, Yangwon Lim, Hankyu Lim, and Hyenki Kim. 2012. Architecture of Automatic Warning System on Urgent Traffic Situation for Headphone Users. *Int. J. Multimed. Ubiquitous Eng.* 7, 2 (April 2012), 421–426.

[134] Shengdong Zhao, Pierre Dragicevic, Mark Chignell, Ravin Balakrishnan, and Patrick Baudisch. 2007. earPod: Eyes-free Menu Selection using Touch Input and Reactive Audio Feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, 1395–1404. DOI:https://doi.org/10.1145/1240624.1240836

[135] John Zimmerman and Jodi Forlizzi. 2008. The Role of Design Artifacts in Design Theory Construction. *Artifact* 2, 1 (2008), 41–45.

APPENDIX OVERVIEW

A. INCLUDED PAPERS

This appendix contains an overview of the included papers and each paper.

B. DOCUMENTATION OF SOUND ZONES IN LAB SETUP

This appendix contains measurements documenting the lab setup used for studies 5-7.

A. INCLUDED PAPERS

This appendix contains the following papers included in the dissertation:

(Please note that the author of this dissertation was published as Stine S. Lundgaard from 2017 to 2020 – the author is marked in bold for each paper.)

[P1] **Stine S. Lundgaard**, Jesper Kjeldskov, and Mikael B. Skov. 2019. Temporal Constraints in Human--Building Interaction. *ACM Trans. Comput.-Hum. Interact.* 26, 2, Article 8 (April 2019), 29 pages. DOI: https://doi.org/10.1145/3301424

[P2] **Stine S. Lundgaard** and Peter Axel Nielsen. 2019. Personalised Soundscapes in Homes. In *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19).* Association for Computing Machinery, New York, NY, USA, 813–822. DOI: https://doi.org/10.1145/3322276.3322364

[P3] **Stine S. Johansen**, Peter Axel Nielsen, Kashmiri Stec, and Jesper Kjeldskov. 2021 (accepted for publication). Experiences of Personal Sound Technologies. In *IFIP Conference on Human-Computer Interaction (INTERACT'21).* Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-85616-8_30

[P4] **Stine S. Lundgaard**, Peter Axel Nielsen, and Jesper Kjeldskov. 2020. Designing for Domestic Sound Zone Interaction. *Personal and Ubiquitous Computing* (March 2020), 1-12. DOI: https://doi.org/10.1007/s00779-020-01387-2

[P5] **Stine S. Johansen**, Kashmiri Stec, Peter A. Nielsen, and Jesper Kjeldskov. (Submitted to CHI'22). Shedding Light on Sound Zones.

[P6] **Stine S. Johansen**, Timothy Merritt, Rune M. Jacobsen, Peter A. Nielsen, and Jesper Kjeldskov. (Submitted to CHI'22). Investigating Potentials of Shape-Changing Interfaces for Sound Zones.

In the following pages, for each paper, the first page presents the title and publication information. This is followed by the paper formatted according to the publishers' guidelines. The electronically available version of this dissertation is redacted and only contains the title, publication information and abstract for each paper. For published versions, please follow the provided link. For questions regarding the manuscripts, please contact Stine S. Johansen.

[P1] TEMPORAL CONSTRAINTS IN HUMAN-BUILDING INTERACTION

Stine S. Lundgaard, Jesper Kjeldskov, and Mikael B. Skov. 2019. Temporal Constraints in Human--Building Interaction. *ACM Trans. Comput.-Hum. Interact.* 26, 2, Article 8 (April 2019), 29 pages. DOI: https://doi.org/10.1145/3301424

ABSTRACT

Human-building interaction is converging the fields of architecture and interaction design, leading to new and interesting tensions in perspectives and methodological approaches. One such tension is related to temporal constraints. Architecture and interaction design typically produce outcomes with very different lifetime expectancies and, predominantly, use methods with very different pace. As an example, fast, iterative approaches of contemporary interaction design, consisting of frequent updates and redesigns, contrasts with much slower, plan-driven and long-term vision driven approaches within architecture. One question emerging from this tension is how to meaningfully combine perspectives and approaches. One suggestion, among others, has been that interaction design methods such as participatory design can be used to heighten the involvement of inhabitants and other stakeholders in continuous adaptations of the buildings they inhabit. While an interesting proposal, we believe that methodological considerations only partly address the complexity of the tension at play from the different lifetime expectancies of buildings and interactive computer systems. Unfolding this complexity further, we therefore propose a framework of temporal constraints at three levels of abstraction: 1) rationale, 2) method, and 3) outcome. Inspired by previous work, we discuss temporal constraints in human-building interaction at these levels. We argue that designing for human-building interaction requires an understanding of temporally constrained design conventions that apply meaningfully to both the short-term and long-term.

