Built for Performance: Designing Digital Musical Instruments for Professional Use

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Abstract

The field of digital musical instrument (DMI) design is highly interdisciplinary and comprises a variety of different approaches to developing new instruments and putting them into artistic use. While these vibrant ecosystems of design and creative practice thrive in certain communities, they tend to be concentrated within the context of contemporary experimental musical practice and academic research. In more widespread professional performance communities, while digital technology is ubiquitous, the use of truly novel DMIs is uncommon.

The aim of this dissertation is to investigate the unique demands that active and professional performers place on their instruments, and identify ways to address these concerns throughout the design process that can facilitate development of instruments that are viable and appealing for professionals to take up into long-term practice. The work presented here represents three phases of user-driven research, using methods drawn from the fields of Human-Computer Interaction and Human-Centered Design. First, a survey of musicians was conducted to understand how DMIs are used across diverse performance practices and identify factors for user engagement with new instruments. Second, design workshops were developed and run with groups of expert musicians that employed non-functional prototyping and design fiction as methods to discover design priorities of performers and develop tangible specifications for future instrument designs. Finally, multiple new DMIs have been designed in two primary contexts: first, three instruments were developed in response to the workshop specifications to meet general criteria for DMI performance; second, two systems for augmented harp performance were built and integrated into a musician's professional practice based on a long-term research-design collaboration.

Through these projects, I propose the following contributions that will aid designers in the development of new DMIs intended for professional performers. The survey results have been distilled into a list of considerations for designers to address the unique demands and priorities of active performers in the development of new DMIs. A complete methodology has been developed to generate design specifications for novel DMIs that leverages the tacit knowledge of skilled performers. Finally, I offer practical guidelines, tools and suggestions in the technical design and manufacture of instruments that will be viable for use in long-term professional practice.

Résumé

Le domaine de la conception d'instruments numériques de musique (INM) touche plusieurs disciplines et comprend diverses approches pour développer de nouveaux instruments qui seront utilisés de manière artistique. Bien que ces écosystèmes dynamiques de conception et de pratique créative prospèrent dans certaines communautés, ils demeurent majoritairement centrés sur la performance musicale expérimentale et contemporaine et la recherche universitaire. De plus, les technologies numériques sont bien présentes au sein des communautés musicales et pratiques professionnelles, toutefois, l'utilisation d'INMs novatrices reste toujours limitée.

L'objectif de cette thèse est d'étudier les exigences uniques des musiciens professionnels lorsqu'ils pratiquent activement un instrument de musique, et d'identifier les moyens de répondre à ces préoccupations tout au long du processus de conception, pouvant ainsi faciliter le développement durable d'instruments attrayants pour ces professionnels. Cette thèse s'échelonne en trois phases de recherche orientées sur l'utilisateur, proposant des méthodes tirées du domaine de l'interaction homme-machine et de la conception centrée sur l'humain. D'abord, des musiciens ont rempli un questionnaire afin de comprendre comment les INMs sont utilisées dans différentes pratiques musicales et d'identifier les facteurs d'engagement des utilisateurs avec les nouveaux instruments. Deuxièmement, des ateliers de conception ont été élaborés et organisés avec des groupes de musiciens experts. Ces derniers ont utilisé le prototypage non fonctionnel et la fiction de conception comme méthodes pour déceler les priorités des interprètes lors de la conception d'instruments numériques et développer des spécifications tangibles. Enfin, deux contextes ont dirigé la création des INMs : premièrement, suite aux résultats issus de l'atelier, trois instruments ont été créés pour répondre aux critères généraux qui ont été proposés quant aux performances avec INMs; deuxièmement, deux systèmes de performance de harpe augmentée ont été construits et intégrés dans la pratique professionnelle d'une musicienne basée sur une collaboration de recherche-conception à long terme.

À travers ces projets, je propose les contributions suivantes qui aideront les concepteurs dans le développement de nouvelles INMs destinées aux musiciens professionnels. Les résultats du questionnaire ont été condensés dans une liste de considérations pour les concepteurs qui répondent aux demandes et aux priorités des interprètes quant au développement de nouvelles INMs. Une méthodologie a été développée pour produire des spécifications lors de la conception d'INMs, qui tire profit des connaissances tacites des musiciens professionnels. Enfin, je présente des lignes directrices pratiques, des outils et des suggestions pour la conception technique et la fabrication d'instruments durables qui seront utilisés dans la pratique professionnelle d'un instrument de musique à long terme.

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First and foremost, I would like to express my deepest gratitude to my two co-supervisors, Marcelo M. Wanderley and Catherine Guastavino. Marcelo, thank you for your direction and encouragement, and for teaching me how to be a good researcher, writer and academic. Catherine, thank you for providing me with perspective and clarity on my research topic and methods, and providing throughtful feedback when it was most needed. Thank you both for your generous funding, longstanding patience and support.

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To Mandeep.

Contribution of authors

This dissertation has been prepared as a manuscript-based thesis and includes the following publications. The research and results are my own original work carried out under the guidance of my supervisors Prof. Marcelo M. Wanderley and Prof. Catherine Guastavino, with contributions from others as described below.

- **Chapter 2**: Sullivan, J., Guastavino, C., & Wanderley, M. M. Surveying Digital Musical Instrument Use in Diverse Performance Communities. (submitted)
- **Chapter 3**: Sullivan, J., Wanderley, M. M., & Guastavino, C. From Fiction to Function: Designing New Musical Instruments With Expert Musicians. (submitted)
- **Chapter 4**: Sullivan, J., Vanasse, J., Guastavino, C., & Wanderley, M. M. (2020). Reinventing the Noisebox: Designing Embedded Instruments for Active Musicians. *Proceedings of the International Conference on New Interfaces for Musical Expression*, 5–10.

In **Chapter 2**, Ivan Franco contributed questions and helped to revise the survey questionnaire. Andrew McPherson and Fabio Morreale (Augmented Instruments Laboratory, Queen Mary University, London) provided assistance and insight for the analysis during a research exchange to Queen Mary University in 2018. The exchange was made possible by an Inter-Centre Research Exchange Funding Award from the Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT). A preliminary report of the results was first published in:

- Sullivan, J., & Wanderley, M. M. (2019). Surveying Digital Musical Instrument Use Across Diverse Communities of Practice. *Proceedings of the International Symposium on Computer Music Multimedia Research*, 745–756.

In **Chapter 3**, Christine Kerrigan provided valuable advice and feedback in the design of the study. Collin Wang was my assistant for the Design for Performance workshops. He helped with the workshop development and setup, and served as the workshop photographer.

In **Chapter 4**, three new instruments are introduced. While the overall design of hardware and software is my own, others contributed to their development. Julian Vanasse worked on the initial software design and testing for the Tapbox instrument.

Patrick Cowden contributed hardware and software improvements and updates for the Keybox instrument. Additionally, two of the instruments utilize custom circuit boards developed by Ivan Franco as part of the Prynth framework for embedded instruments. Additional methods and materials used are the product of shared knowledge and experience between related projects and colleagues from the Input Devices and Music Interaction Laboratory (IDMIL). Hardware fabrication was conducted at CIRMMT with the assistance of Yves Méthot. The original Noisebox instrument design was published in:

- Sullivan, J. (2015b). Noisebox: Design and Prototype of a New Digital Musical Instrument. *Proceedings of the International Computer Music Conference*, 266–269.

Chapter 5 reports on two practice-based research projects undertaken with professional harpist Alexandra Tibbitts. In the first project I organized and directed the motion capture study and was assisted by Tibbitts. The study was carried out at CIRMMT with support from Yves Méthot and Julien Boissenot. The gestural control hardware was designed by Ólafur Bogason and Genki Instruments. The original musical work for gesture control system was composed by Brice Gatinet. Results of this project were first published in:

- Sullivan, J., Tibbitts, A., Gatinet, B., & Wanderley, M. M. (2018). Gestural Control of Augmented Instrumental Performance: A Case Study of the Concert Harp. *Proceedings of the International Conference on Movement and Computing*, (October), 1–8.

In the second project, conceptual design and prototyping of the Bionic Harpist controllers was carried out by Tibbitts and myself. The hardware and software design is my own original work, however the controllers utilize a circuit board that was adapted from Franco's Prynth framework.

Each study was approved by the McGill University Research Ethics Board and is certified under the following REB File Numbers: 254-1117, 188-0918, 361-0117. The ethics certificates are included in Appendix D.

Contents

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List of Acronyms

BLE-MIDI	MIDI over Bluetooth Low Energy
CAD	Computer-Aided Design
CHI	ACM Conference on Human Factors in Computing Systems
CIRMMT	Centre for Interdisciplinary Research in Music Media and Technology
CMMR	International Symposium on Computer Music Multidisciplinary Research
COBS	Consistent Overhead Byte Stuffing
CoI	Community of Interest
CoP	Community of Practice
DMI	Digital Music Instrument
DSP	Digital Signal Processing
DTW	Dynamic Time Warping
EDM	Electronic Dance Music
EMG	Electromyography
EMI	Electronic Musical Instrument
ERM	Eccentric Rotating Mass
FM	Frequency Modulation
GUI	Graphical User Interface
HCD	Human-Centered Design
HCI	Human-Computer Interaction
HD	High Definition
I^2C	Inter-Integrated Circuit
ICMC	International Computer Music Conference
ICLI	International Conference on Live Interfaces

IMU	Inertial Measurement Unit
ISO	International Organization for Standardization
LED	Light Emitting Diode
MARG	Magnetic, Angular Rate, and Gravity
MIDI	Musical Instrument Digital Interface
NIME	New Interfaces for Musical Expression
OLED	Organic Light-Emitting Diode
OSC	Open Sound Control
PCB	Printed Circuit Board
PD	Participatory Design
SDT	Self Determination Theory
SMC	Sound and Music Computing (Conference)
SMPTE	Society of Motion Picture and Television Engineers
TIEM	Taxonomy of Realtime Interfaces for Electronic Music Performance
UCD	User Centered Design
UDP	User Datagram Protocol

Chapter 1

Introduction

This is a thesis about designing and performing with novel digital musical instruments. Over the last century, electronic and digital technologies have permeated all facets of our lives and are deeply integrated into how we work, study, communicate, entertain ourselves, and more. This has carried over into musical practice as well. Performing with digital instruments and technology is commonplace and by itself not exactly remarkable. However, if we focus on the digital tools that performers use, we find that the overwhelming majority can fit into a few recognizable categories such as keyboard synthesizers, MIDI controllers connected to computer software or DJ tools like digital turntables and mixers.

On the other hand, the field of digital musical instrument (DMI) design encompasses a flourishing community of designers, researchers, musicians and more, collectively producing a vast array of novel instruments that provide expansive interaction and sound-production possibilities for performers. The field is notable for its interdisciplinarity, merging technical engineering with musical practice through both scientific research and artistic production. For many DMI practitioners, an active practice includes performing with the digital instruments they design, designing for other performers, or performing with instruments designed by others.

Unfortunately this vibrant ecosystem of new instruments and creative performance practice tends to concentrated in the narrow context of contemporary experimental and largely academic musical communities. Researchers in the field have found DMIs to be somewhat ephemeral by nature (Mamedes et al., 2014), with few evolving into mature instruments suitable for long-term use around which a community can develop (Morreale & McPherson, 2017). These circumstances may contribute to the relative absence of novel DMIs in professional use, especially among more popular styles like electronic dance music, indie rock, R&B and hip-hop, which actively embrace and integrate emerging digital technologies in their continuing evolution.

1.1 Research focus

While prior research has examined various aspects around integrating DMIs into artistic practice, there is a lack of dedicated scholarship on the particular demands of professional musical performance or how these can be addressed in the design of new instruments. Thus, the aim of this dissertation is to disentangle several related factors around professional performance with DMIs, and propose new user-driven guidelines for the design of new instruments that support long-term, active use by music professionals.

The work presented here is grounded in human-centered design (HCD) (Cooley, 1989), an approach described by Norman (2013) where human needs, capabilities and behaviors are identified first, then designs are implemented to accommodate them.[1] Therefore this thesis is decidedly performer-centric, and musicians have been closely involved in each phase of the research.

My research is framed by the following questions:

[1] HCD, along with many of the methods utilized in this dissertation, is closely related to user-centered design (Greenberg et al., 2011). An introduction and discussion of both is provided in Chapter 3, Section 3.2.2.

1. How do active and professional performers across diverse communities of practice engage with new instruments?
2. Can designers effectively leverage the embodied knowledge and experience of performers through applied design activities?
3. How can ongoing collaboration with active musicians support the development of new DMIs that are optimized for long-term professional use?

The questions were formulated to approach the investigation of DMI design and performance from a few different angles. The first intends to gain background knowledge about active and professional DMI use from the perspective of musicians, while the second and third explore user-driven methods for DMI design through applied research activities. By combining both evidence-based and practice-based approaches, my intent has been to develop and present a holistic understanding of DMI design that can adequately support the needs of professional performing musicians.

