Diverse Sounds

Enabling Inclusive Sonic Interaction

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Abstract

This compilation thesis collects a series of publications on designing sonic interactions for diversity and inclusion. The presented papers focus on case studies in which musical interfaces were either developed or reviewed. While the described studies are substantially different in their nature, they all contribute to the thesis by providing reflections on how musical interfaces could be designed to enable inclusion rather than exclusion. Building on this work, I introduce two terms: *inclusive sonic interaction design* and *Accessible Digital Musical Instruments (ADMIs)*. I also define nine properties to consider in the design and evaluation of ADMIs: expressiveness, playability, longevity, customizability, pleasure, sonic quality, robustness, multimodality and causality. Inspired by the experience of playing an acoustic instrument, I propose to enable musical inclusion for under-represented groups (for example persons with visual- and hearing-impairments, as well as elderly people) through the design of Digital Musical Instruments (DMIs) in the form of rich multisensory experiences allowing for multiple modes of interaction. At the same time, it is important to enable customization to fit user needs, both in terms of gestural control and provided sonic output. I conclude that the computer music community has the potential to actively engage more people in music-making activities. In addition, I stress the importance of identifying challenges that people face in these contexts, thereby enabling initiatives towards changing practices.

Sammanfattning

I denna sammanläggningsavhandling presenteras ett antal artiklar med fokus på mångfald och breddat deltagande inom fältet sonisk interaktionsdesign (engelska: *Sonic Interaction Design*). Publikationerna behandlar utvecklingen av musikgränssnitt samt en översikt av sådana system. De studier som beskrivs i denna avhandling skiljer sig väsentligt åt sinsemellan men bidrar alla till avhandlingens tes genom att förse läsaren med reflektioner kring hur musikgränssnitt kan utformas för att främja breddat deltagande inom musikskapande. Baserat på dessa studier introducerar jag två begrepp: *inkluderande sonisk interaktionsdesign* (engelska: *inclusive sonic interaction design*) och *tillgängliga digitala musikinstrument* (engelska: *Accessible Digital Musical Instruments, ADMIs*). Jag definierar även nio egenskaper att ta i beaktning vid design och utvärdering av sådana instrument: uttrycksfullhet, spelbarhet, livslängd, anpassningsbarhet, nöje/välbehag, musik och ljudkvalitet, robusthet, multimodalitet samt kausalitiet. Inspirerad av akustiska musikinstrument föreslår jag att främja ökat deltagande av underrepresenterade grupper (exempelvis personer med syn- eller hörselnedsättningar samt äldre människor) genom att designa digitala musikinstrument i form av multimodala gränssnitt. På så sätt kan instrumenten öppna upp för fler olika interaktionssätt och möjliggöra multisensorisk återkoppling. Det är också viktigt att dessa instrument kan anpassas till respektive användares behov, både när det gäller ljudskapande gester samt ljudande material. Jag drar slutsatsen att forskningsfältet inom datormusik (engelska: computer music) har potential att främja breddat deltagande inom musikskapande. Genom att identifiera de utmaningar som personer i underrepresenterade grupper möter kan vi agera för att skapa en mer inkluderande praktik.

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List of Acronyms

ADMI Accessible Digital Musical Instrument

AI Artificial Intelligence

BCMI Brain-Computer Music Interface

CHI ACM Conference on Human Factors in Computing Systems

DMI Digital Musical Instrument

GUI Graphical User Interface

HCI Human Computer Interaction

HRI Human Robot Interaction

ICAD International Conference on Auditory Display

ICMC International Computer Music Conference

ISMIR International Society for Music Information Retrieval (Conference)

MIDI Musical Instrument Digital Interface

MIR Music Information Retrieval

NIME (International Conference on) New Interfaces for Musical Expression

SID Sonic Interaction Design

SMC Sound and Music Computing (Conference)

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Chapter 1

Introduction

1.1 Preface

According to article 27 of the Universal Declaration of the Human Rights (UN General Assembly, 1948), *"Everyone has the right freely to participate in the cultural life of the community, to enjoy the arts and to share in scientific advancements and its benefits"*. Moreover, article 19 states that *"Everyone has the right to freedom of opinion and expression (...)"*. The premise of this thesis is that everyone should have the right to express themselves through music. As such, partaking in musical activities can be considered an essential part of human rights and freedom of expression. Despite this, many people are still largely excluded from the artistic practice of music-making.

Although the field of computer music is far from new, relatively little work in this domain has yet focused on aspects of inclusion and diversity. The communities focusing on creation of New Interfaces for Musical Expression (NIME) and Digital Musical Instruments (DMIs) still consist of a rather homogeneous group of researchers, creators and practitioners. To be more precise, some groups are not well represented, and the field is not diverse in the sense that people from various cultural and financial backgrounds, ethnicities, gender identities and diverse abilities take active part. Nevertheless, I believe that the very nature of the field, as well as today's increasingly cheap tools and systems readily available for development of interactive interfaces, makes it an excellent platform for promoting music-making for all.

Forgoing designing technology with inclusion in mind, design decisions can inadvertently result in exclusion. In the context of music, audition is (of course) the most important modality involved; however, the haptic and visual senses also play important roles. Musical experiences are inherently multisensory in their nature. Thus, one may argue that musical instruments should not focus solely on one single sense, thereby excluding potential user groups from active participation. In this thesis I reflect on a series of sonic systems and musical interfaces that I have worked on during my PhD. I also discuss how they, in terms of afforded multimodal properties, relate to the topic of *"inclusive sonic interaction design"*. In the context of this thesis, I define this term as *"sonic interaction design aimed at widening participation in sonic and musical interaction"*. This concept is related to the idea of designing sonic and musical interactions for all, regardless of age, gender identity, ethnicity, class, diverse abilities, or musical background.

The work presented in this thesis is based on a set of case studies focusing on various aspects of sonic interaction design, which may, in turn, provide insights into topics related to designing musical interfaces for inclusion. For this purpose, I have introduced the term *Accessible Digital Musical Instruments (AMDIs)* and defined nine properties to consider when designing such instruments. I hope that the work presented in this thesis can spark ideas on how to remove obstacles for music creation, for example through the use of haptic feedback. Although the work is mainly intended to be of interest to practitioners and researchers focusing on sonic interaction design and New Interfaces for Musical Expression (NIME), it could potentially also be relevant for a larger group of readers working in fields related to music, Human Computer Interaction (HCI) and usability. In addition, the results may provide insights on strategies for innovation.

In summary, this thesis work attempts to present an overview and case studies of musical interfaces that can be used for musical inclusion. This involves describing the current technical situation in the field and providing suggestions for directions for future research, as well as drawing attention to the underrepresentation of certain user groups, thereby encouraging technical development.

1.2 Methodology

The work presented in this thesis focuses on a set of distinct projects, each with its own specific aims and hypotheses. As a result, defining one single research question was a somewhat challenging task. In general, the work can be positioned as research conducted within the fields of Sound and Music Computing (SMC) and Sonic Interaction Design (SID). The thesis focuses on how musical interfaces, more precisely Digital Musical Instruments (DMIs), can be designed for the purpose of enabling inclusion and diversity. For this purpose, the following research question was defined: ***How can musical interfaces be designed for inclusion?*** This was followed up with the sub-question: ***How can multimodal feedback be used in digital musical instruments in order to promote inclusion and empowerment?*** Guided by these questions, I have explored concepts related to diversity and inclusion in the computer music field, see for example Paper I focusing on widening participation in DMI practice, and Paper II focusing on sonification of female authors publishing in the field of Sound and Music Computing (SMC).

A range of different methods were adopted in order to achieve the defined knowledge aims of this thesis work. In general, I have approached the research questions from the perspective of an engineer with a background in Media/Audio Technology, but also from the perspective of a musician. These perspectives have, of course, shaped the studies carried out during the thesis work, in particular when it comes to evaluation of sonic interactions and aesthetic goals. Overall, the work presented in this thesis is based on empirical research methodologies employing a mixed approach combining both quantitative and qualitative methods. The research is highly inspired by HCI methods and concepts such as participatory design, iterative prototyping, and user interface evaluation. I have attempted to frame my work in the context of the SMC and computer music communities, but also published at more HCI-focused conferences, such as ACM Conference on Human Factors in Computing Systems (CHI).

1.3 Limitations

This thesis does not seek to propose design principles for all categories of musical interfaces, nor for all potential user groups. The work presents a set of case studies related to the topic of inclusive sonic interaction, diversity and widened participation in music-making. As such, this thesis should be considered as a set of reflections based on a couple of use cases, and suggestions for how the task of designing inclusive sonic interactions could be approached. The thesis does not present any studies on practical work with larger groups of users with diverse abilities. It is possible that more insights on the thesis topics could have been gained through more active prototyping, as well as actual development of, DMIs for under-represented user groups. Nevertheless, I believe that the results may still be of interest for those concerned with designing inclusive sonic interactions, and also for the wider computer music community working with DMIs.

1.4 Thesis Outline

This is a compilation thesis comprised of five peer-reviewed publications published[1] in international journals or conference proceedings. The thesis is organized as follows: Chapter 1 discusses methodological aspects and knowledge contribution of the presented research. This chapter also includes a summary of the papers included in the thesis, specifying my contribution for respective publication. Moreover, a list of additional publications that supplement the papers presented in this thesis, as well as other work carried out during my PhD that is not directly linked to my thesis, is presented. Chapter 2 presents the theoretical framework that serves as foundation for the research carried out. This chapter is divided into three sections. Section 2.1 introduces important research areas in sound and music research. Section 2.2 introduces concepts related to music, diversity and inclusion. It also includes a discussion on accessibility and what I in this thesis refer to as *Accessible Digital Musical Instruments (AMDIs)*. Section 2.3 presents concepts related to the multimodal experience of

[1] At the time of writing, Paper V was submitted for publication; it had not been formally published yet.

interacting with musical instruments, musical haptics, as well as reflections on the design and customization of multimodal musical interfaces. The main contribution of respective publication included in this thesis is described in Chapter 3, along with examples of properties to be considered in ADMI design. In Chapter 4, I present a discussion focusing on how findings from the thesis work could be used to promote inclusion and diversity in music-making, summarizing the main conclusions of this thesis work.

1.5 Included Publications

The scientific contribution of this dissertation is derived from the international peer-reviewed publications presented below. All publications share a common focus on inclusive sonic interaction design. These publications are referred to by their roman numerals (Paper I-V) in subsequent chapters. The publications are supplemented by a number of additional papers (paper i-xii), as described in Section 1.6.

Paper I: Accessible Digital Musical Instruments - A Review of Musical Interfaces in Inclusive Music Practice

Emma Frid
Multimodal Technologies and Interaction, Special Issue on Sonic Interaction for Diversity, 2019

Paper I is an extended version of a conference paper presented at the International Computer Music Conference (ICMC) in 2018 (see paper v). This conference paper describes a systematic review of Accessible Digital Musical Instruments (ADMIs) presented at the International Conference on New Interfaces for Musical Expression (NIME), Sound and Music Computing Conference (SMC) and International Computer Music Conference (ICMC). The term Accessible Digital Musical Instruments is defined as *"accessible musical control interfaces used in electronic music, inclusive music practice and music therapy settings"*. Paper I expands on this previous work into a full review taking journal publications, book sections and doctoral theses into account. The paper outlines the current state of the field through a systematic analysis of ADMIs. I am the sole author of this work.

Paper II: Sound Forest - Evaluation of an Accessible Multisensory Music Installation

Emma Frid, Hans Lindetorp, Kjetil Falkenberg Hansen, Ludvig Elblaus and Roberto Bresin
ACM CHI Conference on Human Computing Systems, 2019

Sound Forest (Ljudskogen) is a multisensory music installation consisting of a room with light-emitting interactive strings, vibrating platforms and speakers, situated at the Swedish Museum of Performing Arts in Stockholm (see paper vii and viii). Apart from being involved in the conceptual design of this music installation, my main contribution to this work was in the design and development of a haptic floor providing whole-body vibrations (vibrotactile feedback). Paper II presents an exploratory study in which composers produced music for Sound Forest. In this study, we were interested in how the users described and perceived whole-body vibrations, and if/how haptic sensations added to the overall experience for different user groups. Several research questions were addressed in this study (see full paper for a detailed description). My contribution to this work was primarily focused on the evaluation of the haptic experience. I was also in charge of the main part of the paper writing.

Paper III: Sonification of Women in Sound and Music Computing - The Sound of Female Authorship in ICMC, SMC and NIME Proceedings

Emma Frid
International Computer Music Conference, 2017 (pages 233-238)

Discussions on diversity and inclusion in the computer music field should not only consider those who are active users of already available musical interfaces, but also those who develop these technologies. It is, however, relatively common that these two roles overlap in the computer music community. Paper III was presented at the International Computer Music Conference (ICMC) in 2017. The study used gender prediction of author names to estimate the number of female authors publishing their work in the proceedings of the International Computer Music Conference (ICMC, 1975-2016[2]), Sound and Music Computing Conference (SMC, 2004-2016) and International Conference on New Interfaces for Musical Expression (NIME, 2001-2016). These results were also sonified, i.e. translated into sonic representations. The work sheds light on the fact that few women are actively publishing research at these conferences. Figures presented in this study should not be considered actual statistics of the number of authors identifying themselves as female in the field, but as predictions based on first names. However, a rather low percentage of unidentified author names (ranging from 1.2 to 3.3% for respective conference) suggests that the estimates should be somewhat reliable. In terms of contribution, I am the sole author of this work.

Paper IV: Interactive Sonification of a Fluid Dance Movement: An Exploratory Study

Emma Frid, Ludvig Elblaus and Roberto Bresin
Journal of Multimodal User Interfaces, 2018 (pages 1-12)

The work presented in this paper was carried out within the context of the European H2020 project *DANCE*. The purpose of *DANCE* was to investigate if it would be possible to perceive expressive movement qualities in dance solely through the auditory channel, by listening to sounds produced through movement sonification. The main goal of the *DANCE* project was to use interactive sonification of dance gestures to convey movements to persons who are blind. Paper IV was a continuation of a pilot study presented at the International Sonification Workshop in 2016 (paper x). The journal paper presents exploratory research focusing on which sound properties that are important when it comes to expressing fluid (i.e. smooth and continuous) movements through sounds. My contribution to this work was mainly in the experimental design and data analysis. I also conducted the experiments and was in charge of the paper writing.