[P2] PERSONALISED SOUNDSCAPES IN HOMES

Stine S. Lundgaard and Peter Axel Nielsen. 2019. Personalised Soundscapes in Homes. In *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19)*. Association for Computing Machinery, New York, NY, USA, 813–822. DOI: https://doi.org/10.1145/3322276.3322364

ABSTRACT

Sound zone technology is being developed to provide users with the ability to modify their personal soundscape. In this paper, we take first steps toward studying how and when users could use sound zone technology within the domestic context. We present a design ethnographical study of sounds in homes and potentials for utilising sound zone technology to modify soundscapes. Based on two rounds of qualitative interviews with seven participating households of diverse composition, dwelling type, and area type, we develop a design-oriented framework. The framework posits particular situations in which sound zone technology can support domestic activities. These are described and validated through the qualitative data collected in the households. The framework consists of two dimensions leading to four generalised situations: private versus social situations, and separate versus connected situations. A number of implications for designing interaction with sound zone systems in homes are derived from the framework.

[P3] EXPERIENCES OF PERSONAL SOUND TECHNOLOGIES

Stine Schmieg Johansen, Peter Axel Nielsen, Kashmiri Stec, and Jesper Kjeldskov. 2021 (accepted for publication). Experiences of Personal Sound Technologies. In *IFIP Conference on Human-Computer Interaction (INTERACT'21).* Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-85616-8_30

ABSTRACT

Listening to sound individually while in close proximity of other people is increasingly enabled by a range of technologies. One still in development is sound zone technology that aims to provide personal sound without headphones or other wearable speakers. User-oriented studies in the area of personal listening primarily emerge from the fields of acoustics and sound engineering but are gaining increasing interest within HCI research. In this paper, we present a study investigating the experience of personal sound in relation to different types of situations and personal sound technologies. Our findings show strategies for adjusting personal sound and social interaction, descriptions of sound quality in relation to sound and situation types, and insights into participants' experiences of awareness using personal sound technology. The paper contributes with a thematic characterisation of this type of technology, serving as a foundation for further studies. This furthermore initiates a discussion on personal sound technology and soundscape composition in how situation types affect which sounds to include or exclude, and when.

[P4] DESIGNING FOR DOMESTIC SOUND ZONE INTERACTION

Stine S. Lundgaard, Peter Axel Nielsen, and Jesper Kjeldskov. 2020. Designing for Domestic Sound Zone Interaction. *Personal and Ubiquitous Computing* (March 2020), 1-12. DOI: https://doi.org/10.1007/s00779-020-01387-2

ABSTRACT

Sound zone technology has been actively developed for more than two decades with a promise to provide users with personal sound without wearing headphones. In this paper, we build on this development from the perspective of interaction design in two ways. First, we explore the relation between sound zones and the acoustic environment, referred to as a soundscape, through a theoretical exploration of related research in both areas. Second, we present eight interaction design challenges resulting from this. Four different interaction approaches to potentially take on the challenges are sketched and discussed in a workshop and collecting qualitative data from the process. These approaches include tangible representation, light projections, familiar objects, and handheld devices. We group the approaches as visual displays, and user-centred and sound zone-centred interfaces. Overall, our research provides a new perspective on interaction with sound zone technology with specific outlines for further research in this area.

[P5] SHEDDING LIGHT ON SOUND ZONES

Stine S. Johansen, Peter Axel Nielsen, Kashmiri Stec, and Jesper Kjeldskov. (Submitted to CHI'22). Shedding Light on Sound Zones.