In total, this research has spanned three phases. Table 1.1 provides a roadmap of the work presented in this dissertation, showing the three research questions, the phases of research in which they are addressed, and the corresponding chapters of this document.

Research question	**Phase**	**Chapter**
How do active and professional performers across diverse communities of practice engage with new instruments?	The Electronic Musical Instrument Survey	Chapter 2
Can designers effectively leverage the embodied knowledge and experience of performers through applied design activities?	Design for Performance study	Chapters 3 & 4
How can ongoing collaboration with active musicians support the development of new DMIs that are optimized for long-term professional use?	Collaborative design of augmented harp interfaces	Chapter 5

Table 1.1 Research questions with corresponding phases of research and chapters

Question one has been investigated through a survey to understand how musicians engage with new instruments and technologies across different performance communities in both academic and popular music contexts. Questions two and three are closely related and have been explored through two distinct bodies of work. First, design workshops were held with expert musicians generate specifications for novel new designs, and from these three new DMIs were developed. Second, a long term collaboration between a professional performer and myself has generated two different sets of hardware and software for solo electroacoustic performance with an augmented concert harp. In the former work, several musicians contributed insights leading to multiple instruments intended for a general audience of professional DMI performers, while in the latter, dedicated study with an individual performer has lead to custom solutions for their unique and specialized practice. Each has provided insights and outcomes, and each helps to address these research questions in different ways. A full description of each research phase is provided in Section 1.3.

1.2 Research context

The context for this research is outlined across three distinct areas. First, my experience as a professional performer provided the initial interest and personal connection to this work. Second, from this experience I was specifically interested in examining the link between design and professional practice, and therefore, a clear definition and context of professional practice in music is necessary. Third, the work comes out of, and hopefully extends, long-running research situated within an academic and artistic community of DMI practitioners exemplified by the International Conference on New Interfaces for Musical Expression (NIME), to which I provide a short introduction.

1.2.1 Motivation

Starting with piano lessons when I was young, I have played music for as long as I can remember. I received my bachelor's degree in contemporary music performance with a focus on jazz guitar and began my professional career, playing in a variety of different rock bands. My main instrument as a professional was bass guitar, but I also played a variety of other instruments depending on the group and context including guitar, double bass and keyboards, as well as various electronics and computer-based instruments. As my career progressed I frequently performed as a multi-instrumentalist, switching between several different instruments during a single concert. My career as a professional performer extended over 15 years, and my experiences in this time have informed my research in a couple fundamental ways.

First, I had to maintain a large inventory of professional equipment, including conventional acoustic and electric instruments, and hardware and software for computer-based performance. Needless to say, ensuring everything was performance-ready when I needed it was a constant task. However, performing with a variety of instruments was also highly rewarding. Part of the enjoyment of working at a professional level was the opportunity to try out and acquire new instruments and technology, and to perform in a variety of different contexts. Through this, I have acquired a high degree of knowledge about the demands that professional practice places on instruments, and a great amount of specific experience with a wide variety of instruments - acoustic, electric and digital - in terms of maintenance, compatibility and industry standards.

Second, as I became more of a multi-instrumentalist, and especially as I toured internationally, I became highly invested in reducing the physical footprint of my gear. As I was already performing with hybrid setups involving a laptop and controllers along with my conventional instruments, I spent considerable time customizing and experimenting with complex computer-based setups to accommodate less switching of physical instruments, using more digital emulations of conventional instruments so that I could travel lighter. While this was mostly a success, there were also tradeoffs and occasional failures. I required less gear, but digital emulations often don't measure up to the instrument they are replacing, and a crash or software issue could bring my entire performance to a standstill. On the other hand, as my technical experience grew I refined my performance setup and eventually moved from customizing instruments and controllers I owned to designing and building my own. Ultimately, this has evolved into my current practice, where I no longer perform professionally but am an active researcher and designer of new digital musical instruments and interfaces.

Given this applied experience as a musician, my perspective spans the domains of both professional artistic practice and technical engineering and design. The passion for interface design is strong, but I remain a musician at heart, and this sensibility greatly informs and motivates my work, both as an instrument designer and researcher.

1.2.2 Design for professional performers

Throughout this thesis terms like "professional musicians" and "professional musical practice" are used frequently. Of course, a musician may embody a number of different professional roles: live performer, producer, studio musician, composer, not to mention other roles where playing an actual instrument may be secondary, such as teaching or music therapy. While all of these activities (and many more not mentioned) may have relevance to our discussion, the main focus of this dissertation are those musicians who are first and foremost instrumental performers, and the primary use case is that of live performance. Other specific and non-obvious contexts are explicitly identified in the text.

The Random House Unabridged Dictionary[2] provides four definitions for the adjec-

[2]provided by https://www.dictionary.com

tive *professional*:

1. following an occupation as a means of livelihood or gain
2. of, relating to, or connected with a profession
3. appropriate to a profession
4. engaged in one of the learned professions (theology, law and medicine)

While the fourth is not relevant here, the first three definitions bear particular significance to our consideration of instruments designed for use by professional performers. Each listed here, with their relevant aspects summarized.

1. Occupation as a means of livelihood: A significant portion (and perhaps all) of an individual's income is generated from their musical practice. Reciprocally, a large part of the professional musician's time is devoted to their musical practice. Furthermore, this criteria differentiates professional practice from that of an amateur or recreational musician, who may play an instrument (and even occasionally engage in typically professional activities like live performance or recording sessions) in their leisure time or without financial compensation.

2. Connected to a profession: An individual's musical activities are professional in nature: performing, rehearsing, recording, learning or composing new material (and as new instruments are involved: testing, experimenting with, configuring/programming new instruments, setups, etc.), not to mention various non-musical activities: traveling and touring, booking, press obligations and such.

3. Appropriate to a profession: Activities, equipment and other aspects meet professional standards and expectations in terms of expertise, quality (of performance and instruments!), compatibility with other systems, performers, venues and industry protocols. Also included here would be more general aspects of professional decorum, such as maintaining obligations and busy schedules, and working in close collaboration with other performers and music professionals.

While these individual aspects are not generally specified throughout the thesis, they are all relevant to the discussion and cumulatively describe our criteria for professional practice.

1.2.3 New Interfaces for Musical Expression

New Interfaces for Musical Expression, or NIME, is another term that is used frequently throughout this thesis. A great deal of activity and scholarship on DMIs comes from the NIME community, which includes researchers, designers, performers and artists associated with the International Conference on New Interfaces for Musical Expression.[3] The annual conference serves as a gathering point for the community to present and discuss research on new musical interface design through presentations of peer-reviewed scientific papers, demonstrations, workshops and concerts. Outside of the conference, the NIME website provides an archive of the NIME proceedings, including all papers (numbering over 1800, several of which are referenced here) which are open access and freely available to the public. NIME continues to grow, both as an organization and community, with new resources and developments such as the establishment of committees and initiatives to promote diversity, inclusivity, environmental sustainability and other ethical considerations of NIME practice.

Though NIME is perhaps the most recognizable research community around design of, and creative practice with, novel musical interfaces and instruments, it is not alone. NIME began as a workshop at the 2001 ACM Conference on Human Factors in Computing Systems (CHI) (Jensenius & Lyons, 2017; Poupyrev et al., 2001), but prior to that the fields of musical interaction and interface design were already well

[3] https://www.nime.org/

established and documented. Volumes like Wanderley and Battier's e-book *Trends in Gestural Control of Music* (2000) and Chadabe's *Electric Sound: The Past and Promise of Electronic Music* (1997) contained a great deal of information on the topic, as did numerous contributions to conferences like the International Computer Music Conference (ICMC) and journals like the Computer Music Journal, which got their starts in 1974 and 1977 respectively. Today, several other conferences and journals exist with dedicated scholarship on musical interface design and artistic practice, such as the Sound and Music Computing (SMC) Conference, the International Symposium on Computer Music Multidisciplinary Research (CMMR), the International Conference on Live Interfaces (ICLI), the Journal of New Music Research and Organised Sound, to name just a few.

NIME is discussed frequently throughout this thesis. While much of the review and associated research presented here explicitly references NIME, we may liberally extend our concept of this community to include these other associations of academic-based musical interface research and practice.

1.3 The three research phases

The research undertaken for this dissertation was carried out across three phases: a survey and two practice-based works, each of which involved multiple projects and stages. An overview is provided here, along with the methodological approaches used for each.

1.3.1 The Electronic Musical Instrument Survey

The first phase of research entailed an online survey of musicians entitled the Electronic Musical Instrument Survey. The aim of the survey was to gather data on DMI performance practice across different communities. 85 musicians responded, 62 of whom actively use digital and electronic instruments in performance. The online questionnaire collected information about the respondents' musical training and background, current performance practice, details and opinions on the instruments they use, and perspectives on the uptake, continued use or abandonment of new instruments.

The workshop responses were analyzed using a thematic analysis approach offered by Braun and Clarke (2006) which provided varied methods for different parts of the survey. Data was first coded and classified using a bottom-up, exploratory approach to identify desirable and undesirable qualities of DMIs. Then a top-down analysis was applied to one section of the survey that contextualized responses within a framework for user engagement, taken from theoretical research on human-computer interaction (HCI) and psychology. In a final step, a separate exploratory analysis was conducted to crosstabulate key performance attributes that could help to identify differences between different practices. Results of the complete survey analysis are presented as a list of considerations for designers to better understand the needs and desires of active performers.

1.3.2 Design for Performance

The second phase of research occurred in two parts. First, two design workshops were held with expert musicians who actively perform with DMIs. The workshop structure was adapted from the "Magic Machine Workshops" developed by Andersen (2017), where participants built non-functional musical instrument prototypes from basic crafting materials. The methodology draws on existing techniques and approaches to early stage design such as paper prototyping (Sefelin et al., 2003), focusing on the use of *design fiction* to explore a problem space through the crafting of fictional narratives and prototypes (Blythe et al., 2016). The workshop results, which included video-recorded presentations and discussions with the participants, were analyzed with the same thematic analysis methodology used previously with the survey. Several key design elements were identified towards the development of new DMIs that the participants would want to use in their own performance practices. These key elements were then used to develop several design specifications for the creation of three new functional instruments.

In the second part of this phase, the design specifications were applied to the design for three new DMIs based on a family of existing instruments called Noiseboxes. The Noiseboxes provided a well-developed framework for building embedded acoustic instruments, which are self-contained instruments that possess an onboard processor for computation and sound generation, embedded sensors for performance control, onboard sound generation and battery power for stand-alone performance. The work for this section applied practice-based methods drawn from existing DMI literature as well as our own personal technical experience, utilizing and developing tools and techniques for rapid prototyping of hardware and software.

1.3.3 Designing musical interfaces for professionals

The final phase of research in this thesis is comprised of a long-term collaboration with a professional concert harpist to explore methods for augmenting acoustic harp performance to develop a live solo electroacoustic performance setup. The work occurred across two distinct projects. In the first we investigated movement and gesture in harp playing through a motion capture study. The resulting analysis provided a basis for the design of a gesture control system comprised of small hardware gesture controllers worn by the performer and a software interface to connect the devices to live performance software, which was used in professional live performances.

The second project followed with a new set of design specifications taken from lessons learned from the first project along with Tibbitts' ongoing development of her own artistic performance practice. Our design objective was to physically augment the harp itself to better integrate the control interface with the natural performance movements of the harpist. Multiple methods for early ideation and prototyping were utilized in an iterative approach that led to the production of two isomorphic controllers that have been successfully integrated into the harpist's professional practice, which has included a high profile audiovisual performance at a well known international festival.

The methods for both projects in this phase were based in HCI and design, and revolved around artistically-driven practice-based research. Building from the approaches to hardware and software prototyping and production that were developed during the design of the Noisebox-based instruments, the work here has refined a methodology for the robust development of stable DMIs, especially towards the design of wireless interfaces for augmenting acoustic instruments. In particular, this work focused on the particular requirements for instruments to be viable in professional contexts, as evidenced by their successful implementation into practice.

From general purpose to bespoke instruments

While the move from phase two (design workshops) to phase three (collaboration with a professional performer) allowed for continued development of design and fabrication methods, it has also facilitated investigation of different perspectives on DMI design. The design workshops explored prospects for the development of new instruments based on a set of specifications intended to meet general needs and criteria of a variety of performers. Alternately, work in the third phase was largely focused on bespoke design for specific use cases, and especially with the final project's design of custom hardware controllers fit to the performer's instrument, was based on the specific and individual needs of a single performer. While this mode of DMI design and use is common in NIME, it is much less frequent in more widespread performance communities that use digital instruments. Thus both approaches provide different insights into factors for uptake and long-term use of new instruments in different scenarios, and contribute a broad perspective on DMI design and performance.