[2]Publication lists from years 1974 and 1976 were not available and could therefore not be included in the analysis.

Paper V: Music Creation by Example

Emma Frid, Celso Gomes and Zeyu Jin
Manuscript submitted for publication, 2019

Advancements in machine learning and artificial intelligence (AI) have paved the way for development of new systems allowing for autonomous music generation. However, such systems often require domain-specific knowledge to operate. In this paper, we aim to close this knowledge gap by providing a novel interaction paradigm that allows users to select an existing song as input reference to an AI music generation system. The system then lets users interactively mix and match music properties (e.g. melody and beats) from generated music. This user interface enables users who are musical novices to take active part in music-making, leaving theoretical aspects of the music creation to the AI tools. In this work, we applied a participatory design approach, involving more than 104 users at several stages of our development process. While this particular project focused on music generation for short videos, findings may also provide valuable insights into the field of human-AI interaction. My contribution to this study was mainly in the design of the interface and the musical interaction, work that was largely based on user studies that I both designed and conducted. I also analysed data from the experiments and was responsible for the paper writing.

1.6 Additional Publications

In addition to the publications described in previous section, I have throughout my PhD also published additional papers related to topics such as haptic feedback, sonification and multimodal interaction. For example, such work has focused on multimodal interfaces providing haptic rendering combined with movement sonification and effects of audio in such contexts, sound design in the context of Human Robot Interaction (HRI), interactive sonification, and relations between movement qualities and sounds. Published papers that are not directly connected to the thesis topic are listed below. Out of these papers, paper v supplements Paper I, paper vii-viii supplement Paper II, and paper x supplements Paper IV.

paper i Claudio Panariello, Mattias Sköld, Emma Frid, and Roberto Bresin. 2019. From Vocal-Sketching to Sound Models by Means of a Sound-Based Musical Transcription System. In *Proceedings of the Sound and Music Computing Conference (SMC)*

paper ii Adrian Benigno Latupeirissa, Emma Frid, and Roberto Bresin. 2019. Sonic Characteristics of Robots in Films. In *Proceedings of the Sound and Music Computing Conference (SMC)*

paper iii Emma Frid, Jonas Moll, Roberto Bresin, and Eva-Lotta Sallnäs Pysander. 2018b. Haptic Feedback Combined with Movement Sonification using a Friction Sound Improves Task Performance in a Virtual Throwing Task. *Journal on Multimodal User Interfaces*, pages 279–290

paper iv Emma Frid, Roberto Bresin, and Simon Alexanderson. 2018a. Perception of Mechanical Sounds Inherent to Expressive Gestures of a NAO Robot - Implications for Movement Sonification of Humanoids. In *Proceedings of the Sound and Music Computing Conference (SMC)*, pages 43–51

paper v Emma Frid. 2018. Accessible Digital Musical Instruments: A Survey of Inclusive Instruments Presented at the NIME, SMC and ICMC Conferences. In *Proceedings of the International Computer Music Conference (ICMC)*, pages 53–59

paper vi Emma Frid, Roberto Bresin, Eva-Lotta Sallnäs Pysander, and Jonas Moll. 2017. An Exploratory Study on the Effect of Auditory Feedback on Gaze Behavior in a Virtual Throwing Task with and without Haptic Feedback. *Proceedings of the Sound and Music Computing Conference (SMC)*, pages 242–249

paper vii Roberto Bresin, Ludvig Elblaus, Emma Frid, Federico Favero, Lars Annersten, David Berner, and Fabio Morreale. 2016. Sound Forest/Ljudskogen: A Large-Scale String-Based Interactive Musical Instrument. In *Proceedings of the Sound and Music Computing Conference (SMC)*, pages 79–84 paper viii Jimmie Paloranta, Anders Lundstrom, Ludvig Elblaus, Roberto Bresin, and Emma Frid. 2016. Interaction with a Large Sized Augmented String Instrument Intended for a Public Setting. In *Proceedings of the Sound and Music Computing Conference (SMC)*, pages 388–395

paper ix Emma Frid, Roberto Bresin, Paolo Alborno, and Ludvig Elblaus. 2016a. Interactive Sonification of Spontaneous Movement of Children - Cross-Modal Mapping and the Perception of Body Movement Qualities through Sound. *Frontiers in Neuroscience*, 10:521

paper x Emma Frid, Ludvig Elblaus, and Roberto Bresin. 2016b. Sonification of Fluidity - An Exploration of Perceptual Connotations of a Particular Movement Feature. In *Proceedings of the Interactive Sonification Workshop (ISon)*, pages 11–17

paper xi Marcello Giordano, Ian Hattwick, Ivan Franco, Deborah Egloff, Emma Frid, Valérie Lamontagne, Maurizio Martinucci, Chris Salter, and Marcelo M Wanderley. 2015. Design and Implementation of a Whole-Body Haptic Suit for Ilinx, a Multisensory Art Installation. In *Proceedings of the Sound and Music Computing Conference (SMC)*, pages 169–175

paper xii Emma Frid, Marcello Giordano, Marlon M Schumacher, and Marcelo M Wanderley. 2014. Physical and Perceptual Characterization of a Tactile Display for a Live-Electronics Notification System. In *Proceedings of the Joint International Computer Music Conference and Sound and Music Computing Conference (ICMC|SMC)*

Chapter 2

Background

2.1 Sound and Music (Computing)

This thesis presents work in the intersection of the following research areas: Sound and Music Computing (SMC), Computer Music, Music Technology and Sonic Interaction Design (SID). According to the Roadmap of Sound and Music Computing, SMC research approaches the whole sound and music communication chain from a multidisciplinary point of view (The S2S^2 Consortium, 2007). It aims at understanding, modelling and generating sound and music through computational approaches, by combining scientific, technological and artistic methodologies. Below follows an introduction to concepts and terms in SMC research that are good to be familiar with when reading this thesis.

Sonic Interaction Design

Sonic Interaction Design (SID) considers sound as an active medium that can enable novel phenomenological and social experiences with and through interactive technology (Franinović and Salter, 2013). Sonic Interaction Design could perhaps be considered a sub domain of the field of *Sound Design*, a term which is often used in a context-specific manner, focusing on the art and practice of designing and creating sounds. SID was first formalized in a European COST

Action[1] led by Davide Rocchesso and the field is positioned at the intersection of auditory display, ubiquitous computing, interaction design and interactive arts (Rocchesso et al., 2008). SID works with emergent research topics related to multisensory, performative and tactile aspects of sonic experiences, exploring how sounds can be used to convey information, meaning, and aesthetic and emotional qualities in interactive contexts. In Sonic Interaction Design, multimodality, in particular the connection between audition, touch and movement, is examined in an ecological framework in order to develop new design principles and apply these to novel interfaces. Thus, SID moves away from techniques traditionally adopted in the Sound and Music Computing communities, such as e.g. formal listening tests, replacing them with exploratory design and evaluation principles (Franinović and Salter, 2013). Sonic Interaction Design can be used to describe practice into any of the different roles that sound plays in the interaction loop between users and artefacts, services, or environments, in applications ranging from functionality (e.g. of an auditory alarm) to artistic significance of a musical creation (Rocchesso et al., 2008).

Musical Instruments and Musical Interfaces

Throughout the years, researchers have proposed several frameworks for classifying the varied forms that musical devices and musical interfaces can take. A term that often is used in this context is *NIME*, an acronym that may take on several different meanings. For example; N = new or novel, I=interfaces or instruments, M=musical or multimedia and E=expression or exploration (Jensenius and Lyons, 2017). The first NIME workshop was held during the ACM Conference on Human Factors in Computing Systems (CHI) in 2001 (Poupyrev et al., 2001). Today, the work within this community is displayed mainly within the annual International Conference on New Interfaces for Musical Expression (NIME)[2].

The science of musical instruments and their classifications have traditionally been studied in the field of *organology*. Different perspectives have been adopted for different classification systems. Some systems have taken a historical perspective with a priority on the visible form of the instrument, while others

[1]https://www.cost.eu/actions/IC0601/
[2]https://www.nime.org/

have focused more on the sound producing qualities of the instrument (Kvifte and Jensen, 2007). Several different instrument ontologies have been introduced, for example, the classification of musical instruments of Mahillon (1900), Galpin (1910) and Von Hornbostel and Sachs (1961). More recently, seven criteria for an object to be classified as a musical instrument were presented by Hardjowirogo (2017): 1) sound production, 2) intention/purpose, 3) learnability/virtuosity, 4) playability/control/immediacy/agency/interaction, 5) expressivity/effort/corporeality, 6) immaterial features/cultural embeddedness, and 7) auditory perception/liveliness. It has been suggested that classification of new musical technologies is fraught with difficulties and that these instruments do not fit comfortably into traditional organological classifications, since they are made of so many different digital materials of diverse origins (Magnusson, 2017). A new approach is thus required for classification of these instruments, taking a multiplicity of perspectives into account, including materials, sensors, sound, mapping, gestures, reuse of proprioceptive skills, manufacturer, cultural context and musical style (Magnusson, 2017).

Digital Musical Instruments

The interfaces discussed in this thesis can broadly be described as musical devices. More specifically, some of the interfaces can be defined as *Digital Musical Instruments (DMIs)*. Several different definitions of DMIs have been proposed throughout the years. Moog (1988) defined DMIs using a modular description consisting of three parts: *"the sound generator, the interface between the musician and the sound generator and the tactile and visual reality of the instrument that makes a musician feel good when using it"*. Another definition was suggested by Pressing (1990), who viewed a DMI from the perspective of a control interface, processor and output. The assumption that an electronic instrument consists only of an interface and a sound generator was challenged by Hunt et al. (2003), who emphasized the importance of mapping between input and system parameters, suggesting that mappings define the essence of an instrument. Similarly, Miranda and Wanderley (2006b) presented a definition in which a DMI is described as an instrument consisting of a controller surface (a gestural or performance controller, an input device, or a hardware interface) and a sound generation unit. The controller and sound generation parts can be viewed as independent modules relating to each other by mapping strategies. The *"gestural controller"* of the instrument constitutes of one or several sensors assembled as part of a unique device, something which is usually referred to as an *"input device"* in HCI contexts.

Notwithstanding the difficulties related to DMI classification, several instrument ontologies for these instruments have been proposed. Wanderley and Depalle (2004) and Miranda and Wanderley (2006a) divided gestural controllers into the following subcategories: *instrument-like*, i.e. replicates of acoustic instruments, *instrument-inspired*, i.e. interfaces inspired from acoustic interfaces but with a final goal that is different from the original acoustic instrument, *extended/augmented/hyper instruments*, i.e. acoustic instruments with additional sensors, and *alternate controllers*, which have completely new designs, thus being in principle less demanding for non-expert performers. Orio et al. (2001) classified input devices used for musical expression into the following categories: *instrument-like controllers* attempting to emulate the control interfaces of existing acoustic instruments, *instrument-inspired controllers* designed to loosely follow characteristics of existing instruments, *extended instruments* in the form of acoustic instruments augmented by several senses, and *alternate controllers*, with designs that do not follow the design of any existing instrument. Birnbaum et al. (2005) presented a phenomenological dimension space for musical devices that could be used to characterize musical instruments. Seven dimensions are discussed: required expertise, musical control, feedback modalities, degrees of freedom, inter-actors (number of people involved in the musical interaction), distribution of space (physical area in which the interaction takes place) and the role of sound (ranging from artistic/expressive, environmental and informational). Others have emphasized criteria such as playability, progression and learnability in this context (Jordà, 2004).

Interestingly, some of the above described classifications have received critique since they do not allow analysis of the conceptual and music-theoretical content of musical instruments (see e.g. Magnusson, 2010a). A reassessment of the problems of organology in the electronic age, emphasizing the analysis of playing technique, was presented by Kvifte and Jensen (2007). They stress that the central issue for classification is not how the sound is produced by the instrument, but how the instrument is used to control musical sound, emphasizing that it is important to recognize the difference between the instrument itself and the associated playing technique. Since playing technique is so closely linked to the instrument construction and acoustic qualities, it is difficult to discuss these concepts in isolation. An epistemic dimension space for musical devices was presented by Magnusson (2010b), taking into account how musical instruments are inscribed with knowledge, how theory is encapsulated in their design, and how users engage with this embedded theory. The model included the following dimensions: expressive constraints, autonomy, music theory, explorability, required foreknowledge, improvisation, generality and creative-simulation. Further discussions on alternative approaches to the traditional hierarchical tree-structure of musical instrument classification was presented in work by Magnusson in 2017, in which he proposed a philosophical concept system with a dynamic architectural information-space applying modern media technologies, rather than a strict classification scheme.

Apart from achieving general advancements in music research and creating a terminology to analyse and reference developments in the field, classification of DMIs may provide understanding of musical interactions. Different interfaces may stem from categories of instruments with various levels of performance traditions. This is particularly the case for extended instruments that are based on (traditional) instruments with a history of their own. Moreover, the division of DMIs into different categories could provide some insights into which modes of interaction that are available for music-making. To be more precise, different types of DMIs may be more or less suitable for certain user groups. By thinking of a DMI as a modular system that could be modified or adapted in terms of its elements, one can tailor instruments to certain individuals' capabilities and needs, both in terms of interaction with the system (sensory inputs and gestural capabilities) or other ways that the player may provide energy to the system (Ward et al., 2017). In Paper I, I expand on the definition of a DMI to *Accessible Digital Musical Instruments (ADMIs)*, which I define as *"accessible musical control interfaces used in electronic music, inclusive music practice and music therapy settings"*.

Sonification

An *auditory display* can broadly be defined as a display that uses sound to communicate information (Walker and Nees, 2011). Such displays may be used to present *sonification*, a concept that can be defined as *"the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation"* (Kramer et al., 2010). This definition was further expanded by Thomas Hermann[3] to *"the data dependent generation of sound, if the transformation is systematic, objective and reproducible, so that it can be used as scientific method"*. Sonification has been extensively applied to map physical dimensions into auditory ones (see Dubus and Bresin, 2013, for an overview). *Interactive sonification*[4] is an emerging field of research that focuses on the interactive representation of data by means of sound. It can be considered as the acoustic counterpart of interactive visualization, and is especially useful for data exploration where there is a need for real-time feedback and when data changes over time, such as for body movement data. The most common sonification strategy is Parameter Mapping Sonification (PMSon), which involves the mapping of data features onto acoustic parameters of sonic events (e.g. pitch, level, duration and onset time) (Grond and Berger, 2011). The importance of parameter mapping has also been stressed in the context of electronic instrument design (Hunt et al., 2003).