ABSTRACT

The invisibility of sound zones presents new interaction design challenges. We investigate light as feedback modality for sound zone systems and present findings from two studies. In the first study (N = 27), novice users are introduced to different colours and brightness values on a volume controller and asked to relate those to volume and size of a sound zone. In the second study (N = 36), novice users turned up the volume of one sound zone to affect another. When the sound zones overlap, one of 12 animated light patterns are displayed. They related these patterns to information statements regarding properties of the sound zones. Our findings show that brightness can be used for feedback regarding sound zone sizes. For overlaps, participants experienced instant light patterns as better indicators of overlaps compared to gradual light patterns. These findings form a foundation for using light for sound zone feedback and to guide future research.

[P6] INVESTIGATING POTENTIALS OF SHAPE-CHANGING INTERFACES FOR SOUND ZONES

Stine S. Johansen, Timothy Merritt, Rune Møberg Jacobsen, Peter Axel Nielsen, and Jesper Kjeldskov. (Submitted to CHI'22). Investigating Potentials of Shape-Changing Interfaces for Sound Zones.

ABSTRACT

A core challenge in sound zone research is to support users' understanding of the unique spatial properties sound zones introduce. Shape-changing interfaces present new opportunities for addressing this. In this paper, we investigate the use of shape-change for interaction with sound zones. We present a structured design and evaluation process in two parts. First, we set constraints for our design and leveraged the knowledge of 12 sound experts to define a set of basic shapes and movements. Second, we constructed a prototype and conducted an elicitation study with 17 novice users, investigating the experience of these shapes and movements. Our findings show that physical visualizations of sound zones can be useful in supporting users' experience of sound zones. We present a framework of 4 basic pattern categories that prompt different experiences for users and outline future research areas for shape-change in supporting sound zone interaction.

B. DOCUMENTATION OF SOUND ZONES IN LAB SETUP

In this appendix, I provide graphs of measurements of the lab setups for studies 5 to 7. Figure B.1 shows the lab setup for studies 5 and 6 regarding light and for the start condition of study 7 regarding shape-change. For studies 5 and 7, only Person A was present, but the sound zone for Person B was active. Figure B.2 shows the setup for the final condition in study 7. Like the start condition, only Person A was present, but Person B's sound zone was active.

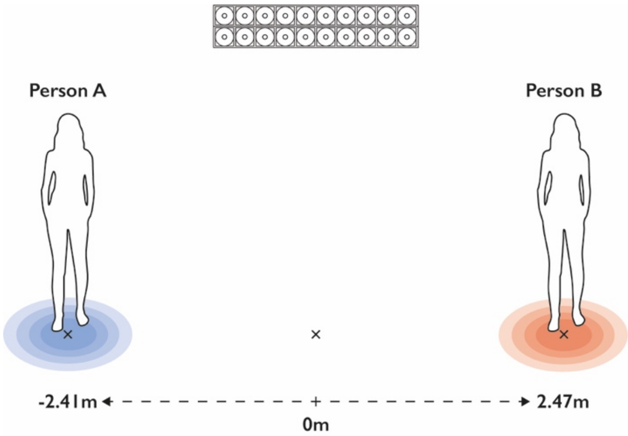


Figure B.1: Lab setup for studies 5 and 6 (regarding light) as well as the start condition for study 7 (regarding shape-change).

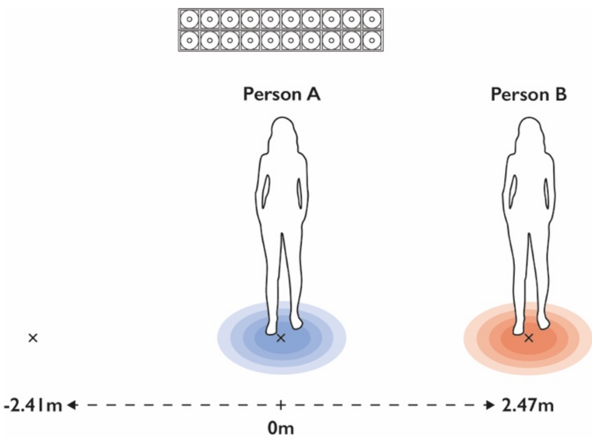


Figure B.2: Lab setup for the final condition for study 7 (regarding shape-change).