1.4 Contributions

This dissertation aims to present outcomes that are theoretical, methodological and practical in nature. Insights and immediate contributions are drawn at the close of each chapter. In the final chapter, the outcomes are gathered together into a full set of contributions relating back to the research questions introduced in Section 1.1.

Theoretical: While the research presented here has been largely practice-based, I have actively examined and engaged with existing theories from HCI and design, and can offer updated information and theoretical models in particular areas. One area is through the investigation of user engagement with DMIs, in which two existing models of engagement, one short-term and one long-term, were applied to survey data on the uptake and longitudinal use of new instruments, which led to a unified model for engagement with DMIs. A second area of contribution concerns theoretical design frameworks, especially linking idea generation to design outcomes, to which I can offer experience-based insight. Additionally, I share additional perspective on the process of collaborative arts-based design research.

Methodological: From a methodological perspective, I have actively applied formal methods for several different activities within the DMI research and design ecosystem and beyond, including qualitative data analysis, design workshops, digital prototyping and hardware and software development. Based on my own implementation and adaptation of existing methods in these areas, I offer a road map for the practical development and production of stable, performance-ready DMIs that are catered towards the unique demands of professionals.

Practical: Finally, the theories and methods explored in this dissertation have been applied to the tangible design and manufacture of functional musical instruments for professionals. I provide two sets of practical information for perspective designers. First, findings from the Electronic Musical Instrument Survey provide organized and practical information about DMI performers that can be considered in the design process. Second, through applied practice and firsthand experience, I can provide technical and procedural information and resources for the development and manufacture of DMIs in the areas of early low-fidelity prototyping, computer-aided design, hardware fabrication and embedded instrument design.

1.5 Thesis Structure

To accommodate the manuscript format of this dissertation, a separate literature review is conducted for each of the three studies at the beginning of **Chapters 2**, **3** and **5**. They cover the relevant literature and provide theoretical and methodological background for the work that follows.

Chapters

- In **Chapter 2** the Electronic Musical Instrument Survey is presented. The analysis results are compiled into a list of considerations for designers to consider in the development of DMIs intended for use by active and professional performers.
- In **Chapter 3** the Design for Performance workshops are presented, in which expert musicians developed fictional prototypes of instruments they would want to use in their own practice. Through analysis of workshop presentations and discussion, key design elements are identified, from which are drawn a list of

design specifications for the development of new DMIs.

- **Chapter 4** represents the second half of the Design for Performance study. The design specifications generated from the workshops are applied in the development of three new instrument prototypes based on a technical framework for embedded musical instruments called Noiseboxes.
- In **Chapter 5** a long-term collaboration between myself and a professional harpist is presented, in which we conducted research, and designed and implemented two distinct systems for augmenting the concert harp to be used in live solo electroacoustic performance.
- In **Chapter 6** I summarize the methods and results of the research I have presented. I reflect on my three main research questions, enumerating the contributions of knowledge that this dissertation intends to provide. I discuss the limitations of the current work and indications for future research, both for myself and other researchers in the field. Finally, I provide closing remarks on the unique challenges of, and prospects for, designing novel instruments that can be successfully taken up into professional practice.

Appendices

- **Appendix A** contains the survey questionnaire from the Electronic Musical Instrument Survey presented in Chapter 2.
- **Appendix B** contains the codebooks and crosstabulation results from the thematic analysis of the Electronic Musical Instrument Survey in Chapter 2.
- **Appendix C** contains supplementary materials related to the Design for Performance workshop presented in Chapter 3, including the workshop schedule and script, results of in-workshop activities, and analysis results of the workshop presentations.

- **Appendix D** contains the McGill University Research Ethics Board II (REB II) ethics approval certificates that were issued for the research undertaken in this dissertation.

Chapter 2

Surveying DMI Use in Active Musical Practice

This chapter is based on the following research article:

- Sullivan, J., Guastavino, C., & Wanderley, M. M. Surveying Digital Musical Instrument Use in Diverse Performance Communities. (submitted)

Abstract

While research on the design of, and performance with, new digital musical instruments is well established, it has been frequently noted that most new designs fail to make it into sustained use in the hands of active and professional musicians. To provide designers with clear insights about performers who use novel technologies in their practices, a survey of active musicians was conducted, yielding a set of design considerations and attributes for user engagement that can be applied in the design of instruments that are viable for real-world active and professional performance contexts.

2.1 Introduction

The field of novel digital musical instrument (DMI) design, and much of the music technology domain wherein it resides, relies on the existence of musicians that actively engage in musical practice. Simply put, new instruments need people to play them. In particular, DMI designers would seem to be especially dependent on performers who would take up novel instruments and engage with new technologies and methods of music-making. The relationship between design musical practice can be mutually beneficial, as innovations in instrument design can inspire new musical practices, while evolving performance techniques and styles can inform design research in new directions.

However, scholars have repeatedly shown that most DMIs have short life spans. Many fail to make the jump from initial designs and prototypes to finished instruments put to service in real-world musical applications. One issue lies in what McPherson and Kim (2012) call "the problem of the second performer", which highlights the significant challenge of building a community for a new instrument beyond an initial single user. To compound the issue, a NIME survey by Morreale and McPherson (2017) found that design of new DMIs is frequently carried out in service to specific research-based inquiries, resulting in technical probes and prototypes that are never intended to be put to real-world musical use.

More general issues with DMI adoption and longevity have been suggested as well: Mamedes et al. (2014) proposed three primary reasons for relative scarcity of established DMIs in use: new instruments lack established playing techniques; new forms of musical notation are needed to accommodate novel forms of musical output with new DMIs; established repertoires don't yet exist for new instruments. However, there may also be evidence to the contrary. A study by Marquez-Borbon (2020) found that playing techniques can be quickly developed within a small group, and notation and repertoire are not always required or expected in many performance communities.

2.1.1 What are DMIs, and who uses them?

The technical definition of a DMI is relatively straightforward, designated by Miranda and Wanderley as "an instrument that uses computer-generated sound... and consists of a control surface or gestural controller, which drives the musical parameters of a sound synthesizer in real time" (Miranda & Wanderley, 2006, p. 1). In practice, the term is most commonly associated with non-commercial, atypical musical instruments and interfaces that are not generally found in mainstream music performance. This constrained scope tends to be transferred to the prevailing research on DMI users as well, with most scholarship on DMI performance situated within academic and experimental music contexts. However, beyond these focused communities there is a diverse ecosystem of performers who use novel instruments and interfaces that may fit the technical definition of a DMI but not the typical social and cultural context associated with the term.

While studies of DMI-centric musical practice are valuable, they may fail to capture unique and diverse perspectives coming from other communities. For example, electronic dance music (EDM) and hip hop producers, DJs, experimental rock bands and modular synthesizer enthusiasts are just a few highly active areas of practice that rely heavily on existing and emerging digital technologies for performance, but are not typically included in the discourse around DMI design and practice. Input from these groups can broaden the understanding of where and how new instruments and technologies are being used in different contexts, and ultimately inform the design and evaluation of new DMIs towards their successful and long-term use in more widespread active musical practices.

In this chapter we describe our work to identify and characterize DMI use across diverse musical practices via an online survey of musicians, with an aim to develop a set of design heuristics to aid the uptake of new instruments. we begin with a discussion of performance communities in Section 2.2, starting with a review of research focused on the NIME community, then looking beyond to consider DMI use in broader contexts. In Section 2.3 we review past DMI surveys, including a short preliminary survey of our own. We then introduce the main contribution of this chapter, the Electronic Musical Instrument Survey. The methodology is presented in Section 2.4. We report the results in Section 2.5, providing analysis on the respondents' impressions of the instruments they use, factors for uptake and long-term use of DMIs based on a conceptual framework for user engagement, and an extended analysis to relate findings to specific performance characteristics of musical style and level of activity. Finally, in Section 2.6 we consolidate our to present an updated report on DMI use across both NIME and popular music communities and offer suggestions for instrument designers to facilitate the uptake and long-term use of novel DMIs across diverse and active performance practices.

2.2 Communities of practice, communities of interest

2.2.1 NIME and DMI research communities

One of the most compelling attributes of the DMI design community is that it overlaps a great deal with the performance community. This is readily apparent in NIME, the annual conference dedicated to "publishing and discussing pioneering artistic and technical endeavours" ("NIME Conference 2020", n.d.) on new musical interface design.

Historically, *community* has been frequently discussed in NIME literature without formal definition. As such, the term merely signifies some grouping of researchers or practitioners sharing a common pursuit or interest. Without a better framework for delineating and characterizing different communities, we may lack the tools to adequately examine some of the key ways that communities form and interact, and to understand strategies for building and sharing knowledge.

Communities of practice

Communities have been a topic of considerable interest more recently. Marquez-Borbon and Stapleton (2015) examined the notion of community within NIME through the *community of practice* (CoP) framework. The term "community of practice" comes from the social sciences and was first coined by Lave and Wenger (1991). CoPs are described as "groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly" (Wenger & Trayner-Wenger, 2015, p. 1) and possess three essential characteristics: 1) the community's identity is defined by a shared domain of interest; 2) members of the community engage in joint activities, share information and knowledge, help and support other members, and learn from one another; 3) the community is composed of practitioners who share a repertoire of resources.

Of particular interest is how teaching and learning is carried out in CoPs and how this relates to the domain of DMI design and performance. The CoP model is closely related to the situated learning framework by Lave and Wenger (1991), in which "knowledge is inextricably a product of the activity and situations in which it is produced" (Marquez-Borbon & Stapleton, 2015, p. 308), as opposed to *formal learning*, where the exchange of knowledge is separate from its actual use in practice and carried out in controlled teacher/class environments.

Communities of interest

While learning is a key component in characterizing the community, another important consideration is the range of activities that goes on in the NIME community. In this regard, Marquez-Borbon and Stapleton observe that NIME may alternately be characterized as a *community of interest* (CoI) (Fischer, 2001), a "community of communities" in which a common task is approached by practitioners from different disciplines (e.g., HCI, design, computer science, engineering, hacking/making, music composition and performance, etc.).

The interdisciplinary nature of NIME research sees practitioners freely operating across and between disciplines. However, the CoI structure may also be problematic. When knowledge is tacitly distributed across different disciplines, a condition is formed where stakeholders each "possess an important and yet incomplete understanding of the problem" (Fischer, 2001, p. 2), known as a *symmetry of ignorance*. Differing perspectives and vocabularies coming from different domains may further obfuscate the common task of a community.

On the other hand, with different disciplines engaged it is no surprise that there is no single common task in NIME. Cantrell (2017) extends the CoP/CoI analysis by identifying five distinct areas of NIME research practice: Practical Research, Artistic Performance, Hacking/Making, Commercial Production, and Self Reflexivity. Cantrell provides examples of previous NIME projects that engage these different areas to greater or lesser extents, where scientific research mixes freely with creative practice, illustrating the wide diversity and interdisciplinarity found within DMI research.

2.2.2 Focus on communities of performance

So far our review of NIME and related research shows a strong interdisciplinary community actively involved in many facets of DMI design and performance. In the next section we review how surveys have been used in these communities to identify and illuminate DMI practice, in preparation for our own survey. We make a general initial observation here, and a key distinction in the aims of our own study: while design and performance roles are deeply interrelated in research-based communities like NIME, this is largely not the case in more active and professional music communities that are not research-based. Generally speaking, performing musicians perform, and leave the design and development of new instruments to others. Therefore, as we prepare our own survey that might inform a performance-centered DMI design methodology, we are interested to isolate performance from design, and focus specifically on these aspects of communities using DMIs.

2.3 Past surveys

In the interest of providing designers with better tools and more information to aid the creation of new instruments, researchers have utilized questionnaires to survey performers about the use of DMIs in their musical practice. In this section we review methods and results of several previous surveys, which provide a basis for the formulation of our own survey in Section 2.4.

2.3.1 Dual performer-designer roles

An online survey was conducted by Magnusson and Hurtado (2008) to investigate the embodied connections between performers and their instruments, and contrast between acoustic and digital instruments. A call for participation was circulated across several audio programming mailing lists and by the time of first publication, the survey had received over 200 responses. Given the focus on audio programming, which included an optional evaluation section on the authors' own audio software, *ixi*,[1] questions around digital instruments were mainly focused on software and excluded specific discussion about hardware such as physical input devices or embedded instruments.

Two particular findings of the survey highlight the specialized nature of the DMI user community that was investigated. First, respondents prize the ability to easily create and modify digital instruments, mainly via editing software and writing code,

[1] http://www.ixi-audio.net

according to specific needs of a performance or composition. These "easy" designs and modifications require advanced non-musical skillsets, most importantly computer programming skills, that are not possessed by many musicians. Furthermore, it shows that many of the respondents identify as instrument designers as well as as performers.

Second, the respondents tended to be more critical of digital instruments than their acoustic counterparts. Entropic (non-deterministic) characteristics of digital instruments were generally considered to be flaws or errors in the system, whereas entropy in acoustic instruments was regarded favorably as giving the instrument character leading to discovery of new sounds or playing techniques. This outlook indicates a *design-centric* evaluation of an instrument, understandable given that most respondents were instrument builders themselves and well-versed in the craft of the field.