Hermann et al. (2008) have advocated for closer connections between sonic interaction design and sonification. In the current thesis, both sonic interactions involving sonification and musical interactions of DMIs are discussed. There are many similarities between these two concepts, and what can be considered a DMI versus an interactive sonification system depends mainly on how the creator defines the sonic interaction taking place. Generally, DMIs are developed for the purpose of musical expression, while sonification interfaces usually have a scientific purpose. In other words, these interfaces differ in terms of the role of the sound, which could range from artistic/expressive to informational, as described in the dimension space for musical devices presented by Birnbaum et al. (2005).

[3]http://sonification.de/son/definition
[4]http://interactive-sonification.org/

2.2 Music, Diversity and Inclusion

Different design strategies dedicated to the development of interfaces *for all* have been proposed throughout the years. In the following section, I present several design frameworks that are relevant to inclusive sonic interaction design. Key concepts such as inclusive music practice and the notion of creative empowerment in the context of music therapy are also discussed, as well as aspects related to representation in the computer music community.

Universal/Inclusive/Accessible Design

The Cambridge English Dictionary defines inclusion as *"the idea that everyone should be able to use the same facilities, take part in the same activities, and enjoy the same experiences, including people who have a disability or other disadvantage"*[5]. Inclusion is listed as one of the aims of Goal 10 of the *United Nations Sustainable Development Goals*, focusing on inequality (UN General Assembly, 2015). One of the targets of Goal 10 is to empower and promote social, economic and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion, economic (or other) status, by 2030[6].

Several initiatives aimed at promoting inclusion in design of products and services have emerged throughout the years. Examples include *universal design*, *inclusive design*, *accessible design* and *design for all*. Although the concept of accessibility is being considered to a greater or smaller extent in most projects in which interactive systems are developed, the notion of accessible design varies across different professions, cultures and interest groups; there is currently no consensus when it comes to defining the accessibility concept in different fields (Persson et al., 2015).

The term *universal design* was introduced by Ronald L. Mace (1996), who described it as designing products and environments for the needs of people, regardless of their age, ability or status in life. Universal design can be defined as *"the design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design"* (Connell et al., 1997). A concept related to universal design is *inclusive design*, a term

[5] https://dictionary.cambridge.org/dictionary/english/inclusion
[6] https://www.un.org/sustainabledevelopment/inequality/

mostly used in the UK (Persson et al., 2015). Several different definitions of inclusive design have been proposed, one of them being *"the design of mainstream products and/or services that are accessible to, and usable by, as many people as reasonably possible on a global basis, in a wide variety of situations and to the greatest extent possible without the need for special adaptation or specialized design"* (Keates, 2005). In this context, designing universally accessible user interfaces means designing for diversity in end-users and context of use (Savidis and Stephanidis, 2004). This implies making alternative design decisions at various levels, resulting in diversity in the final design outcomes.

Accessible design, on the other hand, is defined in ISO's Guide 71 (ISO: ISO/IEC Guide 71:2001) as *"design focused on principles of extending standard design to persons with some type of performance limitation to maximize the number potential customers who can readily use a product, building or service, which may be achieved by 1) designing products, services and environments that are readily usable by most users without any modification, 2) making products or services adaptable to different users (adapting user interfaces), and 3) having standardized interfaces to be compatible with special products for persons with disabilities"*. Finally, the European Institute for Design and Disability (EIDD) defines *design for all* as *"design for human diversity, social inclusion and equality"* (EIDD, 2004).

Empowerment through Music (Technology)

The term *empowerment* is extensively used in contexts in which inclusion and diversity are discussed. However, the word often occurs in the literature without being explicitly defined. Although a full description of empowerment theory is outside the scope of this thesis, it is important to define the term, as it is often listed as a potential benefit of using music interfaces for health purposes. The Cambridge English dictionary defines empowerment as *"the process of gaining freedom and power to do what you want or to control what happens to you"*[7]. Perkins and Zimmerman (1995), on the other hand, define empowerment as processes and outcomes related to issues of control, critical awareness and participation. A working definition of empowerment in the context of psychological rehabilitation was proposed by Chamberlin and Schene (1997), who

[7] https://dictionary.cambridge.org/dictionary/english/empowerment

defined it as a process characterized by a number of qualities, rather than an event. Examples of such qualities include having access to information and resources as well as options to choose from, a feeling that the individual can make a difference, critical thinking, learning skills that the individual defines as important, growth and change, as well as overcoming stigma and increasing one's positive self-image.

In the context of accessibility research, *design for user empowerment* involves that users of technology are empowered to solve their own accessibility problems, and is characterized by two main human characteristics needed for design: self-determination (that the users have control of, and are not just passive recipients of, technology designs intended for them) and technical expertise (that the users are technically competent to solve the addressed problems) (Ladner, 2015). Rolvsjord (2004) suggests that *musical empowerment* is not so much a process of acquiring a certain level of culturally valued musical skills and resources as it is a process of regaining rights to music. In this thesis, I refer to the general concept of empowerment as a sensation of being in charge and in control, as well as having influence.

Partesotti et al. (2018) introduced the term *creative empowerment* in the context of DMI technologies. From an embodied cognition paradigm point of view, in which the human motor system as well as gestures and body movements play a crucial role in the perception of music (Leman and Maes, 2015; Godøy and Leman, 2010), technology could be considered an extension of the body; a malleable tool that can be used by persons with restricted mobility or cognitive problems, in order to stimulate self-expression, creative composition and motor rehabilitation. This sensation of control is what Partesotti et al. (2018) refer to as *creative empowerment*: it is when a continuous and cyclical interaction between user and technology is enabled. A person immersed in a DMI-based system can thus express her/himself in a way that strengthens experiences of resilience, while at the same time producing therapeutic benefits.

Shifting the focus back to technology, the rise of Do It Yourself (DIY) and maker communities has been argued to be a political development that has to do with empowerment of the individual in global, corporate societies, and with democracy on many different levels, including gender (Richards, 2016). This relates to the idea of democracy of music-making brought by technologies. Interestingly, it has been suggested that electronic music also has been influenced by these cultural phenomena (Richards, 2016). For example, the rise of technologies such as MIDI (Musical Instrument Digital Interface) has allowed more people to easily transcribe music into scores, merely by using a keyboard, thus lowering the threshold to music access by not requiring music theory knowledge. Other important technological developments in this context include the sequencer and Digital Audio Workstation (DAW). Jack et al. (2018) mention that while electronic technology has been a contributor to the decline of amateur performance, it has also frequently been proposed as an enabler; the ready availability of cheap computing could perhaps make musical performance more accessible to novices. However, other voices have raised concerns about participation in maker communities, concluding that the area remains a hobby for the privileged and that these communities seem to be increasingly co-opted by corporate interests (Ames et al., 2014). It has been suggested that those who participate in maker communities mostly are from middle and upper classes, and that the representation of women and minority groups remains low in these contexts (Ames and Rosner, 2014).

Inclusive Music Practice

Several different terms are used to describe research focusing on making music technology accessible for everyone. There seems to be no consensus on a commonly agreed-upon definition. One term that is used is *adapted/adaptive music*, which refers to the field of research concerned with development and implementations that facilitate full participation in music-making by people with health conditions or impairments (Knox, 2004). Adaptive music assumes that music-making, in itself, is a mode of human activity that requires no justification beyond its own praxis. In other words, music is considered one of the basic human rights (Knox, 2004). According to Knox (2004), adapted music and music therapy are related areas which may be understood as distinct but yet overlapping; music therapists use musical adaptations and have also contributed significantly to the adapted music literature (see e.g. Kirk et al.,1994; Correa et al., 2009; Krout et al., 1993; Spitzer, 1989). Graham-Knight and Tzanetakis (2015) expand on this concept using the term *adaptive music technology*, which they define as the use of digital technologies allowing a person who cannot otherwise play a traditional musical instrument to play unaided. The term *adaptive* is also used by Vamvakousis and Ramirez (2016), who refer to instruments adopted in inclusive music practice as *Adaptive Digital Musical Instruments*. Finally, the term *Assistive Music Technology (AMT)* also appears in the literature (see e.g. Magee, 2014; Cappelen and Andersson, 2014; Challis, 2011; Lucas et al., 2019). Graham-Knight and Tzanetakis (2015) stress that the word *assistance* implies an external source that provides aid to a person in need, whereas *adaptive* implies a constant state of refinement and adjustment to the musician.

Another term that appears in this context is *inclusive music* (Samuels, 2014). Samuels (2015) defines this concept as *"the use of music interfaces, aiming to overcome disabling barriers to music-making faced by people with disabilities"*. These barriers can be viewed differently depending on two predominant theoretical models: the medical and the social model (Lubet, 2011). The medical model focuses on the disabling factor within a musician, whereas the social model focuses on the exclusionary designs of musical interfaces and non-inclusive attitudes as disabling factors. As such, the social model shifts focus to the implementation of techniques and assistive technologies in order to overcome barriers in music-making. Research on inclusive music practice has commonly emphasized facilitated processes (Anderson and Smith, 1996). Historically, a key focus has been on MIDI controllers with switches that trigger acoustic events. Some studies have also focused on adapting existing musical instruments to fit specific user needs (see e.g. Harrison and McPherson, 2017; Bell, 2014). Today, new technologies and sensors enable the creation of a wide range of alternative controllers that can be adapted to each and every user's need.

Harrison and McPherson (2017) make a distinction between two categories of instruments designed for people with disabilities: *therapeutic devices* and *performance-focused instruments*. They describe these instruments as *accessible instruments*. In more recent work conducted by McPherson et al. (2019), the authors further elaborate on the distinction between the two categories, defining *therapeutic instruments* versus *performance-focused instruments* as accessible instruments designed to *"elicit the therapeutic or wellbeing aspects of music-making for disabled people with physical and cognitive impairments and learning difficulties"* versus *"enable virtuosic or masterful performances by physically disabled musicians"*, respectively. The authors describe that many performance-focused instruments require similar learning trajectories as traditional instruments, whereas therapeutic instruments often require the ability to "skip ahead" past the acquisition of musical and instrumental skills, in order to focus on aspects of musical participation. They illustrate this with examples of instruments characterized by ease-of-use and a low barrier to music-making.

Up to date, only a small number of papers focusing on reviews and design strategies for ADMIs have been published. McPherson et al. (2019) recently published a paper focusing on musical instruments for novices, in which part of the work surveyed accessible instruments for disability. The authors also identified five commercially available products that fit their criteria for accessible therapeutic instruments: Soundbeam[8], Skoog[9], Clarion[10], Apollo Ensemble[11] and Beamz[12]. An overview of musical instruments for people with physical disabilities was presented by Larsen et al. (2016). In this work, current state of developments of custom-designed instruments, augmentations/modifications of existing instruments and music-supported therapy were discussed. The authors also elaborated on the potential of 100% adaptive instruments, customizable to user needs. Other relevant publications in this context include the work by Hunt et al. (2004) focusing on the use of music technology in music therapy contexts and Ward et al. (2017), who presented a set of design principles for instruments for users with complex needs in Special Education (SEN) settings. Moreover, Graham-Knight and Tzanetakis (2015) presented a review of existing instruments (both from academia and commercial products) and proposed a set of principles for how to work with "a participant with disabilities" when developing a new musical instrument. Principles included introducing the participant to the technology, determining the range of motion of the participant, enabling the users to produce sound quickly, developing a system for activating sounds that is reproducible for the performer, evolving a relationship with the participant that extends beyond music, making improvements incrementally and evolving a set of exercises that the performer can do to increase mastery of the instrument. Finally, a small-scale review of inclusive DMIs was conducted

[8]https://www.soundbeam.co.uk/

[9]http://skoogmusic.com/

[10]https://www.openorchestras.org/instruments/

[11]http://www.apolloensemble.co.uk/

[12]https://thebeamz.com/

by Wright and Dooley (2019). The authors concluded that constrained DMIs are of great relevance to inclusive musical contexts, since they may provide opportunities for emergence of personal practices and preferences as well as minimize the need for training and support.

On Diversity and Inclusion in Computer Music

Representation and *diversity* are important terms in the context of musical inclusion. The word *diverse* is related to the concept of *diversity*; The Cambridge English Dictionary defines *diverse* as *"including many different types of people or things"*[13], whereas *diversity* is described as *"the fact of many different types of things or people being included in something; a range of different things or people"*[14]. There are many potential benefits of diversity. First of all, removal of disadvantages for persons belonging to certain demographies could be considered an important aspect of democratization and a manifestation of equal rights and feminist values. Moreover, it is likely that majorities potentially could learn from minorities, and that our society would benefit from not creating or reinforcing patterns of unjust social inequality. Arguments about benefits of diversity have been made for example for organizations (Cox, 1994) and businesses (Kochan et al., 2003; Richard, 2000). In the context of HCI, it has been suggested that diversity is legitimate, and a source of richness (Cairns and Thimbleby, 2003). For music, one may suggest that enabling the active participation of people from various backgrounds, ages, gender identities, ethnicities, classes, diverse abilities or previous experiences may influence sonic outcomes; potentially, diversity could result in richer music cultures.

In 2003, Essl pointed out that gender is mostly unexplored in the field of new music interface technology, concluding that gender itself was practically absent from academic discourse in the community of new music technology interface researchers. This despite the fact that theoretical ideas put forward in gender and queer theory suggest that the field is particularly suitable for explorations of differences of gender construction. Recently, there has been an increased awareness of the under-representation of women and gendering of digital technologies in the field (see e.g. Rodgers, 2010; Richards, 2016; Lane, 2016; Ab-

[13] https://dictionary.cambridge.org/dictionary/english/diverse
[14] https://dictionary.cambridge.org/dictionary/english/diversity

tan, 2016; Waters, 2016; Ingleton, 2016). Discussions on the representation of women in audio are presented for example in work by Mathew et al. (2016). A few studies have also focused on the ratio of male versus female students enrolled in music technology programs. Born and Devine (2015, 2016) conducted studies on such programs in British higher education, concluding that the student group was "overwhelmingly male"; approximately 90% of the students were men. Interestingly, demographics of students getting music technology degrees showed that these students were from less advantaged social backgrounds, and slightly more ethnically diverse, compared to students in traditional music (and the national average).