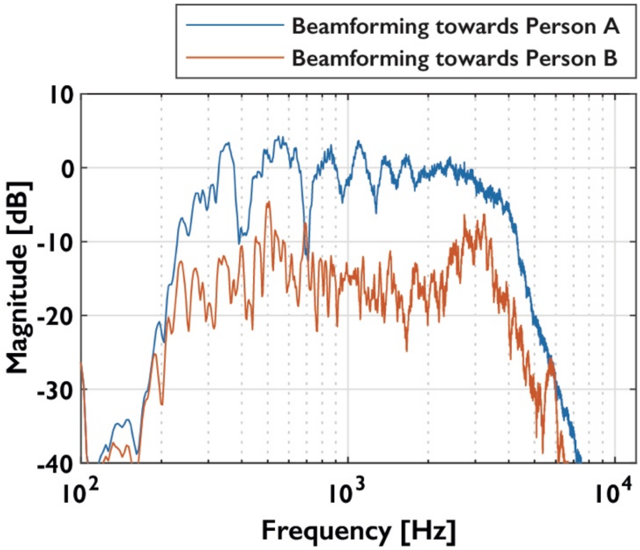


Figure B.3: Sound in Person A's sound zone. Blue is Person A's personal sound, and red is Person B's personal sound. Corresponds to setup in Figure B.1.

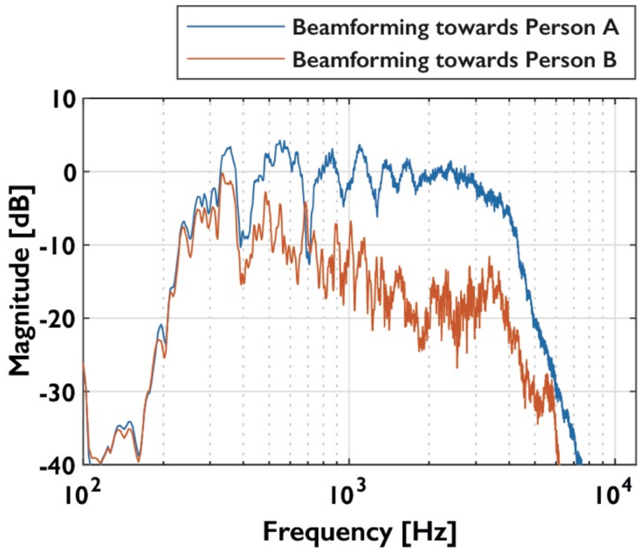


Figure B.4: Sound in Person A's sound zone. Blue is Person A's personal sound, and red is Person B's personal sound. Corresponds to setup in Figure B.2.

Figures B.3 and B.4 show measurements from Person A's sound zones of both sounds when played at the same volume level inside each sound zone. In other words, the figures illustrate what Person A hears inside their own sound zone. Figure B.3 corresponds to the setup illustrated in Figure B.1, and Figure B.4 corresponds to Figure B.2. The lines show the magnitude of frequencies for Person A's sound (blue line) and Person B's sound (red line). It is important to note that the unit of measurement (dB) is expressed on a logarithmic scale which means that the higher the level, the bigger the difference. As is shown with these graphs, Person A can mostly hear their own sound except for certain frequency ranges. For example, when standing near Person B (Figure B.2), Person A can hear lower frequencies from the other sound zone almost at the same level as their own sound.

SUMMARY

This dissertation is based on research conducted from 2018 to 2021 at the Department of Computer Science, Aalborg University. The dissertation consists of six full papers as well as a synopsis that outlines research questions, related work, research design, a summary of the paper contributions, and a discussion that positions the research. In this research, I investigate how to support users' understanding and control of sound zone systems with interaction designs. I do so in seven studies in field and lab settings where I apply approaches to (1) articulate experiences of sound zones in different situations and (2) designing interaction with sound zones. From this investigation, I make three propositions towards a theory of sound zone configurations. The research offers a foundation for asking and investigating more far-reaching questions that pertain to experiences of and designing for sound zone systems.

ISSN (online): 2446-1628
ISBN (online): 978-87-7210-974-9

AALBORG UNIVERSITETSFORLAG