The Taxonomy of Realtime Interfaces for Electronic Music Performance (TIEM) survey was subsequently conducted by Paine (2010), which consisted of an online questionnaire for DMI designers and performers to submit information about the instruments they had designed or use in practice. At the time of first publication (2009), 70 complete responses had been received and a public website was created containing a database of the submitted DMIs.[2]

As with Magnusson and Hurtado's survey, respondents identified as both performers and designers. Furthermore, they varied in how they thought of or referred to the systems they were discussing: instruments, interfaces, compositions, or something else. The authors observed that the "notion of interface/instrument considered also in terms of a composition, while familiar to those working in the area, is of course radically different from the concept of a traditional acoustic instrument" (Paine & Drummond, 2009, sec. IV para. 6). Again this illustrates how select and idiosyncratic typically studied DMI performance communities are.

[2]The TIEM website and database are no longer online.

2.3.2 Surveying the NIME community

A pair of surveys by Morreale and McPherson (2017) and Morreale et al. (2018) elucidate some of the limitations around performance and the continued use of DMIs over time. The first surveyed instrument makers whose instruments had been presented at the NIME conference over several years. This was followed by a survey of NIME performers to explore and understand the roles of DMIs in their practice and understand common values among performers. They confirmed that a majority of new DMIs fail to be developed or used beyond their initial design and infrequent use in actual performance, and identified a few primary factors contributing to this trend: DMIs are often designed as research probes or works-in progress not intended for real-world use; instruments are most frequently used by only one or two performers (and most often the primary/only performer is the designer); instruments frequently suffer from maintenance and reliability issues; perspective performers lack the opportunity to use them in performance.

Common themes that were identified around the use of DMIs included the desire for bespoke instruments that could meet personalized and idiosyncratic needs most commonly associated with performing experimental and exploratory styles of music. Consistent with the other surveys discussed in this section, they also found that most (78%) of the performers who responded had designed their own instrument.

2.3.3 Investigating DMI performance beyond NIME

The studies discussed above illustrate an active, engaged, and highly skilled community of performers, researchers and designers moving frequently and fluidly between these roles. As such, they embody both the technical/engineering and creative artistic roles of DMI practice, and contribute greatly to innovation in both instrument design and expanded musical practice.

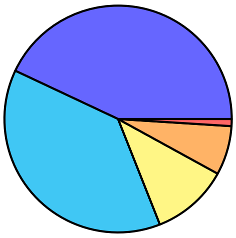


Fig. 2.1 Musician roles of respondents from our preliminary survey, with number of responses in parentheses *(N=100)*.

These types of practices are well represented in the literature and in the academic research community at large, most notably NIME. However, the use of novel digital instruments and technologies in performance is common beyond these typically surveyed communities as well. Whether by virtue of certain instruments' mass appeal and commercial availability, or their appropriation by more conventional and mainstream music styles, perspectives from more populous and highly active communities of digital instrument users are seldom included in DMI user research.

In a previous study I had conducted a preliminary survey about musicians' use of technology across different performance communities (Sullivan, 2015a). Musicians of all kinds were invited to complete the survey, with a call for participation circulated across several different academic and community mailing lists and social media platforms. 100 valid responses were collected, mostly from professional and amateur musicians, with fewer from academic circles (Figure 2.1). The survey contained questions about respondents' background, instrument choices, musical styles performed, as well as experiences with, and attitudes towards, new DMIs. Overall the participants represented a diversity of musical styles, and their primary instrument choices were highly conventional, illustrating a trend toward more popular modes of music performance (Table 2.1).

The objective of this survey was to gain a general overview of trends in DMI use among different performance communities in order to identify areas of focus in prepa-

Musical styles played	**Responses**
Experimental/avant-garde	24%
Rock/popular	22%
Other *(mainly rock sub-genres)*	15%
Classical	14%
Jazz/blues/R&B	7%
Acoustic/folk/country	7%
Electronic/EDM/House	5%
...5 other styles	<5%

Primary instruments	**Responses**
Guitar	66%
Piano	47%
Bass	33%
Drums	23%
Voice	22%
Keyboard	17%
Percussion	12%
...41 other instruments	<12%

Table 2.1 The most common musical styles played *(left)* and primary instruments used *(right)* by respondents from our preliminary survey. Respondents could give multiple answers in both categories.

ration for our current survey. The questions were mostly closed-ended (multiple choice and numerical) to allow for efficient quantitative analysis. However, some of the free-format answers provided especially useful and provocative information for further study in two particular areas.

First, performers' integration of digital musical instruments and related technologies varied dramatically based on musical style. More specifically, a clear distinction was shown between users of noncommercial technology (including DIY instruments and interfaces, user-programmed software, research-based prototypes, and experimental instruments) and commercially available mass-marketed hardware and software instruments. In contrast to previously mentioned surveys, in which most participants used noncommercial instruments, in this survey, with rock and popular music styles more heavily represented, commercial instruments and interfaces were much more predominant.

Second, responses showed that basic issues of instrument *stability*, *reliability*, and *compatibility* (with other instruments, performers and industry standards) are primary factors that lead to the abandonment of new instruments and technologies. This motivated a separate study in which a meta-review of DMI design literature was conducted to identify essential qualities necessary for DMIs to be viable for use in professional performance situations (Sullivan & Wanderley, 2018).

2.4 The Electronic Musical Instrument Survey

Following our previous work, we were interested to conduct a more comprehensive online survey that again targeted performers across a wide variety of performance practices and focused on factors that contribute to uptake and long-term engagement with new DMIs in performance. Additionally, we wanted to understand what types of performers were using DMIs and how behaviors and preferences vary between different communities.

To do this, we created the Electronic Musical Instrument Survey, an online survey for performing musicians. To encourage participation by performers from diverse musical practices, we chose to use the term *electronic musical instrument* (EMI) as a generic and inclusive name for various overlapping terminologies used in the field such as DMI, NIME, computer-based instrument, interface, controller, etc. By avoiding domain-specific jargon we hoped to make the survey accessible and applicable to anyone who might choose to take it.

2.4.1 Participant criteria and recruitment

The survey was open to all performers, with no specific requirement that they use electronic musical instruments (EMIs) in performance. The questionnaire was conditionally formatted so only those who reported using EMIs were directed to the relevant sections. Participants were required to be 18 years of age. Beyond that, the only requirement was that respondents identified themselves as “active musicians”. As an incentive for participating, respondents were invited to enter a drawing for a $100 CAD gift certificate to an online music retailer.

The call for participation was sent via the following channels:

- McGill University Schulich School of Music Student mailing lists
- University of Montreal Music Faculty Student mailing lists
- Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT)[3] regular and student member mailing lists
- Eastern Bloc New Media and Production Centre[4] mailing list and social media
- New Music World[5] mailing list
- social media (Facebook, Twitter and Instagram, shared and reposted by friends and colleagues in music performance circles)
- circulated by colleagues in academic and music performance communities

2.4.2 Questionnaire

Our previous survey had used mostly closed-ended and short-answer questions to both minimize the length of time to complete the survey (and in doing so, maximize the number of respondents) and to optimize and automate analysis of the data. For this survey we chose to ask more open-ended questions and with a focus on qualitative methods of analysis to collect richer data about performance practices.

Organized in two parts with multiple sections, the survey contained several different elements intended to gather a wide range of data about DMI performance across different types of performance communities. Table 2.2 provides an overview of the sections and questions. The questionnaire is included as Appendix A.

In part one, sections 1A and 1B collected demographic and background information about the respondents and their musical training, including how long they had been playing music, details on formal training, areas of focus, and experience with computer

[3]https://cirmmt.org

[4]https://easternbloc.ca

[5]New Music World was a community-based online resource for global new music events and content, founded by Joel Chadabe and affiliated with the Electronic Music Foundation Institute (https://emfinstitute.org/). It was retired in 2019.

Sections and Subsections	Questions
1. Performance Practice	
A. Background info	1 - 3
B. Musical training and experience	4 - 6
C. Performance practice	7 - 12
2. Electronic Musical Instruments and Controllers	
A. Use of electronic musical instruments and controllers	13 - 15
B. Description and functionality	16 - 24
C. Acquisition and continued use	25 - 30
D. Conclusion	31 - 32

Table 2.2 Overview of sections and questions in the EMI Survey. The full questionnaire is included in Appendix A.

programming and electronics. Section 1C asked asked about their performance practice: primary genres and sub-genres of music that they perform, frequency and types of performance, what kinds and sizes of venues, if they play solo or with groups/ensembles, and what kinds of instruments and setups are used.

Part two of the questionnaire was dedicated to the use of electronic musical instruments and controllers. Because the survey was open to all performers, it started with a filter question, "Do you use electronic musical instruments in performance?" If a respondent answered no, the survey concluded at that point. If they answered yes, they moved to section 2A, which asked about the types of instruments and controllers they use. In section 2B, they were asked to give information about the instrument or controller they use the most, and could repeat the section up to three times to give information on multiple instruments. Section 2C contained several open-ended questions about the respondent's opinions on acquisition and continued use of EMIs.

In total the survey contained 32 questions, though the exact number a respondent might answer varied, based on conditional logic that would skip or reveal additional questions depending on respondents' answers to certain questions. Respondents were allowed to skip any questions they didn't care to answer, and we estimated it would take between 10 and 30 minutes to complete.

2.4.3 Data collection and processing

A website was built to host the survey and put online at the domain https://emisurvey.online. [6] The survey was open for two months. While it ran, responses were saved to a database on the web host server.

Respondent identities were kept anonymous. Names and other personally identifying data were not recorded on the survey. Email addresses, which were collected if the participants wished to participate in the gift certificate drawing, were removed from the dataset before analysis.

When the survey concluded, the full dataset was downloaded from the website database as a .csv file and imported into Microsoft Excel for initial processing and data cleanup. The data was visually inspected and any invalid entries (including abandoned or nonsense entries) were removed. Any email addresses that were collected were moved to a separate key file and associated with a corresponding participant ID code (P01 - PN).

2.4.4 Analysis methods

The initial approach for analysis was to use a grounded theory methodology (Strauss & Corbin, 1994). However, while the basic tools of data coding and classification were appropriate, the formalized methodology of theory development felt too prescriptive for our initial open-ended exploration of the data. Instead we conducted a thematic analysis, as defined by Braun and Clarke (2006), which uses similar tools for coding and identification of themes, while remaining flexible and adaptable for the specific contexts in which it is applied.

[6] The website is archived at https://emisurvey.johnnyvenom.com.

The analysis was organized in three parts. First, responses were coded and classified responses around the respondents' descriptions and impressions of the electronic and digital instruments they use in performance. The process was *inductive* (Creswell & Creswell, 2018), and several themes emerged around what types of performers use DMIs, characteristics of their performance practice, instruments used desirable features and attributes of DMIs. Braun and Clarke characterize this part of the analysis as *semantic*, in that the themes were drawn directly from the data and we did not attempt to interpret the participants' responses or make implicit assumptions about their meanings beyond what they had written.

Part two of the analysis identified factors that influence uptake, long-term use, and retirement of instruments. Responses to this specific section of the survey were coded using a top-down, *deductive* approach (Creswell & Creswell, 2018) to contextualize the results within a conceptual framework based on short- and long-term models of user engagement found in literature. Short-term engagement is taken from O'Brien and Toms (2008) where engagement is described across the four stages of *initial engagement*, *sustained engagement*, *disengagement* and *reengagement*. While not absolute, the model is mostly oriented to a event-level time scale, describing engagement attributes during a single activity. While this is relevant in the context of musical instrument use, the survey is also interested in long-term engagement and factors that influence performers' retention and continued use of instruments (or alternately cause them to retire or abandon them). To address this, a study of longitudinal instrument use by amateur musicians (Wallis et al., 2013) was consulted, which identified attributes for long-term engagement. Despite the different time-scales of the two models, there was considerable overlap between them and this section of analysis yielded an integrated model that was applied to the survey data.

In part three, as a follow-up to our main thematic analysis and investigation for future work, we crosstabulated the results from the previous steps across different respondent attributes to explore variations between performance communities.

The analysis was carried out using Nvivo qualitative data analysis software (version 12 for Mac, by QSR International)[7], with additional steps carried out in Excel. The codebook for our thematic analysis and spreadsheets for the crosstabulation analysis can be found in Appendix B.2.

2.5 Results

Here we report the results of our survey. As the survey contained multiple sections and varied approaches to analysis, for each grouping of results we list the corresponding survey section(s) (and questions where necessary) that the results are based on. For reference, an overview of the survey is shown in Table 2.2 from Section 2.4.2.