In the *NIME Reader*, in which works from 15 years of NIME research is presented, the atmosphere of the NIME community is described as "open and inclusive" (Jensenius and Lyons, 2017). This is supported by the fact that all conference proceedings are available freely online[15]. In *Trends in NIME - Reflections on Editing a NIME Reader*, Jensenius and Lyons (2016) reflect on some of the trends observed in re-discovering the collection of papers published throughout the history of the NIME conferences. Among other approaches, they envisage sociological or ethnographic studies and studies on gender (im)balance in higher music technology, similar to the work presented by Born and Devine (2015), as the NIME community is "still male-dominated". Jensenius and Lyons (2017) further emphasize that it would be valuable to survey the members of the NIME community about their experiences and expectations about how the community should be further developed.

The roles of instrument creators and performers often overlap in computer music; it is not uncommon that those who build musical devices also are the ones actively engaging with these instruments. Therefore, it is important to study aspects related to representation in the group of researchers who are actively publishing in this field. Several meta-studies focusing on gender ratios in music technology-related conferences such as International Conference on Auditory Display[16](ICAD) (Andreopoulou and Goudarzi, 2017), International Society for Music Information Retrieval Conference [17](ISMIR) (Hu et al.,

[15]See http://www.nime.org/archive/
[16]https://www.icad.org/
[17]https://www.ismir.net/

2016) and NIME (Xambó, 2018) have have been published. Andreopoulou and Goudarzi (2017) conducted a temporal analysis of authors in ICAD proceedings, observing an increase in number of publications co-authored by female researchers. However, the annual percentage of female authors remained on relatively unchanged levels through the history of the ICAD conferences (average 17.9%). This number is within reported percentages of female representation in related disciplines, such as *International Computer Music Association (ICMA)* and ISMIR, but significantly higher than in more audio engineering-related communities such as Audio Engineering Society[18] (AES). According to Hu et al. (2016), the Music Information Retrieval (MIR) community is reportedly becoming increasingly more aware of gender imbalance evident in ISMIR participation and publication. In their work, papers from the ISMIR proceedings from 2000 to 2015 were analysed. The authors concluded that only 14.1% of the conference papers were led by female researchers. Moreover, results suggested that the percentage of lead female authors had not improved over the years, but that more papers with female co-authors have been published recently.

When it comes to representation of different user groups, meta-studies and review papers on ADMIs have focused for example on persons with physical disabilities (Larsen et al., 2016), persons with complex needs in special education (SEN) settings (Farrimond et al., 2011; Ward et al., 2017) and more generally, on music therapy settings (Partesotti et al., 2018). The music therapy field is important in this context, since many ADMIs are designed to be used in such practice. Hahna et al. (2012) conducted a study in which 600 music therapists completed a survey about the use of music technology in a clinical setting. Music therapists report using music technology clinically, but many lacked formal music technology training. Interestingly, more men than women or transgender music therapists used music technology in their practice.

Designing musical instruments to make performance accessible to novices is a goal that precedes digital technology (McPherson et al., 2019). Novice users, or non-professional musicians, should also be considered in the context of inclusive music-making. According to McPherson et al. (2019), a specially-designed DMI could provide an immediately engaging experience of producing music with minimal prior training, thus perhaps reducing traditional barriers to

[18] http://www.aes.org/

learning to play a musical instrument, something that has been referred to as a "low entry fee" in previous work by Wessel and Wright (2002). In the work by McPherson et al. (2019), authors reviewed 80 instruments with the main aim to make musical performance and participation "easy", concluding that the interest remains high in creating musical instruments aimed at non-musicians.

2.3 Music as a Multisensory Experience

Playing a musical instrument requires a complex skill set that depends on the brain's ability to integrate information from multiple senses (Zimmerman and Lahav, 2012). Understanding multisensory perception and multimodal aspects of musical interaction can thus be of great importance when designing experiences for inclusive music practice. This section highlights how different modalities could be used in order to promote alternative displays of musical content. Properties of haptic and visual perception are discussed, as well as general design principles for multimodal interfaces.

Multimodal Feedback

Playing a musical instrument is a multisensory experience; we simultaneously make use of several senses when interacting with a musical device. Multimodal feedback is a term that refers to feedback for two or more modalities, i.e. feedback that stimulates several senses. The term auditory feedback relates to sounds that are produced in response to user actions. There are several means of incorporating auditory feedback in computer interfaces: *sonification* (Hermann et al., 2008; Kramer et al., 2010), *audification* (Dombois and Eckel, 2011), *auditory icons* (Gaver, 1993) and *earcons* (Brewster et al., 1993). Haptic feedback refers to feedback that we can sense through our sense of touch. The haptic system uses sensory information derived from mechanoreceptors and thermoreceptors embedded in the skin (*cutaneous* inputs) together with mechanoreceptors embedded in muscles, tendons, and joints (*kinesthetic*, also sometimes referred to as *proprioceptive*, inputs) (Lederman and Klatzky, 2009). Proprioception is defined as *"the process in which nerve endings in the muscles and joints are stimulated when the body moves, so that a person is aware of their* *body's position"*[19]. The cutaneous (tactile) inputs contribute to the human perception of various sensations such as e.g. pressure, vibration, skin deformation and temperature, whereas the kinesthetic (proprioceptive) inputs contribute to the human perception of limb position and limb movement in space (Lederman and Klatzky, 2009). The inputs are combined and weighted in different ways to serve various haptic functions (Lederman and Klatzky, 2009).

Different sensory modalities have different sensory limits. Due to the perceptual strengths and weaknesses of each sense, different modalities can be more or less suitable for different types of data representation. The modalities differ in terms of sensitivity to frequency ranges and temporal resolution. For example, the frequency range of human hearing usually lies between 20 and 20 000 Hz (Cutnell and Johnson, 1998). In general, the tactile frequency range is not as wide as the one for hearing. Different frequency ranges have been reported for different mechanoreceptor types (see e.g. Makous et al., 1995 and Bolanowski Jr et al., 1988). Kruger et al. (1996) reported vibrotactile ranges between 0.4 to 500 Hz, depending on mechanoreceptor. For vibrotactile feedback, the optimal sensing vibration frequency has been found to be around 250 Hz (Makous et al., 1995). It has been shown that the temporal resolving power of touch is worse than that of the audition but that the temporal resolution of touch is better than that of vision (Lederman and Klatzky, 2009). The motivations and rationales for displaying information through sound rather than a visual representation have been extensively discussed in the literature (see e.g. Bly et al., 1985; Hereford and Winn, 1994; Kramer, 1994). When information is displayed as complex patterns or changes in time, audition may be the most appropriate modality (Walker and Nees, 2011).

Apart from auditory and haptic feedback, feedback systems may also provide visual, olfactory (smell) or gustatory (taste) feedback, although the latter are less common in practical applications (especially for musical interfaces).

[19]https://dictionary.cambridge.org/dictionary/english/proprioception

Multisensory Perception and Crossmodal Interaction

A variety of different terms are employed in the discourse on multisensory perception and interaction. The terms most relevant in the context of this thesis work are *multisensory* and *cross-modal*. As the word suggests, multisensory refers to something *"involving more than one sense"*[20]. The term *cross-modal interaction* can be defined as *"the process of coordinating information from different sensory channels into a final percept"* (Driver and Spence, 1998) and relates to the continuous integration of information from vision, hearing and touch. This neural processes involved in synthesizing information from cross-modal stimuli, i.e. stimuli from two or more sensory modalities, is usually referred to as multisensory integration (Stein and Stanford, 2008).

Traditionally, the brain was considered to consist of several modality-specific (unisensory) regions. However, recent research has indicated that brain regions are actually multisensory in their nature. Studies suggest that cortical pathways are modulated by signals from other modalities; they are not sensory specific (Shimojo and Shams, 2001). Somatosensory and visual inputs have been observed in the auditory cortex, somatosensory and auditory inputs in the visual cortex, and auditory as well as visual inputs in the somatosensory cortex (see e.g. Zimmerman and Lahav, 2012). Moreover, musical training may alter brain structure and function within and across brain regions through brain plasticity (Zimmerman and Lahav, 2012). For example, violin players have increased somatosensory representation in their left hand (Elbert et al., 1995). Interestingly, Shibata (2001) also found that some deaf people process vibrations sensed via touch in the part of the brain used by most people for hearing.

Several documented phenomena demonstrate how auditory and visual information can reinforce or modify sensory perception, see for example the *Ventriloquism effect* (Howard, 1966), the *McGurk effect* (McGurk and MacDonald, 1976) and *synthesthesia* (Cytowic, 1989). As a result of multisensory integration, the response to a cross-modal stimulus can be greater than the response to the most effective of its component stimuli, resulting in multisensory enhancement, or smaller than the response to the most effective of its component stimuli, resulting in multisensory depression (Stein and Stanford, 2008).

[20] https://www.collinsdictionary.com/dictionary/english/multisensory

Moreover, multisensory integration can also alter the salience of cross-modal events (Stein and Stanford, 2008). If multimodal feedback is correctly designed, enhancement of certain sensorial aspects can be achieved, augmenting the user experience beyond what is possible when only one modality is used. For example, detection of unimodal events and objects can be enhanced by a temporally and/or spatially co-occurring stimulus in another modality (Vroomen and Gelder, 2000; Lovelace et al., 2003; Noesselt et al., 2008).

Musical Haptics

The importance of haptic feedback in the form of vibrations (vibrotactile feedback) has been stressed in the context of musical instruments (Marshall and Wanderley, 2006). The fields of music and haptics are tightly connected in numerous ways. Sound is the auditory counterpart of vibration. Therefore, musical experiences involve both perceiving airborne acoustic waves but also vibratory cues conveyed through air and solid media (Papetti and Saitis, 2018). A comprehensive overview of interactions between the auditory and haptic modalities in human information processing was presented by Kitagawa and Spence (2006). This topic is also discussed more in detail in my previous work (see paper ix).

Papetti and Saitis (2018) define *musical haptics* as an interdisciplinary field focused on investigating touch and proprioception in music scenarios from the perspective of haptic engineering, HCI, applied psychology, musical acoustics, aesthetics and music performance. Interestingly, aspects related to proprioception, as well as the role of movement and gesture, have also been emphasized in literature focusing on music perception, see e.g. the comprehensive overview presented by Godøy and Leman (2010). The goal of research on musical haptics is to understand the role of haptic interaction in music experience and instrumental performance, as well as to create new musical devices which may provide meaningful haptic feedback (Papetti and Saitis, 2018).

Sounds produced by acoustic and electroacoustic musical instruments come from vibrating components (Papetti and Saitis, 2018). Playing an instrument involves a complex action-perception loop in which the player physically interacts with the instrument while at the same time perceiving the instrument's physical response. The haptic channel could thus be assumed to support performance control (e.g. intonation and timing) as well as expressivity (e.g. timbre, emotion). For example, skilled performers are known to establish intimate rich haptic exchange with their instruments, resulting in truly embodied interaction (Papetti and Saitis, 2018). Auditory-tactile experience of music, especially the multimodal perception of attending a concert, have been stressed (Merchel and Altinsoy, 2013). It has been shown that whole-body vibrations, the same type of haptic feedback as the ones used in Sound Forest in Paper II, have significant influence on loudness perception (Merchel et al., 2009). Moreover, based on results from studies on perception of instrument quality for violins and pianos, the vibrotactile component of haptic feedback perceived while playing has been found to provide an important part of the integrated sensory information that the musician experiences in musical interaction with the instrument (Saitis et al., 2018). In addition, research has suggested that tactile metaphors are strongly associated with musical variables (Eitan and Rothschild, 2011).

Haptic technology can assist musicians in making gestures (Berdahl et al., 2009). Computer music has been suggested as a major field of research and application for haptics (Castagné et al., 2010). For DMIs, haptic feedback becomes a design factor (MacLean, 2000). Young et al. (2018) investigated the functional aspects of haptic feedback in DMI interactions, finding that haptics had a number of significant effects on users' perceptions of usability. Prospects of integrating vibrotactile feedback into DMIs were also discussed in the work by Birnbaum and Wanderley (2007) and Birnbaum (2007). Vibrotactile feedback and stimulation can be implemented in interfaces in order to restore intimacy in instrumental interaction with a DMI, or to enable persons with hearing-impairment to experience music (Giordano and Wanderley, 2013). Interestingly, Nanayakkara et al. (2013) found that musical experiences of persons with hearing-impairment were enhanced through the use of haptic (or visual) feedback. They also concluded that musical representations for hearing-impaired should focus on staying as close to the original as possible and be accompanied by conveying the physics of the representation via an alternate channel of perception.

There are numerous examples of interfaces intended for experiencing sound and music through the sense of touch, see for example paper xi. For example, Gunther and O'Modhrain (2003) created a system based on transducers worn against the body that enabled creation of vibrotactile music, introducing the concept of *tactile composition*. Another example is the haptic chair *EmotiChair* (Karam et al., 2009), a sensory substitution system that translates auditory information into vibrotactile stimuli using an ambient, tactile display. Some commercial products are also available for the purpose of experiencing music through haptic feedback, for example the *Ultrasonic Audio Syntac*[21], the *Loflet Basslet*[22], the *SubPac*[23] and the *Soundbox* and *MiniBox* from *Soundbeam*[24].

Visual Music

The process of hearing is affected by seeing and visual information has been said to play an important role in musical experience. A review on visual influence on aspects of music is presented in work by Schutz (2008). Conclusions include that vision influences many aspects of music, from evaluations of performance quality and audience interest to perception of loudness, timbre and note duration. The visual component of a music performance during a live concert is of central importance for appreciation of music (Platz and Kopiez, 2012). Integration of audio and visuals has also been found to extend the sense of phrasing and help anticipating changes in emotional content (Vines et al., 2006). It has been shown that the perceived duration of a note is affected by the length of a gesture when an audience can see a music performer (Schutz and Lipscomb, 2007). In addition, musical experiences of persons with hearing-impairment have been found to be enhanced through the use of visual feedback (Nanayakkara et al., 2013).

Chion (1994) proposed that images and sounds are not perceived in separate channels, but that we audio-view them as a trans-sensory whole. His work *"Audio-Vision - Sound on Screen"* sheds light on the mutual influences of sound and image in audiovisual perception. Evans (2005) defined the term *visual music* as *"time-based visual imagery that establishes a temporal architecture in a way similar to absolute music"*. Substantial work focusing on visualizing music has been presented throughout the years. Examples range from work by Mitroo et

[21] http://www.ultrasonic-audio.com/products/syntact.html
[22] https://lofelt.com/
[23] https://subpac.com/
[24] https://www.soundbeam.co.uk/vibroacoustics

al. (1979), to modern interactive music visualizations programmed to react in real-time to generated sounds.

In contrast to the above described research, it has also been suggested that visual feedback may not be very important when it comes to playing traditional instruments, as there are numerous examples of professional blind musicians and instrumentalists (Jordà, 2003). However, the visual component could certainly introduce advantages in a musical context, for example by expanding the communication channel between instrument and performer. For example, Jordà (2003) discussed how visual feedback can increase the intuitiveness of an interactive music system. In the context of playing a musical instrument, exploiting the visual mode could also be a way of compensating for the lack of auditory information for persons who are hearing-impaired.

On Designing Multimodal Music Systems

Multimodal design principles should be followed in order to optimize human performance in multimodal systems. Guidelines for multimodal design (discussed in work by Reeves et al., 2004, for example) involve maximizing human cognitive and physical abilities by supporting streamlined interactions based on users' information processing abilities, as well as exploiting the advantages of each modality to reduce memory load. When designing multimodal feedback, perceptual strengths and weaknesses should be taken into account (Reeves et al., 2004). The fundamental connection between multimodal interface design and universal accessibility is discussed by Obrenovic et al. (2007). They propose a unified conceptual framework combining accessibility and multimodal interaction; this involves describing user interfaces as a set of communication channels and connecting this info with the user, the environment and device profiles, thereby describing limitations for usage of respective channel.

It is essential to understand the users' sensory, perceptual and cognitive abilities to successfully implement haptic feedback in multimodal musical systems (Hale and Stanney, 2004). Some attempts towards developing design guidelines for interfaces that incorporate haptic feedback in HCI contexts have been proposed (MacLean, 2000; Van Erp, 2002). It is possible that such guidelines, to a certain extent, could be applied also to the configuration and design of musical interfaces. For example, Hale and Stanney (2004) presented a set of haptic design guidelines based on psychophysical research that aimed to aid developers of multimodal interactive systems. Both tactile and kinesthetic interaction design guidelines were discussed, as well as multimodal design guidelines concerning presenting haptic feedback together with visual displays. At large, these defined guidelines were based on previous findings from perceptual research presented by Sherrick and Cholleviak (1986) and Biggs and Srinivasan (2014). The guidelines include, for example, that haptic input should consider sensitivity to stimuli across various skin locations, that stimuli should be at least 5.5 milliseconds apart to be perceived as separable in the time domain, that pressure limits depend on body loci and gender, and that vibration from a single probe must exceed 28 dB for 0.4-3 Hz frequencies in order to be perceivable. Moreover, Van Erp (2002) presented guidelines on stimulus detection and comfort, as well as pitfalls of applying tactile stimulation.

A few papers have discussed and presented design principles for DMIs (Cook, 2017, 2009; Essl and O'Modhrain, 2006). Moreover, Giordano et al. (2013) have presented tactile feedback and stimulation design principles for music and media applications. They discuss both technological and perceptual aspects that should be taken into account when designing interfaces involving tactile feedback. For example, concepts such as pitch, rhythm, roughness, timbre and spatial domain, as well as tactile illusions and attention, are mentioned. The authors also advice on the choice of actuators, frequency response, placement and activation patterns.

Some general limitations and benefits to carefully consider when implementing music technology for music therapy and health purposes were discussed by Partesotti et al. (2017). For example, it has been shown that high technology sophistication could lead to an overstimulation of the user (Magee and Burland, 2008a) and that visual elements can be distracting (Hunt et al., 2004). Indicators and contraindications for using music technology with clinical populations were discussed in work by Magee (2014). Indicators for use of electronic music technologies include physical abilities which limit access to acoustic instruments, sensory impairments, cases where self-expression is limited on acoustic instruments, particular needs for expression of identity which are difficult to meet with acoustic instruments and difficulties motivating or engaging in therapy. Moreover, Magee suggests that it is important that music technology provides somatosensory experiences just like an acoustic instrument when working with users with special cognitive needs, as this facilitates cause-and-effect awareness. Magee and Burland (2008a) advise against the use of music technology in music therapy if it is established that the client has no understanding of cause and effect. Regarding cognitive states of potential users, Yuksel et al. (2019) presented work on detecting and adapting to user's cognitive and affective state, in order to develop intelligent musical interfaces. The authors stress that the player's communication channels may be limited by the expressivity and resolution of input devices, expressivity of body parts, and human attention bottlenecks, discussing how detecting user's cognitive workload or affective state could support musical learning and creativity.

Chapter 3

Results

This chapter highlights main findings from each publication, viewed from a perspective of inclusive sonic interaction design. I also synthesize these results into a final section focusing on designing and evaluating ADMIs. For abstracts of respective publication, please refer to Section 1.5 in Chapter 1.

3.1 Paper I: Accessible Digital Musical Instruments - A Review of Musical Interfaces in Inclusive Music Practice

Accessible Digital Musical Instruments (ADMIs) are defined as *"accessible musical control interfaces used in electronic music, inclusive music practice and music therapy settings"*. In this paper, 113 publications, presenting 83 different ADMIs, were analysed. In total, 45.5% of the DMIs presented visual feedback of some sort (e.g. visualizations, graphical user interfaces, or blinking LED lights), whereas only 15.6% presented vibrotactile feedback. Interestingly, 47.0% made use of unimodal feedback in the form of sound only. In other words, these systems did not use sound visualizations or translations into tactile sound. In the context of this thesis, I refer to feedback as *active* if it is programmed and considered in the mapping strategies for the DMI. To be more precise: many DMIs provide *passive* haptic feedback in the sense that you can touch the instruments,

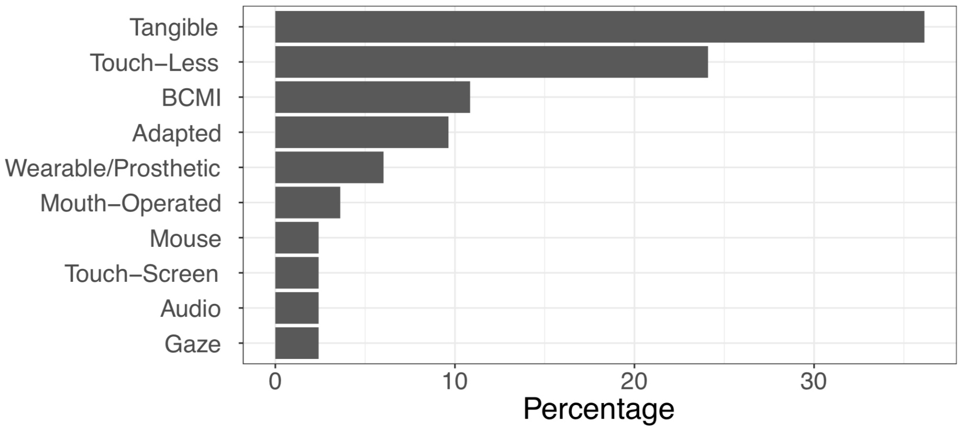

Figure 3.1: ADMIs per control interface category. Categories defined by main mode of interaction.

while simultaneously producing sounds. However, they do not have embedded actuators or loudspeakers that produce vibrotactile stimulation for feedback purposes. Out of the DMIs reviewed in Paper I, 48.2% presented bimodal feedback. The majority of these bimodal ADMIs made use of auditory-visual feedback; only 14.6% presented vibrotactile feedback together with sound.

Interfaces were divided into categories based on main mode of interaction. Results suggested that the majority of the DMIs developed to promote inclusion in music-making were physical (tangible) or touch-less controllers and that the most commonly used sensor technologies were touch sensors, accelerometers and cameras. The choice of technologies in this context was probably guided by the fact that most of the authors strongly advocated for simple and affordable technical solutions. A plot illustrating the division into control interface categories is displayed in Figure 3.1. Examples of interfaces belonging to respective category are also presented in Figure 3.2.

Regarding the users that the DMIs were designed for, the largest groups were people with physical disabilities and young users or children. Relatively few instruments were designed specifically for persons with visual or hearing impairments, elderly people or young children. Most of the ADMIs were developed using iterative design processes or participatory design methods, em-

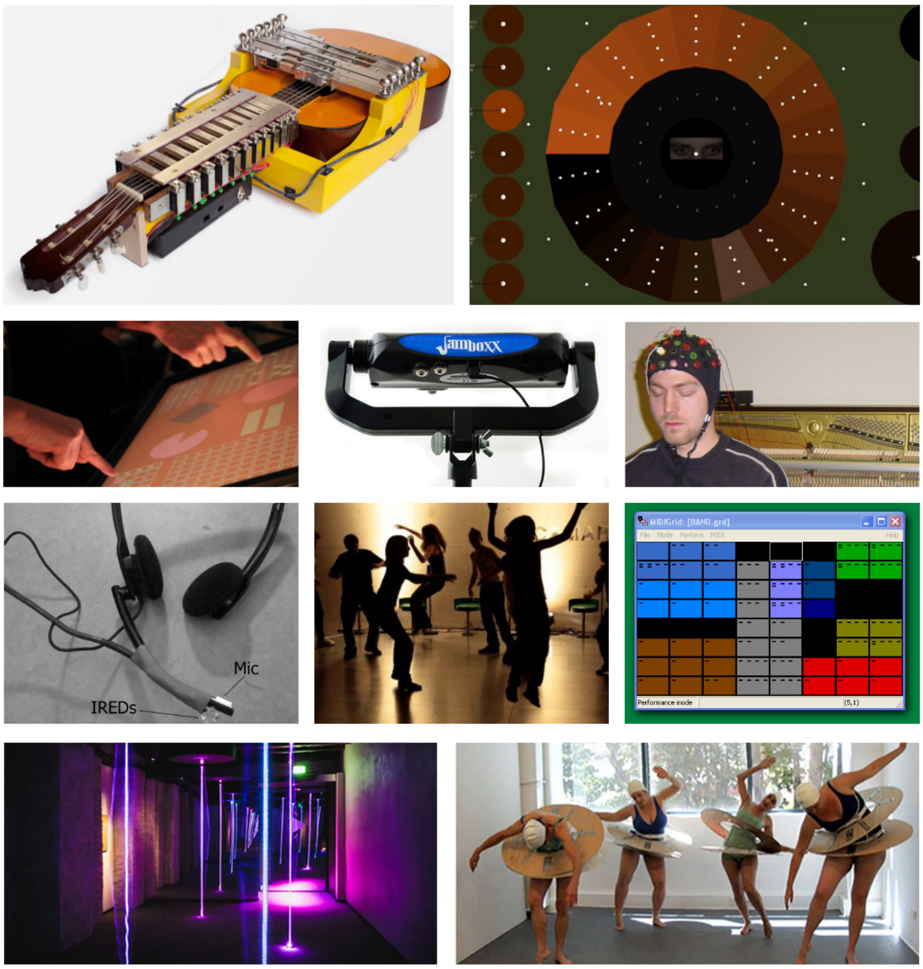

Figure 3.2: Examples of different control interfaces. **Top row:** Left: *GuitarMasheen*, an adapted instrument in the form of an electro-mechanically actuated guitar, by Dave Meckin (Meckin and Bryan-Kinns, 2013). Right: GUI of the *EyeHarp*, a gaze controller (Vamvakousis and Ramirez, 2016). **Second row:** Left: *MusicAid*, a touch-screen controller (Søderberg et al., 2016). Middle: *Jamboxx Pro*, a mouth-operated controller (Jamboxx, 2019). Right: *BCMI Piano*, a Brain–Controlled Music Interface (Miranda and Boskamp, 2005). **Third row:** Left: *The Flote*, an audio controller (Aziz et al., 2008). Middle: *Sound=Space* installation, a touchless interface by Rolf Gehlhaar (Almeida et al., 2011). Right: *MidiGrid*, a mouse-controlled musical interface (The Full Pitcher Music Resources, 2019). **Last row:** Left: *Sound Forest*, a music installation with tangible controllers in the form of interactive strings (paper vii). Right: *HipDiskettes*, a performance ensemble interacting with wearable *HipDisk* controllers (Wilde, 2011). Reprinted with permission.

phasizing the importance of including users in ongoing tests throughout the development process. Often, both users and music therapists were involved in these processes. Interestingly, discussions about sound synthesis methods were in many cases completely left out, or only discussed very briefly. One could suggest that the participatory design process employed when designing ADMIs should focus not only on which gestures that the users may produce, but also on exploring a range of sonic properties that may be more or less interesting and enjoyable for the player.

To conclude, there is a large body of research in the computer music community that potentially could be adopted in ADMI research in order to enable inclusive music-making for all. Aspects judged to be important for successful ADMI design were instrument adaptability and customization, user participation, iterative prototyping, and interdisciplinary development teams. The use of haptic (vibrotactile) feedback and more complex sound synthesis methods, more advanced sensing technologies and gesture acquisition techniques, as well as implementation of more diverse mapping strategies, are suggestions for improvements in this context. Finally, the ability to easily customize aspects of an ADMI to particular users is an important aspect of this type of DMI design, something that should be explored further.

3.2 Paper II: Sound Forest - Evaluation of an Accessible Multisensory Music Installation

Sound Forest (Ljudskogen) is a multisensory music installation consisting of a room with light-emitting interactive strings, vibrating platforms and speakers, situated at the Swedish Museum of Performing Arts in Stockholm (see paper vii). In the study described in this paper, a total of 19 participants, divided into four groups, were invited to take part in an experiment in which five different musical pieces were used as sonic material in the Sound Forest installation (see Figure 3.3). The groups consisted of 1) three persons with physical and intellectual disabilities, using wheelchair (1 woman, 2 men), 2) seven two-to-four-year-old children (3 girls, 4 boys), 3) four twelve-year-old girls and 4) five sixteen-year-old girls. The participants interacted with the strings in Sound

Figure 3.3: The Sound Forest installation. Vertical lines are interactive strings that trigger sounds when plucked by the visitors. Generated sounds are coupled with visual feedback in the form of colors emitted from respective string and haptic feedback in the form of whole-body vibrations presented through the floor. There are five strings in the room, which is decorated with reflecting mirrors.

Forest in three-minute sessions for a total of five music compositions. The compositions made use of different coloured light settings and different vibrotactile feedback.