2.5.1 Preliminary findings

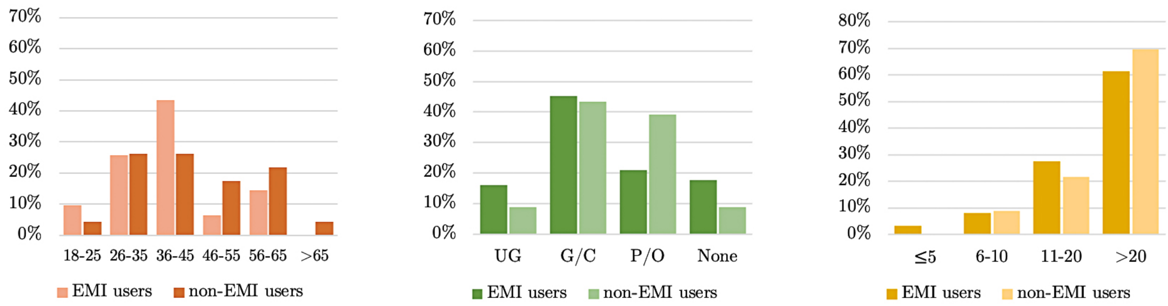
Demographics (Sec. 1A, 1B)

A total of 85 people responded (M=60; F=22; other/not specified=3). 73% of respondents *(N=62)* reported that they use EMIs in their performance practice, while 27% *(N=23)* stated that they do not.[8] Respondents were primarily North American and European, reflecting the main geographic areas where the survey call was circulated.

Figure 2.2 shows age, musical training, and performance experience distributions for respondents who use EMI and those how don't. Overall the survey population is highly experienced. 89% of all respondents reported that they have been performing for more than 10 years (64% more than 20 years). 85% have received formal training, with

[7]https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home

[8]We note that this was self reported and was subject to the respondents' interpretations of what constitutes an EMI, something that we revisit in later sections.



(a) Age (b) Formal training (c) Years performing

Fig. 2.2 Percent of respondents by age, formal training and years of experience performing for EMI users *(N=62)* and non-users *(N=23)*. Categories of formal training for Figure (b) are: *UG: undergraduate, G/C: graduate or conservatory, P/O: Private instruction or other, None: self taught.*

more than 40% having studied music at or above graduate level. The distributions vary somewhat between EMI users and non-users, though overall they are largely consistent.

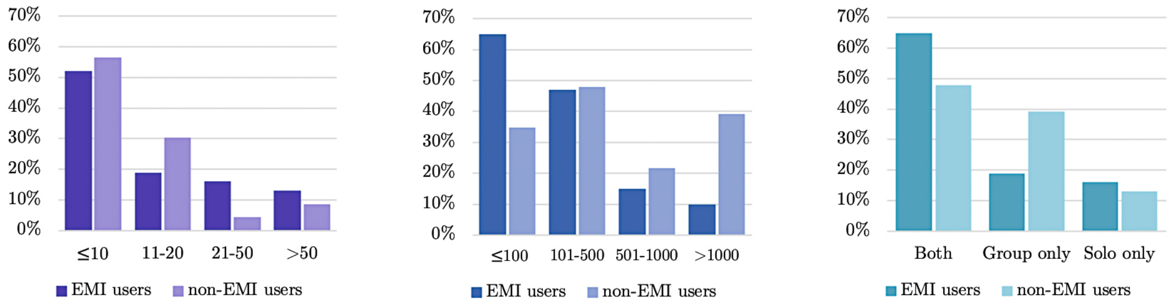
Performance practice (Sec. 1C, q9-11)

As shown in Figure 2.3, there was a wide range of diversity in the frequency and type of performances across respondents. More than half of all respondents perform publicly 10 or fewer times per year. Average audience size varies from less than 100 to over 1000, with EMI users more likely to perform for smaller audiences and much less likely to perform for large audiences. Most respondents perform in groups, at least part of the time. Only a small percentage of respondents perform solo exclusively, while EMI users are somewhat more likely than non-users to perform in both contexts.

Musical style (Sec. 1C, q7 & 8)

To classify musical style, we used a list of genres from AllMusic, an online music database,[9] with some revisions to reflect some of the anticipated nuances and particularities of our expected respondents. For instance, *electronic* may mean very different

[9] https://www.allmusic.com/genres



(a) Performances per year (b) Average audience size (c) Group/solo performance

Fig. 2.3 Percentage distributions of EMI users *(N=62)* and non-users *(N=23)* for three performance metrics. Multiple answers could be chosen for Figure (b).

things to popular or experimental musicians, so we separated it into *EDM* (electronic dance music) and *electroacoustic*. Respondents were asked to select up to two main styles from the list and could write in other styles or sub-genres in an additional open text field. To facilitate our analysis, the totals for musical styles were adjusted to include any sub-genres or written-in styles that we felt belonged to the given categories if they hadn't already been reported by the respondent. Examples included assigning *"house, drum'n'bass, jungle, progressive techno"* to EDM and *"alternative, post-rock, indie"* to pop/rock. Figure 2.4 shows the musical styles reported by EMI users and non-users.

There are two important things to note around the selection and categorization of performance styles and ramifications for our study. For one, while our list of styles adapted from AllMusic aims to be comprehensive, it is admittedly Eurocentric in both scope and categorization, and a comprehensive list of styles originating from a different geopolitical worldview would likely look much different. Furthermore, self-identification of musical style and genre is highly subjective and similar musics may be assigned to different categories by different respondents. We keep these points in mind throughout the analysis, noting where they could influence our findings.

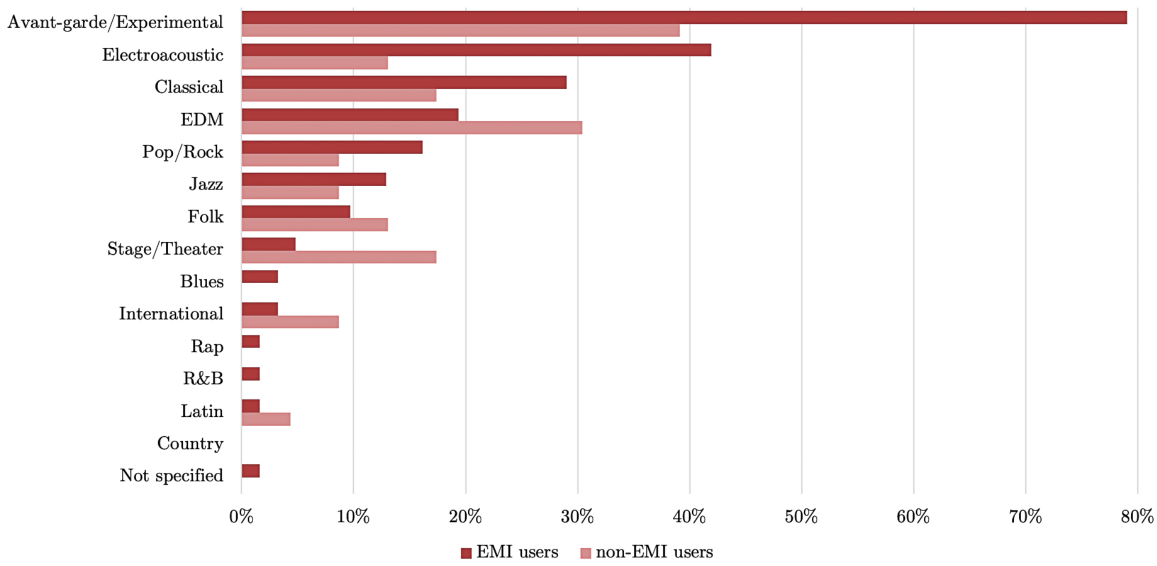


Fig. 2.4 Percentage distributions of EMI users *(N=62)* and non-users *(N=23)* by musical styles performed.

Use of electronic musical instruments (Sec. 2A)

In the second half of the survey, participants were asked if they use electronic musical instruments (EMIs) in performance. Of the 85 total respondents, 23 (27%) answered that they do not, bringing them to the end of the survey. The remaining 62 participants continued to the second half of the survey, where they identified and gave information about their their primary electronic instrument(s) (up to 3), and responded to general questions about instrument uptake and longitudinal use. The instruments were categorized and are shown in Figure 2.5.

The 62 respondents who use EMIs comprise a diverse group of performers active in a variety of different types of practices. All play multiple instruments, and most play a mix of conventional instruments and digital/electronic instruments and interfaces, as well as using computers extensively for their performance setups. While many respondents play infrequently and to smaller audiences, several reported having active practices that include more frequent performances and larger venues. There is a wide musical diversity

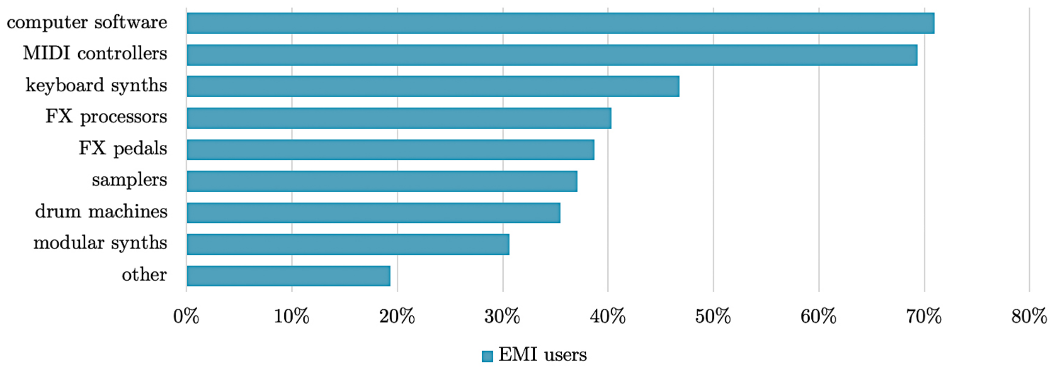


Fig. 2.5 Percent of EMI users *(N=62)* who use each type of electronic musical instrument (EMI).

as well. Most perform avant-garde and experimental styles, however this varies widely from one performer to the next. The other reported styles fall across a range of genres from art and folk to popular musics. The topics of active performance and musical style are further addressed in the final stage of our analysis (in Section 2.5.4).

2.5.2 Instrument qualities, features and issues (Sec. 2B)

In the first part of our thematic analysis, we analyzed responses to questions about the EMIs that performers use: likes and dislikes, desirable and undesirable features, how they configure and use their instruments, overall satisfaction and suggested improvements. The first round of analysis yielded an initial set of codes, which we organized into similar groupings. The coding process was repeated, checking our initial codes and revising them where appropriate. Once complete, we were able to further organize our findings into broader categories out of which we could identify several emergent themes.

For this section of the survey, we classified the coded responses into three groupings: 1) recurrent quality attributes, 2) requested features, and 3) instrument issues. The first grouping was further classified into four general categories: *handling complexity*, *accommodation*, *appropriation*, and *other qualities*. Table 2.3 shows the most frequently mentioned qualities, features and issues. (The full codebook is included in Appendix B, Section B.1.)

Recurrent Quality Attributes

Handling complexity		Accommodation		Appropriation		Other qualities	
flexibility	48%	size/portability	29%	embodiment	23%	sound quality	26%
simplicity	21%	playability	19%	personalization	24%	cost/affordability	15%
		compatibility	16%			aesthetics	10%
		ease of use	13%				

Requested features	
added features/functionality	19%
more/improved controls	19%
more/improved connectivity	18%
high-level programming	6%
better feel/ergonomics	5%
feedback	5%

Instrument issues	
broken bits, knobs, keys, etc.	18%
software issues	15%
limitations of hardware	10%
cables and connections	6%
poor overall quality	6%
general computing devices	5%

Table 2.3 Most frequently mentioned EMI recurrent quality attributes, requested features and instrument issues. Percentages refer to percent of total respondents *(N=62)* with responses coded at each item.

Handling complexity: The most commonly cited quality quality mentioned was flexibility and versatility, mentioned by 48% of respondents. This means different things to different performers. For some the reasons are economical: *"A machine that does one thing very well is half as good as something that does 10 things reasonably well" (P84).* For others, flexibility and versatility affords greater creative freedom and expression in performance: *"The highly flexible modular design . . . allows me to build many possibilities out of the same instrument" (P35).* Also mentioned was the ability to configure or program the instrument more deeply: *". . . versatility to add any code and modify the instrument's behavior" (P13).*

On the other hand, 21% of respondents value simplicity, citing the effectiveness, ease of use, and dedicated functionality of an instrument: *"It's all very simple and, dare I* *say, primitive, which is why I like it" (P59).* These differing points of view were also reflected in a separate question that asked whether respondents preferred computers or dedicated hardware. Responses were divided between those who favor the versatility and configurability of computers and those who favor dedicated hardware, while many replied that it depends on a number of different factors.