Results from interviews revealed mostly positive associations to the presence of haptic feedback. The vibrations were said to enhance the musical experience overall, resulting in stronger and more powerful sensations. However, some of the younger participants mentioned unpleasant “itching” sensations in the feet. The vocabulary used to describe haptic sensations included words such as *shaking, tingling, itching, tickling and rushing [through the body]*. The most frequent loci in which vibrations could be perceived were the feet, however, the heart, head and belly were also mentioned by several participants.

Observations of how the participants interacted with the strings in Sound Forest revealed that the user groups adopted quite different interaction strategies. For example, the three participants using wheelchair tended to stay at one string throughout a test session (three minutes). These participants spent most of the time exploring sounds, vibrations and lights for that particular string. They did not interact much with other participants. In terms of gestures, they focused mainly on shaking the strings, rather than on plucking or hitting them. Interestingly, one of the participants, an almost blind man, commented that he could see the light of the string when he held it against his eye, and that he could sense vibrations coming through his wheelchair, into his body. This participant was generally very positive about the experience, mentioning that he wished that he had such an interactive string to play with at home. As for the other groups, the youngest children mainly enjoyed running between, and in circles, around the strings. Similar to the participants in wheelchair, these children tended to hold onto, shake and hang onto the strings, rather than plucking them. The two groups of older girls, on the other hand, focused mainly on plucking the strings. Participants in these groups spent time exploring the range of different sounds produced by a particular string and collaborated and coordinated their play with other participants to synchronize sounds.

To conclude, this evaluation of Sound Forest revealed mainly positive reactions to haptic feedback. Users of different ages and abilities adopted different interaction strategies. Although the number of participants with diverse abilities in the current study was small, there seem to be a potential for inviting persons with intellectual disabilities and persons using wheelchair to take part in music-making in Sound Forest. Moreover, Sound Forest appears to encourage different types of games and play both for really young as well as older children. In terms of designing multimodal experiences for this music installation, one interesting finding from this study was that the task of composing for the haptic modality was not trivial for the composers. They had never composed vibrotactile music before, and had never experimented with such an interface. The functionality of the vibrating platforms should be more clearly described and explained to composers in future studies. For example, libraries demonstrating the range of different haptic sensations that can be produced could be presented. For a more detailed discussion on this topic, see Section 4.2.

3.3 Paper III: Sonification of Women in Sound and Music Computing - The Sound of Female Authorship in ICMC, SMC and NIME Proceedings

In this study, gender prediction of author names was used to estimate the number of female authors publishing their work in proceedings of the International Computer Music Conference[1] (ICMC, 1975-2016[2]), Sound and Music Computing Conference[3] (SMC, 2004-2016) and International Conference on New Interfaces for Musical Expression[4] (NIME, 2001-2016). The work sheds light on the fact that few women are actively publishing research at these conferences. This research is dual in the sense that it both discusses gender inequalities in the field and introduces an important application of sonification.

Results obtained when summarizing the number of author names classified as female, male, versus unknown for the three conferences between year 2004 and 2016 revealed percentages ranging from 9.5% to 14.3% (mean and median 11.3%). Although no significant trend towards an increase could be observed, the highest percentage was identified for year 2016. These results suggest that male authors still widely outnumber women in the field, at least in terms of authorship in conference proceedings. By looking at presence of female author names for respective conference (collapsing the data across years), one can observe that the total percentage of female names was below 15% for all conferences. To be more precise, the total percentage of female author names from start of respective conference until 2016 was 10.3% for ICMC, 11.9% for SMC and 11.9% for NIME. Mean percentage of female author names throughout the years was 8.8% for ICMC, 12.1% for SMC and 12.2% for NIME. The dataset included years in which the percentage of female authors was as low as 2.5% (ICMC, 1981), but also years in which percentages ranged up to 18.5% (SMC, 2005). Detailed results are shown in Figures 3.4 - 3.6 . As for NIME, results presented in Paper III were persistent with figures presented in work by Xambó (2018).

[1] http://www.computermusic.org/

[2] Publication lists for years 1974 and 1976 were not available and could therefore not be included in the analysis.

[3] http://www.smcnetwork.org/

[4] http://www.nime.org/

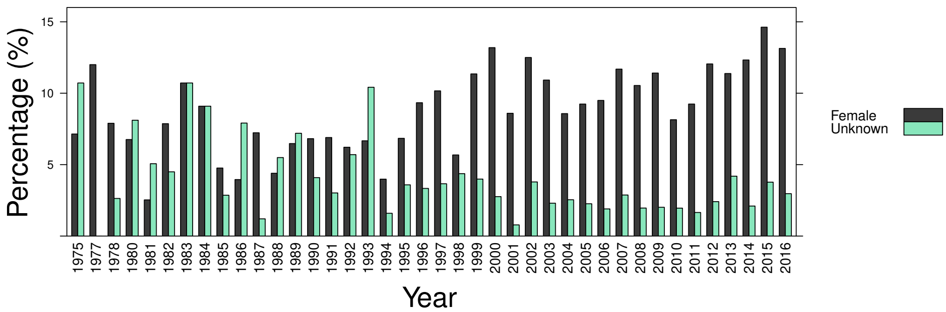

Figure 3.4: Percentage of female (grey) versus unknown (green) author names in ICMC proceedings from 1975 to 2016 (excluding years 1974 and 1976).

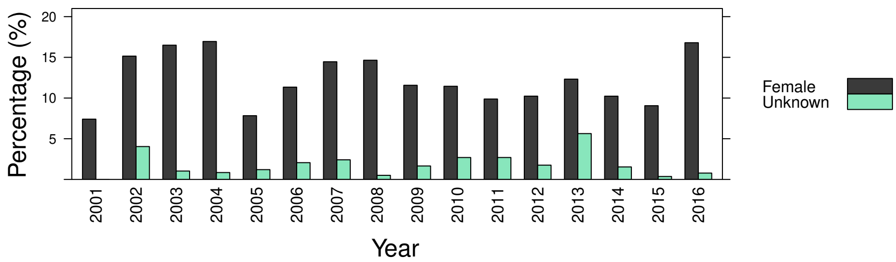

Figure 3.5: Percentage of female (grey) versus unknown (green) author names in NIME proceedings from 2001 to 2016.

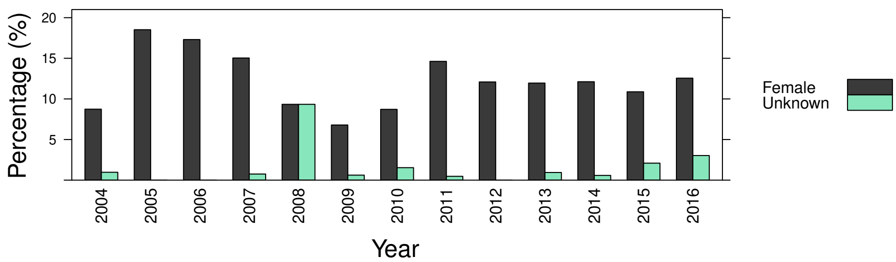

Figure 3.6: Percentage of female (grey) versus unknown (green) author names in SMC proceedings from 2004 to 2016.

In order to get an idea of how the number of female authors has changed over the years, sonifications in the form of longer ambient soundscapes were produced, enabling the listener to scroll between different years and compare their sonic representations. Two sonifications were generated for respective conference. Different sounds were mapped to female versus male authors. By listening to these sonifications, the reader/listener soon understands that the representation of women has, in fact, not changed very much throughout the years. For comparative purposes, the mapping between female versus male authors to sounds were also reversed. This enabled the listener to get an idea of what an alternative situation with reversed gender ratios would have sounded like. The results highlight not only the fact that there still are relatively few women publishing in these conferences, but also that the mapping decisions could have a crucial impact on how data is perceived.

Promoting a change in the field of SMC involves much more than just balancing demographic profiles, but statistics such as the ones presented in this study could help when it comes to understanding the current state of the research community. The ratios of female versus male author names in the proceedings of the three conferences ICMC, SMC and NIME suggest that the field is still far from being gender-balanced. Ideally, these figures should be used to encourage discussions about social structures that discourage increased participation, focusing on creating awareness of the challenges that women and non-binary persons face in their daily work within the field. Although this study focused on quantitative measures based on binary categorizations of gender, it would of course make much more sense to discuss gender balance from a non-binary perspective. Binary categorizations are problematic as they exclude persons people whose gender identity does not align with man or woman. Clearly, there is a need for analysis of existing environments and social relations surrounding music technology and computer music. If we manage to identify the challenges that people face in our research community, we will perhaps be able to create more constructive initiatives towards changing practices.

3.4 Paper IV: Interactive Sonification of a Fluid Dance Movement: An Exploratory Study

The work presented in Paper IV consists of a set of experiments designed to explore sound properties associated with fluid movements. In this context, the term fluid refers to smooth and continuous trajectories (compare Figure 3.7 versus Figure 3.8). We carried out an experiment in which participants interactively adjusted parameters of a sonification model developed for a fluid dance movement. Moreover, a second experiment in which participants vocally sketched sounds portraying fluid versus nonfluid (rigid) sounds, based on videos of a dancer performing movements, was also conducted. *Vocal sketching* involves the use of the voice and body to demonstrate the relationship between action and sonic feedback (Rocchesso et al., 2013).

Consistent findings from the interactive adjustment experiment and vocal sketching sessions indicated that the ideal sound for expressing fluidity occupy a lower register and has less high frequency content, as well as lower bandwidth, than sounds expressing nonfluidity. Fluid sounds are continuous, calm, slow, pitched, reminiscent of wind, water or an acoustic musical instrument. In contrast, the ideal sound to express nonfluidity is harsh, non-continuous, abrupt, dissonant, conceptually associated with metal or wood, unhuman or robotic.

It should be noted that one finding from this study was that it appeared to be difficult for the participants to decouple the somewhat theatrical performance of the dancer from the high-level properties of the movement. In other words, associations to sounds were guided by ideas and metaphors associated with the role that the dancer was enacting. Nevertheless, findings from this study could perhaps be useful for researchers in the field of Sonic Interaction Design, especially for those working with applications concerned with performing smooth and wavelike movement trajectories, for example in sonification of physiotherapy applications. For a more in-depth discussion of concepts related to translation of movement properties into sounds, see also our previous work on sonification of spontaneous movements (paper ix).

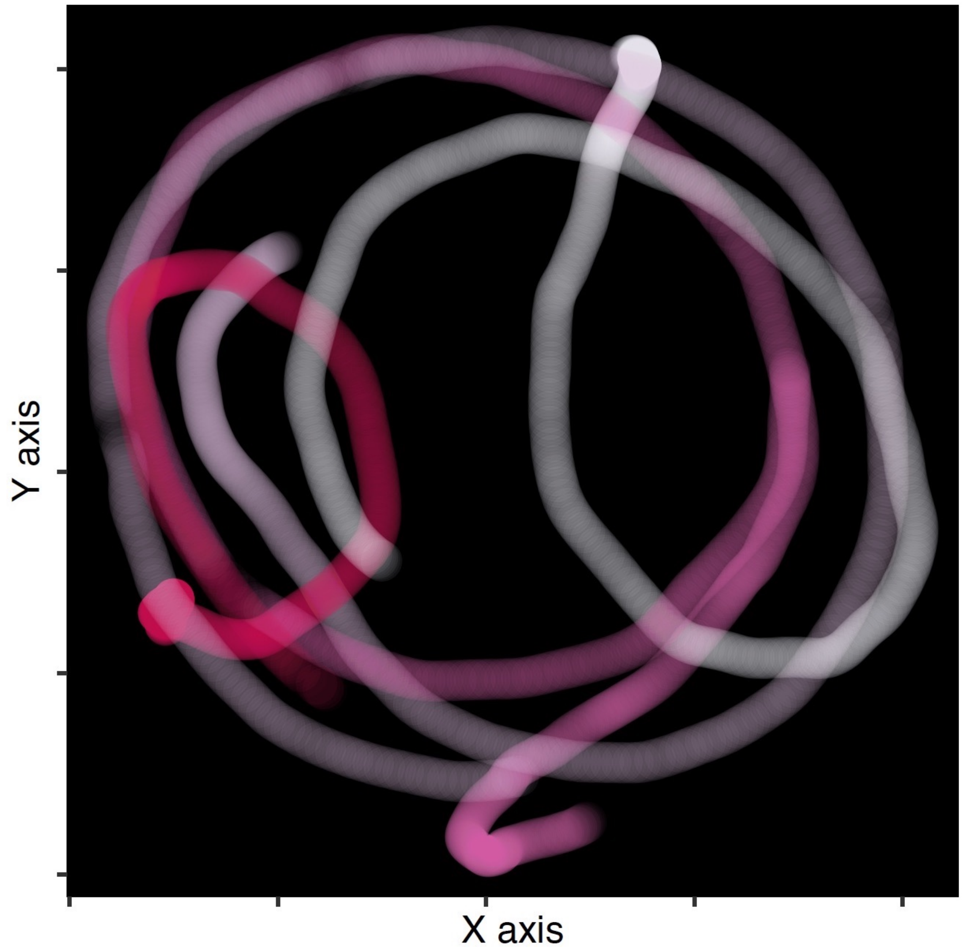

Figure 3.7: Examples of fluid movement trajectories. Each nuance of pink corresponds to a child moving in a 2D space (data collected from the study presented in paper ix). As seen in the visualization, these fluid movement trajectories are smooth and continuous.

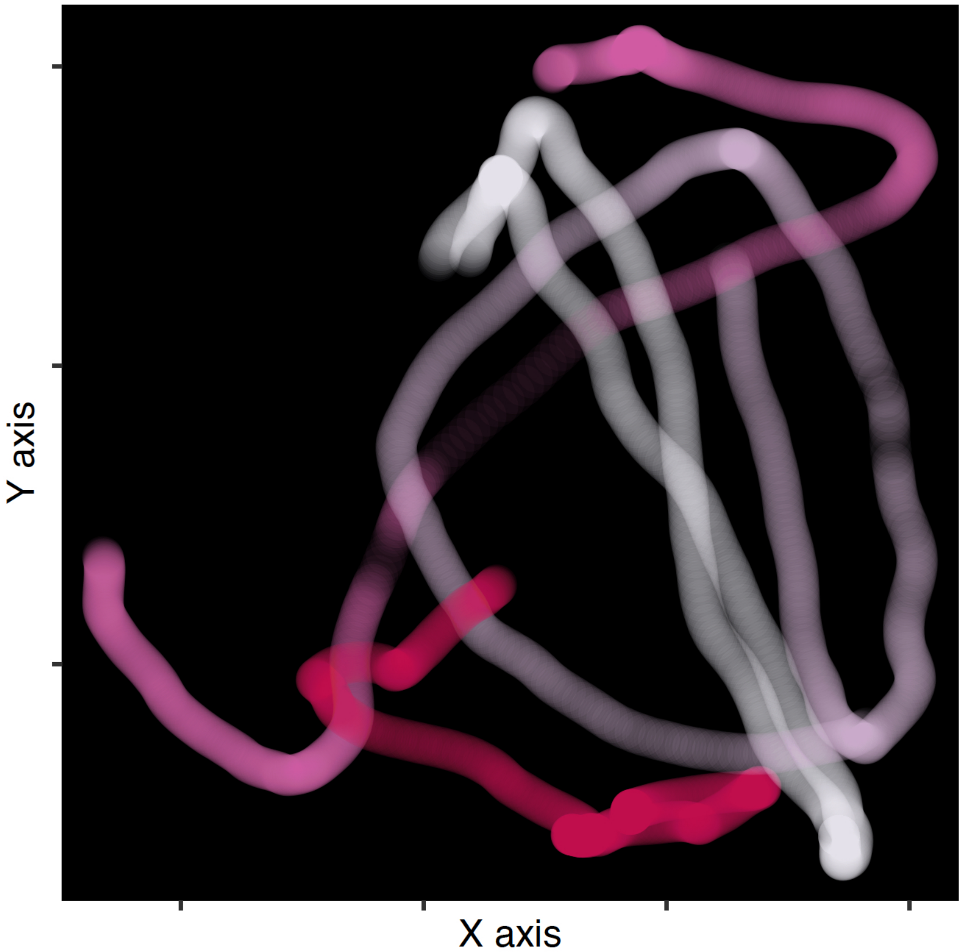

Figure 3.8: Examples of less fluid movement trajectories. Each nuance of pink corresponds to a child moving in a 2D space (data collected from the study presented in paper ix). As seen in the visualization, these movement trajectories are not very smooth; they are jerky and noncontinuous.

3.5 Paper V: Music Creation by Example

Advancements in machine learning and artificial intelligence (AI) have paved the way for development of new systems allowing for autonomous music generation. A number of solutions providing various levels of human engagement have been proposed for this purpose. On one side of the spectrum, AI music generators that use state-of-the-art deep learning methods to synthesize music parts and phrases with high fidelity are available. However, these tools require machine learning knowledge to operate. On the other side of the spectrum, efforts have been made to make AI music tools accessible to non-musicians and non-AI users. However, most of these systems only allow users to specify a set of keywords or parameters for customization, thereby limiting musical creativity.

In this project, we set out to explore new interface solutions bridging AI tools with non-expert users, balancing between automation and controllability. We aimed to make the music generation process straightforward and easily accessible for all. For this purpose, we present a new user interface paradigm for music creation in which an example song is provided as input reference to an AI music system. This approach, which we here refer to as *"music creation by example"*, enables users to create and customize machine-generated music without going through the process of providing abstract descriptions (such as mood and genre) or having to learn complicated composition interfaces. Instead, users provide a piece of music as input to the music-generation system.

The system works as follows: when an example song is defined as input, the analyser extracts musical features from the supplied song and operates an AI music generator to produce a set of alternative renditions serving the same functionality as the provided example. Each generated song has multiple musical features associated with them, such as tempo, baseline, chords and melody. The user can then mix and match these musical aspects in a grid, and/or add more reference songs to get a wider variety of musical aspects to combine. In this way, the user may create and modify music interactively. This grid-based interface for customization and control is visualized in Figure 3.9.

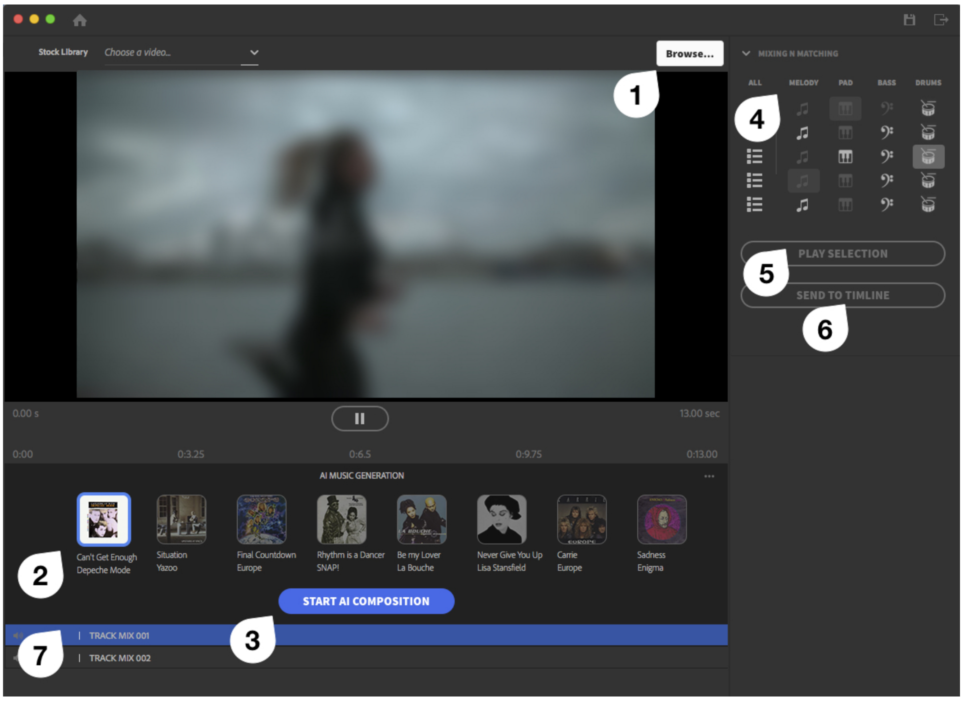

Figure 3.9: Overview of the GUI of the *"Music Creation by Example"* system. 1) Select a video. 2) Select a reference song that goes well with the video. 3) Press to generate several tracks of AI music based on, but not exactly similar to, the reference song. 4) Mix and match melody, pads (sustained chords), bass and drums from different AI-generated tracks using the grid interface. 5) Play a preview of the selected combinations of melody, pads, bass and drums from different AI-generated tracks. 6) Render the mix to the timeline. 7) Your mix shows up here.

This particular project focused on generating music for short video clips (15-20 seconds long), but the user interface paradigm can be used in a range of different situations. The idea of creating music based on example songs was fully informed by user studies focusing on music creation for video. Our findings suggested that novice users might benefit from providing examples (or sonic mood boards) of songs as a source of inspiration for music generation. Moreover, novice users might want to focus on controlling high-level properties of the music, creating music *in collaboration with* an AI system. In other words, they still want to retain a certain level of creative freedom, customization and control in the music generation process. Results from evaluation sessions with twelve video creators supported the effectiveness of our user interface paradigm; users rated the system as being enjoyable to use and easy to learn. On a scale from 0 to 10, where 0 signifies "not satisfied at all" and 10 signifies "very satisfied", all participants rated satisfaction with the audible results as 5 or higher.

To conclude, the main contributions of this paper are: 1) a user interface paradigm for music creation informed by a user-centered design approach, 2) a prototype system that has proven to successfully allow users to create songs in collaboration with an AI music system, and 3) insights and findings from user studies that can inform the design of mixed-initiative interactions (Allen et al., 1999) and research on human-AI interaction in creative practice. The proposed system is one example of how music applications can be designed to enable more people, i.e. not only those with music composition skills, to easily create music.

3.6 Designing and Evaluating ADMIs

The above described papers all discuss technology used in music or sonic interactions. Based on findings from these works, I propose a set of properties that could be used as a starting point when designing and evaluating ADMIs, presented in Table 3.1. Each property is presented together with supporting references to research in music performance or work where these aspects have been discussed in the context of DMI design or evaluation. It is important to remember that different instruments may vary considerably within the range of these defined categories, depending on user group and context of use. The idea here is not that all ADMIs should be designed in a particular way. On the contrary, AMDIs should perhaps be rather different, depending on use case and intended player. A more detailed summary of the different properties is presented below.

1. *Expressiveness.* The ADMI should allow users to express themselves and communicate emotions through control of the instrument (see e.g. Arfib et al., 2005; Juslin and Timmers, 2010). The notion of *expression* and the design of new methods by which to enhance the expressive power of computer music has been widely discussed in the context of NIME, see for example work by Dobrian and Koppelman (2006).

2. *Playability.* This relates to how easy it is for the user to start creating sounds, i.e. having a low barrier to music-making, but also if there is a possibility to learn how to master the instrument, and expand on these skills. In other words, this property is very much linked to the idea of lowering the threshold to participation. For example, Wessel and Wright (2002) have discussed reducing traditional barriers to learning to play a musical instrument and advocated for interfaces that are easy for novices to handle but have no ceiling to virtuosity, while Graham-Knight and Tzanetakis (2015) have stressed the importance of enabling the participant to produce sound quickly.

3. *Longevity.* This property is included since many DMIs traditionally have been very context-specific; they are often used only once or on few occasions, by a single performer (see Marquez-Borbon and Martinez-Avila,

2018). A successful ADMI should be able to survive beyond one musical performance and composition and allow for long-term use, just like a traditional acoustic instrument.

4. *Customizability.* The importance of adapting interfaces to user needs is mentioned in ISO's Guide 71 (ISO: ISO/IEC Guide 71:2001). Interestingly, in an ethnographic study of The Drake Music Project Northern Ireland, a charity which provides music workshops in inclusive ensembles, key findings were that consumer music technology that was not designed to be accessible to a wide spectrum of users could be made accessible by adapting them with other devices or sensor interfaces more suitable for people with unique abilities and specific needs (Samuels, 2019). Some have argued for 100% customizable instruments in this context (Larsen et al., 2016). In this context, customizability refers both to customizing the interface to the gestural capabilities (ergonomics) and preferences of the player, but also the sonic output of the instrument. In other words, it is important that also aesthetic preferences of the player are considered. In addition, this property involves adapting the instrument to make use of multiple modes of interaction and feedback (auditory, haptic or visual), depending on the player's capabilities.

5. *Pleasure*. Research has shown that cognitive, auditory, affective and reward circuits interact to make music pleasurable (Salimpoor et al., 2015). Of course, it is not only important that the ADMI is fully functional, but also that the player gets pleasure from controlling the instrument. A concept that has been suggested as a reliable indicator of pleasure is *"flow"* (El-Shimy and Cooperstock, 2016). The notion of *flow* was formalized by Mihaly Csikszentmihalyi, and can be described as the experience of complete absorption in the present moment (Nakamura and Csikszentmihalyi, 2009). It has also been emphasized as an important aspect of *Music-Centred Design* (Bullock, 2018).

6. *Sonic quality.* This involves both aesthetic aspects of the sound design (something that has often been neglected in favor of interface evaluation in the context of DMI research in HCI) and the overall quality, i.e. resolution, of the audio. It also connects to aspects such as mapping,

since such design decisions can highly influence the aesthetic outcome. Moreover, it relates to the sonic possibilities of the instrument, for example through design decisions guided by demands imposed by a musical style or genre (Hinrichsen and Bovermann, 2016). Interestingly, in a study on the use of technology in music therapy, it was shown that music technology was experienced as offering a lesser aesthetic experience than acoustic instruments (Magee and Burland, 2008b). However, one obvious feature of computer technology is the timbral freedom; while skilled musicians can learn how to master acoustic instruments to produce a wide variety of timbres, such instruments are always constrained by their sound production mechanism (Wessel and Wright, 2002). DMIs, on the other hand, can produce any recorded sound in response to any gesture. Although a complete discussion on aesthetic theory is outside the scope of this thesis work (for an overview of aesthetics in electronic music see e.g. Demers, 2010), it is important to consider the aesthetic experience involved in musical interaction. For the purpose of creating more aesthetically appealing sounds, the ADMI creator may seek to work in multidisciplinary teams that does not only include engineers or interaction designers, but also persons with expertise in composition, music performance and sound design.

7. *Robustness.* The interface should be intact and functional after repeated use. A robustness criterion can be used as a method for evaluating DMI design by stakeholders such as performers, composers, or manufacturers, at the product development phase (O'Modhrain, 2011).

8. *Multimodality.* Several case studies presented in this thesis suggest that multimodal feedback can successfully be implemented in inclusive sonic interaction applications. Haptic technology can assist musicians in producing gestures (Berdahl et al., 2009). Vibrotactile feedback can be implemented in interfaces in order to restore the intimacy in instrumental interaction with a DMI, or to enable persons with hearing-impairment to experience music (Giordano and Wanderley, 2013). There is also evidence that music technology should provide somatosensory experiences, similar to the case of an acoustic instrument, when working with users with spe-

cial cognitive needs, as this facilitates cause-and-effect awareness (Magee, 2014). The instrument should ideally allow for multiple modes of interaction and multisensory experiences, depending on preferences and sensory, perceptual and cognitive abilities of the player. However, it is important to take into consideration that some user groups may have hypo- and hypersensitivity to sensory stimulus. Too many sensory impressions may result in distraction or overstimulation for such user groups.

9. *Causality.* Sound perception and cognition is based both on neurocognition and ecological experience of sound-gesture relationships, including knowledge of causality and sound-producing gestures (see e.g. Rocchesso and Fontana, 2003). Research focusing on the motor theory of perception suggests that we can make sense of what we hear by guessing how the sounds were produced (in this particular case, language perception is linked with mental images of gestures of the vocal apparatus) (Liberman and Mattingly, 1985). Sounds are thus associated with causality, both with sound-producing actions and resonating objects (Godøy et al., 2005). Causality can therefore be considered an important aspect in design of ADMIs. Non-intuitive (non-ecological) motion-sound relationships may be confusing for certain user groups, especially in the context of music therapy. As opposed to acoustic instruments, DMIs often rely on controllers triggering sounds that are (or already have been) synthesized elsewhere; they are thus not always sound sources themselves, which might affect the perceptible gesture-sound causality (Emerson and Egermann, 2017). Mapping decisions should support motion-sound relationships so that the musical interaction demonstrates causal energy to sound relationships, thereby making the interaction intuitive. Moreover, it is usually important that similar gestures result in similar sounds in a way that is predictable for the player. The player wants to feel a sensation of complete control, at least at a high level of abstraction, over the sounds produced by the instrument (Wessel and Wright, 2002). This also relates to aspects such as latency of the sound production. On this topic, it has been suggested that 10 milliseconds is an acceptable upper bound on the computer's audible reaction to gesture, and that a low variation latency not exceeding 1 millisecond is crucial (Wessel and Wright, 2002).