Accommodation: 53% of respondents specifically commented on the way their instruments accommodate their performance practices. Size and portability was most frequently mentioned, by 29% of respondents (also making it the 2nd most frequently mentioned attribute): *"It's compact, lightweight and versatile" (P73)*; *"... can go inside my bassoon case" (P58).* Playability was second most common in accommodation (19% of respondents), which included mentions of expressiveness, articulation, control and ergonomics. Additional accommodation qualities were compatibility and interoperability with other instruments, softwares and setups, and ease of setup and use.

Appropriation: Two general categories of appropriation were frequently mentioned: embodied connections (24%) and personalization (23%). For embodied connections, respondents spoke favorably of tactile and physical interactions with their instruments, citing control, material connection and "muscle memory" with an instrument that enhances their performance. For personalization, many mentioned configurability and programmability of their instruments that leads to "ownership" of highly customized instruments and multi-instrument setups. Some respondents expressed deep appreciation and even affection for their instruments: *"It's just part of my family. I love it unconditionally for it's qualities which both assist me in achieving a sound and for it's limitations which push me to think about things critically and inspire me to solve problems and become a more versatile and capable artist" (P21).*

Other qualities: Three additional qualities were frequently mentioned that did not fit the themes above: sound quality (26%), cost and affordability (15%), and overall pleasing aesthetics of an instrument such as its look and feel (10%).

Requested features: Responses in this category were mainly focused on incremental enhancements to performers' existing instruments – adding or extending specific functionality, adding to or improving the quality of controls and adding connectivity to interface with other instruments and systems: *"The only thing I would add would be more detailed control of the LFO (controls for the attack, decay, sustain, release) and a better synchronization of the LFO with the internal sequencer" (P88)*; *"I would like the option of outputting control voltages" (P84).* Nearly all requests involved features that currently exist on other instruments, though some described highly specific and technical needs:

> *There are small, modern functionalities that I would very much like to incorporate into the instrument's design. Thankfully third-party hardware engineers have created options available, such as the 208 Toolbox which unlocks additional functionality without requiring modifications to the original hardware. I am presently working with an engineer to further expand the possibilities offered by the 208 Toolbox to suit my needs (adding a noise source and voltage controlled LFO) (P35).*

Instrument issues: Respondents described a wide variety of issues with their current instruments. The most common issue was broken or unstable knobs, buttons, keys, and similar parts. Cables and connections were also points of failure. However, most described putting up with – and working around – these issues and continuing to use the instruments. While software issues (and crashes in particular) were the second most mentioned issue (by 15%), some were particularly sympathetic and forgiving of software: *"Since 2000 I've had exactly 6 crashes on stage" (P46).*

2.5.3 User engagement: Uptake and continued use of new instruments and technologies (Sec. 2B; q25 & 28)

Following our previous survey (summarized in Section 2.3.3), we were particularly interested in identifying factors that motivate performers to take up new instruments in their practices, and factors that contribute to the long term success, or alternately abandonment, of new DMIs. Following initial open coding, we investigated two previous models of user engagement to see how we could contextualize respondents' views within a more formal understanding of both short- and long-term engagement with technology.

The survey included two specific questions related to engagement:

25. What factors influence you to take up a new electronic instrument?
28. On average, how long do you typically use an electronic musical instrument before retiring it? What factors influence you to stop using certain electronic instruments?

Initial open coding yielded a list of themes that we associated to the three stages of DMI referred to in the questions: *uptake*, *longevity* (continued use over time) and *abandonment* (discontinuing use of an instrument). The survey didn't ask a specific question about the factors for longevity, and when mentioned, they were often closely connected (or in opposition to) factors for abandonment. Therefore the themes for this step of analysis are shown in Table 2.4 with these two categories combined, followed by our initial observations.

Uptake: Factors related to taking up new instruments primarily fell into three groups. Novelty and variety was most frequently mentioned with respondents seeking out new sounds, exploring new musical possibilities and expanding their setups. Second, respondents look to upgrade to acquire specific functionality or improve certain qualities of their instruments. Third, respondents cited a number of practical concerns that would

Uptake		
Novelty & variety	new or improved sounds, exploration, expand or diversify performance practice	44%
Upgrading	acquire specific functionality and new features, improve interaction or control	44%
Practical concerns	cost and availability, integration with setup, quality and reliability, size and portability	40%
Influence	saw/heard the instrument played, recommendation	8%
Constraints	simplification, constraints of hardware	3%
Other factors	flexibility and versatility, learning curve and ease of use, same computer/new patches	19%

Longevity & abandonment	
never retire instruments	21%
broken or unreliable	21%
loss of interest or usefulness	16%
replace with better or more suitable	16%
obsolescence, incompatibility	15%
constant change	7%
streamline setup, eliminate redundancy	7%
vibe, flow, balance	3%
newer prototype	2%

Table 2.4 Identified factors for uptake, longevity and abandonment of EMIs. Percentages refer to percent of total EMI users *(N=62)* with responses coded at each item.

influence their choice of a new instrument, such as cost and availability, and how it would integrate into their current setup with other instruments.

Beyond these main groups, differing outlooks between hardware and computers/-software were apparent. Towards hardware, most respondents reported seeking our new instruments that provide dedicated functionality and impose constraints. In contrast, one respondent highlighted the ephemeral nature of their computer-based instrument: *"In a sense, I can say that I haven't taken a new instrument in years because I've been performing with a computer for more than a decade. In another sense, I may say that I often change instruments, as every time I develop a new patch my instrument is fundamentally transformed" (P24).*

Longevity and abandonment: Many respondents showed great loyalty to the instruments they use, with several stating that they never retire an instrument. In the case of computer-based performance (well conveyed in the previous quote), this brings into question the blurred lines between instrument and composition as discussed in Section 2.3.1. Consistent with our previous survey findings (and reviewed in depth in Sullivan and Wanderley, 2018), issues of quality, reliability and compatibility were important contributing factors in the abandonment of instruments. Beyond this, many other factors were consistent with the factors for uptake: loss of interest or usefulness (complementary to acquiring new instruments with new features, sounds, etc.), upgrading and seeking novelty or change.

Models of user engagement

The notion of *engagement* is an important concept in HCI, and more generally interaction design, and can be conceptualized in similar terms as our inquiry how DMIs are taken up and used by performers. To provide a formal framework for analysis, we associated participant responses for this part of the survey with related concepts of user engagement from HCI literature.

Short-term user engagement: A prevalent model of user engagement with technology was formulated by O'Brien and Toms (2008). They propose that engagement is a process that moves through four distinct stages: an initial *point of engagement*, a sustained *period of engagement*, ending in *disengagement*, and may eventually by followed by *reengagement*. Along with these four stages, they also recognize the possibility for *nonengagement*. This model for engagement came out of a review of previous domain- and context-specific frameworks around engagement, and an exploratory user study of individuals participating four different computer-based activities: Web searching, online shopping, Webcasting and video gaming. Across the four stages of engagement, O'Brien and Toms identified several attributes, leading to a conceptual and operational definition of engagement as *"a quality of user experiences with technology that is characterized by challenge, aesthetic and sensory appeal, feedback, novelty, interactivity, perceived control* *and time, awareness, motivation, interest and affect"* (O'Brien & Toms, 2008, p. 949).

We characterize this type of engagement as *short-term*, as it is concerned with engagement at the event-level (for example, a single practice session or performance). Because of this scope, it was difficult to apply this model directly to our survey responses, which are concerned with the entire lifespan of an instrument (or at least the complete life of use by an individual performer) and not a single sitting.

On the other hand, we identified many of the same short-term engagement attributes in the respondents' attitudes towards uptake, longevity and abandonment of their DMIs. We explored this by re-coding the responses to our two questions on this topic, this time classifying them according to O'Brien and Toms's list of engagement attributes. The results are shown on the left of Table 2.5.

Short-term engagement ***(O'Brien and Toms)***	
novelty	44%
control	18%
aesthetic & sensory appeal	16%
challenge	15%
interest	15%
motivation	8%
interactivity	6%
affect (negative/positive)	5%
attention	3%
awareness (external/self)	3%
feedback	3%
perception of time	0%

Long-term engagement ***(Wallis et al.)***		
Mastery	complexity	34%
	immediacy	32%
	incrementality	10%
Autonomy	ownership	39%
	operational freedom	15%
Purpose	demonstrability	6%
	cooperation	3%

Table 2.5 Attributes of user engagement. Left: Short-term as defined by O'Brien and Toms (2008). Right: long-term as defined by Wallis et al. (2013). Percentages refer to percent of total EMI users *(N=62)* with responses coded at each item.

Long-term engagement: Prior research has examined long-term engagement with musical instruments. Drawing from psychology, Wallis et al. (2013) applied the *self-*

determination theory (SDT) of motivation by Ryan and Deci (2000) to identify attributes of musical instruments and music-making activities that inspire long-term engagement by amateur musicians. SDT classifies three intrinsic motives that regulate behavior: *mastery*, *autonomy* and *purpose*. Wallis et al. specifically link these intrinsic motives to amateur musical practice as opposed to professional practice which might also be motivated by extrinsic motives (such as the need to make money). Furthermore, intrinsic motives are more closely related to the sense of enjoyment, i.e., playing music for pleasure rather than out of duty. Out of their analysis, Wallis et al. derived seven conceptual and abstract attributes of intrinsic motivation that can be seen to facilitate long-term engagement with musical instruments. We re-coded the corresponding survey responses along these attributes, which are listed in Table 2.5 (right).

Attributes for engagement with EMIs

Both models correlate closely with our responses. Short-term attributes, despite focusing on a much narrower time scale than the survey questions, affectively described many of the themes identified in our initial coding (in Table 2.4), especially the factors for *uptake*. On the other hand the long-term attributes, while more theoretical, explicitly address the aspect of longitudinal use, which is missing from the short-term model and is an important aspect of our investigation. Therefore we found them both beneficial and they are both included in our engagement analysis.

We conclude this stage of analysis by comparing attributes between the models of long- and short-term engagement and the results of our exploratory analysis. Table 2.6 shows all of the attributes and their associations. While there are many interrelated concepts across the three groupings, we highlight three main classifications that were most frequently mentioned by respondents and discuss how the models and data intersect.

Long-term		**Short-term**	**Coded themes**
mastery	**complexity**	challenge	**acquire specific functionality** improved interaction, control newer prototype integration with rest of setup eliminate redundancy, streamline setup same computer, new patches
	immediacy incrementality	attention feedback	quality, reliability **breakage, unreliability** incompatibility, obsolescence cost and availability size and portability simplicity constraints (of hardware) learning curve, ease of use
autonomy	**ownership**	**novelty** interest motivation affect awareness aesthetic appeal sensory appeal	**new or improved sounds** **do not retire instruments** loss of interest or usefulness exploration expand or diversify performance practice new features constant change vibe, flow, balance (or imbalance) never pick up new instruments movement around stage
	operational freedom	control	replace with better, more suitable options, versatility, flexibility
purpose	demonstrability cooperation	interactivity	heard the instrument played recommendation

Table 2.6 Associations of long- and short-term engagement attributes with our coded themes for EMI uptake, longevity and abandonment. The most commonly identified items are highlighted in boldface (mentioned by >20% of respondents).

Ownership and Novelty: The primary qualities shared between the three rounds of coding are closely associated with *ownership* (long-term attribute) and, more narrowly, *novelty* (short-term attribute). In summary, the most compelling factors for acquisition of new instruments, and long-term use of existing instruments, is that they afford novel and ongoing creative and expressive possibilities and allow for embodied and highly personalized connections between instrument and performer. There are divergent views on how to achieve novelty though. For many, this is an external process of experimenting with and acquiring new instruments, for others it is a matter of deep exploration and customization that comes with working with a single instrument or setup for many years.

Complexity and challenge: A related quality that was commonly mentioned is the ability for instruments to facilitate *complexity* and successfully navigate the *challenges* associated with assembling and performing with elaborate and highly specific assemblages and instrumental setups that allow for rich and dynamic musical output. Most references in this group referred to acquiring new instruments, in particular seeking out instruments and interfaces that afford improved interaction and control or provide a particular indispensable features.

Immediacy, incrementality and reliability: The third common category we identified characterizes qualities that support the successful and functional operation of instruments, while minimizing or removing obstacles that would prevent operation. Three related qualities are recognized. First, *immediacy* comprises properties that allow for easy and direct use, such as ease of setup, portability, and affordability. Second, *incrementality* refers to the learning curve of an instrument that will ideally afford a gradual manageable progression from simple operation to mastery and expert operation. Finally, *reliability* pertains to qualities that allow for successful and sustainable operation like an instrument's overall quality, stability and compatibility with other instruments and systems (or conversely, unwanted characteristics like instrument breakage, failure and obsolescence).