Property	**Description**
Expressiveness	Allows for communication of emotional expression (Juslin and Timmers, 2010; Arfib et al., 2005; Calegario, 2019).
Playability	Quickly get started → virtuosic mastery (Wessel and Wright, 2002; McDermott et al., 2013; Graham-Knight and Tzanetakis, 2015; O'Modhrain, 2011; Jordà, 2004; Fels, 2004).
Longevity	Survives over time, beyond one single musical performance and composition (Morreale and McPherson, 2017; Marquez-Borbon and Martinez-Avila, 2018; Elblaus, 2018).
Customizability	Allows for adaptation based on user capabilities/preferences (Larsen et al., 2016; Samuels, 2019; Paper I).
Pleasure	The act of controlling the instrument provides pleasure (O'Modhrain, 2011) and a sensation of flow (El-Shimy and Cooperstock, 2016; Bullock, 2018).
Sonic quality	Overall quality of the sonic output (Medeiros et al., 2014; Jorda, 2005) and sonic possibilities of the instrument (Hinrichsen and Bovermann, 2016).
Robustness	Remains functional after repeated use (O'Modhrain, 2011).
Multimodality	Allows for multiple modes of interaction and multisensory experiences (Young et al., 2018; Marshall and Wanderley, 2006; Berdahl et al., 2009; Giordano and Wanderley, 2013; Birnbaum and Wanderley, 2007; Birnbaum, 2007; MacLean, 2000)).
Causality	Behaves consistent in terms of motion-sound relationships/mapping (Emerson and Egermann, 2017), is characterized by stability, reliability, predictability (Wessel and Wright, 2001, 2002) and reproducibility (Graham-Knight and Tzanetakis, 2015).

Table 3.1: Properties to consider when designing and evaluating ADMIs, presented with references from music performance literature and research on DMI design/evaluation.

Chapter 4

Discussion and Conclusions

4.1 Discussion

This thesis presents a set of studies on inclusive sonic interaction design. The research question of this thesis work was: ***How can musical interfaces be designed for inclusion?*** Which was followed up with the sub-question: ***How can multimodal feedback be used in digital musical instruments in order to promote inclusion and empowerment?*** Below follows a reflection on these topics, based on findings from the five publications included in this thesis.

Findings presented in Paper I suggest that ADMIs more often make use of visual feedback (visualizations, GUIs or blinking LED lights) than active haptic feedback. This despite the tight coupling between sound and vibrations observed among traditional musical instruments. One can argue that several user groups could potentially benefit from presence of haptic feedback when interacting with a musical device. For example, persons with visual impairments or hearing loss may benefit from using haptic vibrations as a source of feedback when interacting with a DMI. Translating audible sound into alternative representations could be a beneficial way of presenting music if one modality is better functioning than others. The full potential of incorporating active haptic feedback to promote inclusion in music-making has not yet been fully explored.

Considering that little work has yet focused on developing DMIs for elderly people, and that such users also often are affected by hearing loss, it would be interesting to investigate how multimodal ADMIs could be introduced for the purpose of musical expression for such users. Up to this point, most of the work on ADMIs appears to have been directed towards research on musical devices developed for persons with physical disabilities or children. Results from Paper I suggest that creating music interfaces that provide vibrotactile feedback could be one way of including user groups that are under-represented in music-making contexts involving DMIs.

One could argue that acoustic musical instruments intrinsically provide vibrotactile feedback, and that it is likely that most players in fact would benefit from having access to such sensations when interacting with a DMI. However, it should be noted that some user groups (e.g. children with autistic spectrum disorder) may be overwhelmed by the presence of multimodal feedback. For such users, limiting the musical experience to few sensory modalities, as well as few means of interaction, might actually be preferable. The key in this context is to understand the sensory, perceptual and cognitive abilities of each user. No matter which modalities and sensors that are used, I believe that it is vital to explore how to map gestures to sonic output in a way that creates a sensation of expressive control, as this is an important aspect of the musical empowerment process. I believe that the computer music community has a lot of expertise in this area, and that this knowledge could successfully be transferred to the field of ADMIs and inclusive music practice. Moreover, a large body of research in computer music practice has already focused on designing DMIs for novices and how to enable long-term use as well as support continuous development. These concepts are of course also relevant for the development of ADMIs.

Results from Paper I shed light on the process of developing ADMIs. For example, incorporating users (and sometimes also therapists) is a vital part of the creation process. Allowing users to have access to, and not merely be passive users of, the technology that is to be developed could potentially create a sensation of empowerment in this context. Overall, aspects judged to be important for successful ADMI design presented in Paper I were instrument adaptability and customization, user participation, iterative prototyping, and interdisciplinary development teams.

An important aspect that was mentioned in many of the reviewed papers was the ability to easily customize and adapt an ADMI according to specific user needs and preferences. This includes allowing the player to choose interaction strategies, as well as feedback types, depending on the best functioning and preferred sensory modalities. Perhaps one could start by providing a range of different interactions and multisensory feedback, and the user, or a therapist, could adjust these according to the needs and preferences of the player. Interestingly, relatively few of the papers discussed in the review described the sound models and sonic possibilities provided by respective ADMI in any greater detail. This despite the fact that some user groups certainly would benefit from customizing also the sonic outcome according to hearing capabilities and personal preferences. Perhaps there is a need for involving more sound designers and composers in the creation and customization of musical sounds for ADMIs. At the same time, there is also a demand for simple and cheap technologies in these contexts; ADMIs are often required to be easy to use both for the intended musicians and music therapists.

Building on the results from Paper I as well as the other works presented in this thesis, a summary of properties to be considered when designing ADMIs was presented in Table 3.1. The properties judged to be important for ADMIs are: expressiveness, playability, longevity, customizability, pleasure, sonic quality, robustness, causality and multimodality. These properties could be used as starting point when developing ADMIs. By defining these nine concepts, I have tried to expand on previous research on DMIs, while including and emphasizing aspects that could be especially important for ADMIs. The idea here is that the benefit of designing ADMIs as inclusive musical interfaces can also lead to better design of DMIs in general. There are many examples in other fields where designs specifically for one user group with diverse abilities has resulted in really good tools to be used by everyone, so called universal design solutions (think for example of the audiobook, Velcro and the automatic door).

Interestingly, it has been found that devices providing a mode of musical interaction that is accessible for a wide spectrum of people and involve simple movements that most people can participate in may also have a negative and stigmatizing effect on participants that do not want to use devices that differentiate them from other musicians (Samuels, 2019). It is not only the design of music technology that makes it accessible, and it is important to remember that technology use takes place in a social context. For example, interrelations between music tutors, participants and music technology are also important, as emphasized by Samuels (2019). However, by being aware of the results that our design decisions may have, we can encourage more inclusive design decisions.

Other perspectives on inclusive sonic interaction are highlighted in Paper II, focusing on the Sound Forest installation. Results from this paper suggested that different user groups used various interaction strategies, but that they all seemed to enjoy the experience of interacting with the instrument. Perhaps a musical instrument allowing for inclusive sonic interaction can be understood using a metaphor of a traditional piano: it allows for different types of interaction strategies, from simple to complicated, solo and ensemble play. In this sense, it can be said to be designed *for all*. Moreover, developing instruments for many potential users and scenarios can perhaps remove the stigma associated with musical instruments that are designed specifically to be "easy to use" for neurodiverse musicians.

The study on Sound Forest suggests that there is a potential benefit of incorporating vibrotactile feedback in this type of DMI. Especially the group of participants with intellectual disabilities, who were also using wheelchairs, seemed to enjoy the tactile aspect of the musical experience. Inclusive design should perhaps focus on enabling rich experiences for all participants, making this a built-in property of the musical instrument itself, thereby providing a wide range of possible means of interaction. To conclude, findings suggest that the multimodal properties of Sound Forest enabled visitors of various ages and abilities to take active part in music-making.

Regarding Paper III and how to promote inclusion and diversity in the computer music community, I believe that transforming data into music is an excellent approach when it comes to representing demographic imbalances. Listening to music could perhaps be more engaging than just reading about statistics. The focus of this particular publication was on the ratio of women publishing in the community. However, there are of course a lot of other groups that are not well represented in this context. Attempting to define why the gender ratio between men and women in the field of computer music has been so persistent throughout the years is beyond the scope of this thesis, however, it would of course be interesting to conduct further research on this topic, in order to investigate which obstacles that these researchers encounter. Such studies should focus on creating awareness about the challenges that these persons face in their daily work and on analysing the social environments that surround music (technology). Once these challenges have been identified, it will be easier to take initiatives towards changing practices. Moreover, there are areas in which the trend of female participation has been reversed, and it is possible that future studies on such environments could provide insights into possible methods of promoting change. Personally, I believe that everyone in the community can contribute in terms of creating “safe” spaces in their research practice, for example by being open, inclusive, and not pass judgement on persons or aspects that we at a first glance are not used to, or do not understand.

In the context of this thesis, Paper IV illustrates a potential for translating musical content from one modality to another. This idea relates to inclusion in the sense that it allows persons who cannot experience musical qualities through sound to get access to musical sensations through translation into other modalities. For the specific purpose of translating fluidity of movement, one could envision applications such as musical instruments designed for therapeutic purposes. This could for example be relevant in motor rehabilitation, especially in situations where it is important to practice or produce smooth and wave-like movements. Moreover, this study also suggests that vocal sketching could successfully be used as a tool when designing sounds that have no “natural” mapping to physical properties. This is interesting in the context of DMI development, where there might not always be clear relationships between gestures and the expected sonic output.

The final paper discussed in this thesis, Paper V, presents a user interface music creation paradigm informed by a user-centered design approach. The proposed system enables users to create music for video content by providing examples songs. This work introduces AI as an active component in the process of music creation and explores aspects related to human-AI interaction through interface design. There are many examples of how machine learning and AI could be used in the context of musical interaction (see e.g. Fiebrink and Scurto, 2016), thereby allowing users to generate interesting musical outcomes. Inclusion and diversity in the context of music creation may, as in this paper, not only involve designing physical interfaces that allow for more customized interaction. It could also involve replacing certain parts of the musical creation process that may be inaccessible to those who do not have music theory knowledge or have a music composition background. In other words, such work involves not only removing physical barriers but also knowledge barriers, thereby enabling music-making for all. As for most DMIs, the challenge in this context is to make sure that the interface itself is easy to use, while allowing for a high level of customization and control, resulting in enjoyable musical experiences.

4.2 Future Work

Based on findings presented in this thesis, it would be interesting to further explore how whole-body vibrations could be used in musical interaction for persons with visual or hearing impairments and elderly people. Moreover, findings suggested that the multimodal properties of Sound Forest enabled visitors of various ages and abilities to take active part in music-making. This motivates further studies on groups with diverse abilities, for example persons using wheelchair. At the point of writing, a follow-up study focusing on assisting composers in their creation and design of whole-body vibrations for the Sound Forest installation has been conducted, and a more detailed discussion on this topic will be presented in a future publication. Regarding aspects related to inclusion and diversity in the computer music field, I believe that more studies focusing on challenges that hinder certain persons from actively participating would benefit the community. Finally, future work could involve explorations of how AI tools could be incorporated in DMIs and ADMIs for the purpose of enabling inclusion and diversity in music-making.

4.3 Conclusions

Up to this point, relatively little research has focused on topics related to diversity and inclusion in the computer music field. In this thesis, I introduce the concept of *inclusive sonic interaction design*, referring to sonic interaction design aimed at widening participation in sonic interaction. I also introduce the term *Accessible Digital Musical Instruments (ADMIs)*, defined as accessible musical control interfaces used in electronic music, inclusive music practice and music therapy settings. The term inclusion in this context relates to representation and diversity among those who make use of DMIs, those who build such instruments, and those who use these tools in their daily practice, for example in music therapy. These topics are investigated through analysis of five case studies. Results indicate that the computer music field is far from being gender-balanced. Findings also highlight the need for widening participation in ADMI research. For example, considerable work in this domain has focused on interfaces for persons with physical disabilities and children, while little attention has been paid to elderly people and persons with visual impairments. Finally, this thesis highlights that there is a large body of research focusing on developing musical interfaces within the computer music community that could be transferred to the area of inclusive music practice in order to promote music-making for all.

Inclusive sonic interaction can be promoted in various ways, for example by designing rich interactions in which the intended user group feels a tight connection between gestures and the generated sonic output, thereby creating a sensation of empowerment. In this thesis I have identified a set of properties that could serve as a starting point, or evaluation criteria, for ADMI design: expressiveness, playability, longevity, customizability, pleasure, sonic quality, robustness, multimodality and causality. Since music is a multisensory experience, I propose that DMIs should provide multimodal feedback. This involves designing experiences not only involving audible sounds, but also music visualizations and tactile sound, thereby enabling a closed multisensory interaction-loop between musical performer and instrument. Since the haptic modality is still relatively rarely used as a means of presenting music (nor actively considered when designing mapping strategies) in ADMI practice, there is a potential for incorporating vibrotactile feedback in this context. Moreover, couplings between music and visuals could also be used in order to provide richer multisensory experiences that emphasize the relationship between cause and effect, resulting in more intuitive and easily comprehensible sonic interactions.

To conclude, multimodal feedback could be explored as a means of enabling inclusion in music-making activities involving DMIs. It should however be noted that certain user groups might find multisensory feedback overwhelming, and that it is important that interfaces are customizable to user needs. Customization in this context may not only refer to defining user-specific gesture acquisition and control, but also to down-scaling to fewer modalities and customizing sonic output based on user preference. Understanding cognitive and emotional needs of the users is essential in this context. For this reason, using participatory design methods is important when it comes to enabling inclusive sonic interaction.

Music technology can be designed, programmed, and customized to become more inclusive. Social constructs and structures may however influence dynamics, power-relations as well as general access to tools for sonic interaction, thereby including or excluding certain user groups from active participation. A deeper understanding of challenges faced by certain users is required in order to take initiatives towards changing practices. Enabling inclusive interaction does thus not only involve aspects related to designing engaging interactions and customizing control for each and every individual, it also involves creating safe spaces enabling free musical expression, for all.

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