Interestingly, there was little mention of *purpose*, the third intrinsic motive of long-term engagement. This motive, as defined in SDT, is "evoked by activities containing a social element or an element of relatedness with other people" (Wallis et al., 2013, p. 56). While it factored strongly in Wallis et al.'s framework for engagement by amateur musicians, there were few mentions by our respondents. Those that did mainly spoke to seeing or hearing an instrument played as inspiration for acquiring it. Regarding cooperation and playing with others, only two mentions were made and in fact one highlighted the desire for better technology to facilitate *less* cooperation: *"[I would start using a new instrument] if the concept of performing the instrument myself is more favorable than collaborating with someone who is already proficient on that instrument" (P21).* The lack of comment on the social aspect is somewhat surprising, as fully 85% of EMI users in the survey report that they perform in ensembles or groups at least part of the time. Given the significant research that has been dedicated to the communal aspects of DMI use (as discussed in Section 2.2), this may suggest an area for future investigation.

2.5.4 Understanding performance communities

For the third and final section of our analysis, we extend our results of the first two sections by returning to our earlier discussion on DMI use (Section 2.1.1) and communities of performance 2.2. We were interested to see if musicians different performance communities prioritize different qualities for instruments that they would want to use in their practice. Furthermore, through our review of previous surveys in Section 2.3.1, we found that existing scholarship on DMI performance tends to be self-reflective of its own research-oriented communities (such as NIME), and there is a lack of information about more popular and widespread practices.

To establish some basic distinctions between different types of practices we looked at two attributes of respondents that use EMIs: frequency of performance (to differentiate between active professionals and amateurs who perform less often), and performance of "NIME" versus "non-NIME" musical styles.[10]

Frequency of performance was quantified directly from question #9 of the survey: *"How many times per year do you perform in public?"* EMI users (N=*62*) were roughly split between two groups: frequent performers who perform more than 10 times per year (48%), and infrequent performers who perform 10 times or less per year (52%).

To associate reported musical styles with typically "NIME" and "non-NIME" modes of performance, we referred to the most common styles reported Morreale et al.'s survey of NIME performers (2018), shown in Figure 2.6: experimental, electronic, noise, acousmatic, and classical, which were selected by between 19% and 82% of their respondents. In our own survey we ascribed analogous musical styles as NIME styles, and the others as non-NIME (as shown in Table 2.7), then classified respondents accordingly: NIME (42%), non-NIME (13%), and those who play both (44%). One respondent who didn't answer questions about musical style was removed. The classifications are shown in Table 2.8, along with further subclassifications of both attributes. These are, of course, imprecise categorizations that were self-reported and somewhat subjective. But they do allow us some draw some general designations around types of practices that may be helpful to our analysis. Additionally, we use the term "NIME" in a loose and inclusive sense, referring not only to the community directly associated with the NIME conference and organization, but to all related communities engaged in research-based

[10]We started with a third, performers who also design instruments versus those who do not, however the survey lacked specific data for this and all of the respondents who could be identified as designers were included in the NIME performance category already, making the classification largely redundant.

practices around musical interface design and performance.

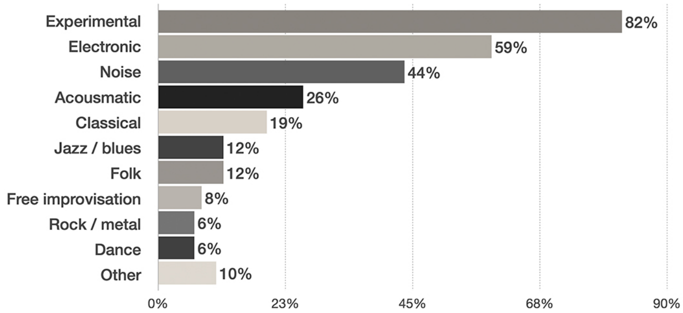


Fig. 2.6 Musical styles reported by NIME performers in Morreale et al. (2018)

"NIME" styles	Avant-garde/ experimental, electroacoustic, classical
"non-NIME" styles	EDM, pop/rock, jazz, folk, stage/theater, blues, international, rap, R&B, Latin, country

Table 2.7 NIME and non-NIME musical styles from the EMI Survey

		Musical style			
		NIME 42% *(N=26)*	non-NIME 13% *(N=8)*	both 44% *(N=27)*	not specified 2% *(N=1)*
Performance frequency	Frequent 48% *(N=30)*	27% *(N=17)*	8% *(N=5)*	11% *(N=7)*	2% *(N=1)*
	Infrequent 52% *(N=32)*	15% *(N=9)*	5% *(N=3)*	32% *(N=20)*	—

Table 2.8 Classifications of EMI performers by musical style (NIME/non-NIME/both) and performance frequency (</> 10 performances per year).

Using these two respondent classifications we computed a crosstabulation of the identified recurrent quality attributes (from Section 2.5.2, Table 2.3) and primary attributes of uptake and long-term engagement with DMIs (Section 2.5.3, Table 2.6). The results are included in Appendix B.2. A detailed discussion of the results is withheld here, as this additional analysis is offered as a supplement the main results already reported and an indication for future continued work. We can, however, point out a few noticeable contrasts between frequent and infrequent performers of NIME and non-NIME musical styles:

Performance frequency

- Infrequent performers (which we associate with amateur musicians and hobbyists) prioritize flexibility and versatility in an instrument, while more frequent performers (active and professional musicians) spoke more favorably about simplicity and constraints.
- Infrequent performers seem to be more likely to seek out novelty and change instruments more often than active performers.
- Frequent performers engage in deeper levels of customization and personalization of their instruments, and prioritize reliability and quality over novelty and variation.

NIME and non-NIME musical styles

- Performers working in non-NIME styles value compatibility and interoperability between instruments and across their instrumental setups, while at the same time prioritizing ease of use and size/portability. This suggests that they tend to use instruments that individually provide more constrained functionality, but incorporate many together into elaborate setups.
- NIME musicians prioritize the embodied connections they have to their instruments, and necessitate greater control for carrying out complex musical performance.
- Non-NIME musicians commented more frequently about the importance of their instruments' sound quality and aesthetics than NIME musicians. They are also highly motivated to acquire and create new sounds. While this was not highlighted in the NIME musicians, this may also be a fundamental difference in the musical styles themselves, where NIME-style music often operates on a more organic level

of sound production (often working with lower-level synthesis parameters), where non-NIME styles, especially pop and dance music, are more likely to acquire and use pre-recorded or programmed samples, presets, etc.

- Additionally, it is important to recognize the different contexts of NIME and non-NIME musicians, as well as more and less active performers. Different practices may vary between investigation, production and live performance modes, each with their own workflows and aesthetic aims.

2.6 Discussion

2.6.1 Considerations for the design of DMIs for performance

In consideration of the challenges that designers face towards the creation of new DMIs that would be viable and appealing for active musicians to work with in real-world performance practices, we summarize our results as a set of considerations for DMI designers. While continued work in these directions may yield more specific guidelines in the future, our intent here is to give designers a more nuanced understanding of musicians using novel technologies in their practice, and to elucidate some of the factors for, and attributes of, instruments put to use in real-world musical practice, especially by active and professional musicians who place the highest demands on their instruments.

1. We define three primary desirable sets of qualities for DMIs to be viable for use in real-world performance practice: a) the instrument's ability to ***handle complexity*** that is appropriate to the user and context; b) its capacity to adequately ***accommodate*** the unique requirements of a performer's practice; and c) its suitability for ***appropriation*** by its user, that can facilitate long-term growth and enjoyment.

2. Additionally ***sound quality***, ***cost and affordability***, and the ***look and feel*** of

an instrument are important characteristics that contribute to performers' positive impressions of their instruments.

3. While acquiring new instruments and retaining existing instruments depends on a number of factors, performers consistently show interest in acquiring new instruments that provide ***improved features, controls and new sounds***.

4. ***Instrument reliability*** is a persistent concern for most performers, yet many put up with minor problems and continue to use a particular instrument despite ongoing issues. In this regard, ***performers often exhibit great loyalty and even affection for their instruments***.

5. We identify three sets of user engagement attributes that contribute to the successful uptake and long-term use of DMIs: a) ***ownership and novelty***, through deep exploration and customization of existing instruments as well as acquiring and experimenting with new instruments, that facilitates ongoing creative and expressive performance; b) ***complexity and challenge***, the ability for instruments to accommodate elaborate and highly specific musical setups and processes, allowing for rich and dynamic output; and c) ***immediacy, incrementality and reliability***, which support the successful, functional and long-lasting operation of instruments while minimizing obstacles that would prevent their use.

6. Lastly, and perhaps most importantly, we take note of diversity across performance practices and between performers. While the high-level considerations listed here are meant to be applicable to all performers, they will be exhibited in different ways depending on a variety of factors. We propose two general ways of classifying performers and types of practices: by frequency of performance (frequent/ infrequent, which suggests a contrast between amateur and professional practice)

and musical style (which we categorize between "NIME" and "non-NIME" styles, characteristic of the DMI design and research community.)

This list is far from exhaustive, and additional considerations may be revealed with continued investigation and analysis around DMI performance. However we hope that these findings shed new light on what it means to perform with novel instruments, especially across and beyond previously studied communities including those surveyed here.

2.6.2 Limitations and Future Work

The EMI Survey was designed to reach a number of different performance communities, but we still found that many respondents fit into typical NIME-style types of practice. More than two-thirds of respondents come from formal training and academic backgrounds, are involved in experimental music practices, and are highly computer literate. This this study was carried out in an academic research environment and the call for participation was distributed across several university networks, and accordingly many of the respondents can be recognized as operating in or adjacent to academic practices. Distribution of the survey was limited geographically as well, with the call distributed mainly in North America and Europe, and only available in English. Undoubtedly, wider distribution and translation to other languages could have delivered more diverse perspectives.

Therefore we recognize the implicit bias of our survey distribution and acknowledge the limits of our attempt to capture a diversity of performance communities. We did, however, find significant variation in the survey population which collectively represented a range of different approaches and perspectives to performance.

We can envision a future survey that could extend our current work in a few key ways. First, recruitment efforts can target diverse types of performance communities based on specific attributes such as: professional versus amateur musicians, performers of popular, classical and experimental styles of music, designers versus non-designers, academic researchers versus non-academic researchers, and more. Crosstabulation analysis could be extended across all different community attributes, to provide a more detailed comparison of DMI trends by performance type, and corresponding implications for design.

The survey has also exposed other topics of interest that will be beneficial to explore in more detail. For one, previous literature has shown the important function of community and socialization towards the success of a new instrument, and it has also been shown to be a factor for long-term engagement. However in the survey, little was mentioned about social aspects of performance despite most respondents reporting that they perform in groups at least some of the time.

Another rich area for investigation is around what constitutes a digital (or electronic) musical instrument. In particular, how does the use of commercial instruments and controllers, non-commercial and self-built instruments, and mixed assemblages of hardware and software affect the outlook and priorities of different performers? Addressing these topics in a future survey may help to develop and refine our list of considerations into more formalized design guidelines.

2.7 Conclusion

In this chapter we have investigated how musicians across diverse communities use DMIs in their performance practice. We began by conceding that many DMIs see limited use in performance for a variety of reasons. We then reviewed previous work that has examined DMI performance, which have frequently risen from, and been oriented towards, more academic- and research-minded communities like NIME. As such, these investigations have served to highlight the dynamic interdisciplinarity of such communities, in particular the trait of individuals who operate across and between traditionally defined roles of designer, composer and performer. Previous survey-based studies have shown that, while common among NIME-style performance communities, this blending of design and performance may be predicated on additional non-musical proficiencies like computer programming or electronics design, that performers from other communities may be less likely to possess.

Thus we were motivated to examine how DMIs, and more generally what we have have termed *electronic musical instruments* (EMIs) are used across more diverse and widespread performance practices, and especially those that are not closely involved with instrument design as well. To investigate this, we carried out the Electronic Musical Instrument Survey, an online survey on musicians who use digital and electronic instruments in live performance. We conducted a thematic analysis of the responses that yielded several of high-level insights about important qualities for DMIs to taken up into use.

We hope that our findings can be helpful for designers and researchers at multiple levels. At a theoretical level, we identified several factors that contribute to performers' initial and lasting engagement with DMIs, and related them to existing models of user engagement found in previous HCI research. At a methodological level, we have presented a structured approach to the analysis of qualitative survey data that uses both bottom-up and top-down methods of thematic analysis, as well as crosstabulation to observe variations between different different types of respondents in our survey. This methodology could be suitable for other analyses where both inductive and deductive approaches are called for. Finally, at a practical level we provide a summary of considerations for the design of new DMIs based on the direct input of performing musicians, that may be helpful for designers whose instruments are intended for real-world musical use.

We also aim to evaluate our findings by applying them to our own instrument design process. The following chapters present two different practice-based design approaches to develop new DMIs for musical practice. Chapters 3 and 4 report on workshops held with expert musicians that led to the design of three new DMIs, and Chapter 5 describes a long-term collaboration with a professional performer to develop bespoke musical interfaces for their interactive live show. It is our belief that thoughtful consideration of the factors that we have identified here can improve the overall quality of designs and viability of new instruments for use in real-world, professional performance practices.

Chapter 3

Design for Performance: From Fiction to Functional Design

This chapter is based on the following research article:

- Sullivan, J., Wanderley, M. M., & Guastavino, C. From Fiction to Function: Designing New Musical Instruments With Expert Musicians. (submitted)

Abstract

A workshop is introduced that was held with expert musicians to imagine novel musical instruments through design fiction. Based on the Magic Machine workshops developed by Kristina Andersen, participants crafted non-functional prototypes of instruments they would want to use in their own performance practice. Through in-situ activities and post-workshop thematic analysis, a set of design specifications were developed that can be applied to the design of new digital musical instruments intended for use in real-world artistic practice. In addition to generating tangible elements for design, the theories and methods utilized, based in human-computer interaction and

human-centered design, are offered as a possible model for merging imaginative idea generation with functional design outputs.

3.1 Introduction

Digital musical instrument design is a broad and interdisciplinary field. Designers engage in the development of new instruments and novel approaches to musical performance (as well as composition and production) for a wide variety of reasons. Even where DMI design is fundamentally research-based, as with NIME, the means and the ends take a variety of forms, ranging from rigorous scientific experimentation to artistically motivated creative practice (Gurevich, 2016). Fittingly, the field, and more generally the broad domain of music technology in which it lies, contributes a wide range of outcomes both within and beyond specifically musical applications, such as the development of new technologies for interactive systems (Malloch et al., 2018) and the advancement of knowledge and theories on technology-mediated artistic performance (Tahlroğlu et al., 2020).

With the work described in this chapter, we were interested to investigate a novel method for the design of instruments expressly intended for real-world musical practice. Motivated by our previous survey-based work that examined key factors for engagement and longitudinal use of DMIs in performance, this chapter reports on two workshops held with expert musicians that led to the the creation of three new instruments. A user-driven approach was used in the initial ideation stages of DMI development, in particular the use of design fiction (Blythe, 2014) and non-functional prototyping (Pigrem & McPherson, 2018), to inspire novel concepts for the new instruments.

In Section 3.2 we will review approaches to, and motivations for, designing novel DMIs. In particular, we consider methods for early stages of ideation and innovation, including user-centered and participatory design approaches drawn from HCI and oriented towards applications for creative practice. From this background, in Section 3.3 we introduce the methodology for the Design for Performance workshop, in which expert musicians built non-functional prototypes of imaginary DMIs. Section 3.4 reports the initial results of the in-workshop activities, and Section 3.5 provides the results of the post-workshop analysis that was conducted, which led to the generation of a list of design specifications for new instruments. Finally, Section 3.6 discusses the potential efficacy of the design fiction approach towards developing instruments that are viable for uptake and long-term use by expert musicians in real-world performance, and outlines future work for robust evaluation of the methods explored.

3.2 Background

The ongoing design of new musical instruments is nothing new. However the last 200 years have brought about major changes in why and how new instruments are created. In his book *Sonic Writing*, Magnusson (2019) identifies the nineteenth, twentieth, and twenty-first centuries as rough delineations of three music technological epistemes representing acoustic, electronic, and digital paradigms respectively. Each has defined its own themes for instrument design and related musical practice.

The acoustic era is characterized by standardization and reproduction, both in instrument design (as with the industrialization and factory/mass production of the piano and other popular instruments) and practice (in which the prevalent mode of performance was the repetition of written scores). New instruments were most commonly derived from existing instruments (Rubine & McAvinney, 1990), often in an effort to address limitations of existing instruments, improve usability, extend functionality or implement better technologies in their design and manufacture (Emerson & Egermann, 2020).

The electronic era, and later the digital era, ushered in tremendous changes in both design and practice. Magnusson (2019) attributes the transition from acoustic as a shift from symbols (as characterized by individual notes written on a score) to signals, in which sounds and user controls are translated into electronic and digital representations that can be easily and flexibly processed, mapped and mixed. Of course, Magnusson's viewpoint seems to be more focused on the written traditions of classical music, and less towards popular styles which were historically based on oral tradition. Nonetheless, these shifts have largely been brought about by technological advancements irrespective of specific musical traditions.

The shift to electronic and then digital introduced the ability to record and play back sound, as well as to synthesize entirely new sounds and manipulate them in many ways. The expanded capabilities of electronic and digital instruments, as well as the wide variety of performance behaviors they afford, is well illustrated by the model of music interaction and performance context developed by Malloch et al. (2006) shown in Figure 3.1. Adapted from Rasmussen's model of human information processing (1986), the figure illustrates a continuum of performance behaviors and contexts from right to left, moving from conventional instruments (consisting of note-level, real-time, skill-based interactions that would be typical of acoustic playing) to novel performance modes and instruments that are rule- and model-based in operation, made possible by advanced electronic and digital technologies for signal processing, sampling, synthesis, mixing, mapping and more.

Perhaps the most consequential aspect of the progression from acoustic to electronic, then digital instruments has been the decoupling of the user input from sound production. With any instrument, sound is typically generated and controlled through the various performative actions of its owner.[1] On an acoustic instrument these sound-

[1] There are, of course, exceptions to this model (especially in the digital domain, such as instruments that behave autonomously or receive input from arbitrary input data) which are outside of our scope of consideration.

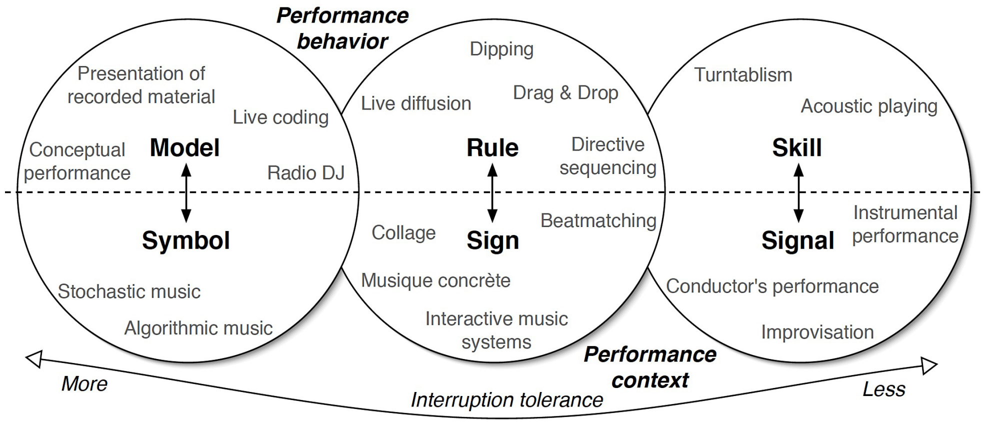


Fig. 3.1 Model of music interaction and performance contexts by Malloch et al. (2006). Note that *symbol* and *signal* are defined here by the figure's authors and unrelated to the terms as used by Magnusson (2019).

producing actions, termed *instrumental gestures* by Cadoz (1988), are physically and mechanically linked to a sonic result, for instance blowing into a saxophone or applying vibrato to a violin string. On the other hand, a digital instrument is not driven by acoustic means and the link between control and sound occurs in the digital realm. Thus, the designer is free to choose any type of input control and any system of mapping controls to sound.

From the designer's perspective this ultimate freedom may be liberating, and is reflected in the increasing quantity, complexity and diversity of new DMIs that have been developed over the last few decades. However this may also present a challenge for designers. Returning to Magnusson's description of the three epistemes, he characterizes the digital era as one in which "any bodily gesture can be mapped to any sound and there is no natural paradigm at play that we can relate to" (2019, p. 34). While the issue of mapping is a deep area of research and scholarship in its own right (see Wanderley (2002) and Wanderley and Malloch (2013) for in-depth reports), here we focus on two more basic inquiries: First, if few technical and conceptual limitations exist, what motivates the design of new DMIs? And second, what methods are effective in the development of novel DMIs that will make them appealing for use in artistic practice?

3.2.1 Motivations for designing new instruments

There are a wide range of factors that motivate the design of DMIs, many of which are specific to different end goals. In research settings like NIME, it may be useful to design DMIs that are specific to a particular experimental context (Marquez-Borbon et al., 2011). Morreale and McPherson (2017) survey of DMI designers at NIME found this to be a common approach: out of the 97 instruments included in the study, 38 (39%) were reported to have been designed as research probes. Depending on various applications and methodological approaches (which may be driven by scientific or artistic goals), these types of instruments may or may not be intended for actual use in musical practice. When considering more widespread audiences for new instruments, social, cultural and economic factors come into play, in particular market and consumer-driven behaviors that influence trends, popularity and visibility of commercial, off-the-shelf instruments (Théberge, 1997). The diversity of design approaches (in particular between commercial and research-based designs) was highlighted by McPherson et al. (2019) in a comparison of instruments emerging from different domains including NIME, HCI, and crowdfunding campaigns.

A study by Emerson and Egermann (2020) focused specifically on the design of DMIs expressly intended for artistic practice. Out of interviews with ten designers, they identified four primary categories of motivation: facilitating greater embodiment in performance, improving audience experience, developing new sounds, and building responsive systems for improvisation. The study also highlighted different motivations based on the context of participants' practices: those more active in academic settings exhibited more interest new sounds and responsive systems for improvisation, while others who performed in club settings were motivated to improve embodiment and audience experience.

3.2.2 DMI design and HCI

The diverse motivations for designing new instruments are also reflected in various design approaches and methodologies used. Much of the prevailing discourse on DMI design research comes from the field of HCI, which can provide prescriptive strategies for for all stages of the design process. Early HCI favored systematic approaches, rigid guidelines and formal methods for designing and evaluating human-machine interfaces (Bødker, 2015). Examples in DMI research include the formulation of quantitative methodologies like Fitts's Law and Meyer's Law to evaluate target acquisition in the context of musical interactions Wanderley and Orio (2002), and schema developed by Vertegaal et al. (1996) to match transducers and feedback modes to specific musical functions.

While recognizing the usefulness in these commonly accepted HCI methodologies, Wanderley and Orio also point out the potential limitations to their usefulness in designing music interactions, which are often characterized by idiosyncratic approaches, driven by "precise artistic demands" (2002, p. 67) that yield highly creative and innovative results.

However, HCI has also evolved. While the first wave of HCI was based on models of human information processing theoretically rooted in cognitive psychology, the second wave emerged to include perspectives on technology within social, cultural and organizational contexts (Kaptelinin et al., 2003). Rigid and largely quantitative methods gave way to qualitative user-driven and participatory approaches theoretically grounded in situated action, distributed cognition and activity theory (Bødker, 2006). The third wave expanded the purview of HCI to accommodate the ubiquitous nature of technology moving beyond the workplace into everyday life and culture, prioritizing experiences, meaning-making and emergent use (Bødker, 2015). S. Harrison et al. (2007) characterize the third paradigm of HCI as phenomenologically situated with a focus on embodied interaction, that can embrace multiple interpretations and yield rich understandings supported by ethnographic and practice-based research approaches.

User-centered, human-centered and participatory design

User-centered design (UCD) is a common approach within HCI where users are systematically involved throughout the design process. Norman (1988) popularized the term, in which the designer should "ask what the goals and needs of the users are, what tools they need, what kinds of tasks they wish to perform, and what methods they prefer to use" (as cited in El-Shimy, 2014, p. 44). UCD is less of a method in and of itself than a high level guideline under which several design strategies fall such as those in Greenberg et al. (2011).

Attitudes towards UCD have evolved over time and, while UCD is still widely used in practice and reference, human-centered design (HCD) has emerged as a subtle but important variation. Norman (2013) describes HCD as a design philosophy and set of procedures that are complementary to more specific areas of focus such as experience design, industrial design and interaction design.[2] While similar in both concept and scope to UCD, the *human*-centered scope of HCD allows for a broader consideration of people with regards to design, instead of "a narrower focus on peoples roles as *users*" (Steen, 2011, p. 45). This points to a shift that corresponds with trends in HCI: "Instead of focusing on how specific tools can be designed to help users accomplish specific tasks, the human-centered perspective encourages developers to strive for a better understanding of how people live in the world, and to design systems accordingly" (El-Shimy, 2014, p. 45).

[2]HCD is also formally defined as an ISO (International Organization for Standardization) standard, however UCD is not.

Participatory design (PD) is an HCD approach that became well-established with second-wave HCI (Bødker, 2015) and has continued to be relevant in third-wave HCI as well (Muller & Druin, 2012). It is predicated on the full participation of end-users through all stages of the design process (Steen, 2011), and is primarily concerned with the *tacit knowledge* of the involved participants which, according to Spinuzzi (2005), is hard to formalize and had been missing from early HCI. PD provides several techniques that are relevant to our work here, including ethnographic methods, workshops, low-tech prototyping and mock-up designs (Muller et al., 1993). However, the roots of PD, which originated in Scandinavia in the 1970s, are also political, and it was envisioned as a way "to rebalance power and agency among managers and workers" (Bannon et al., 2018, p. 1). Some current PD practices have been critiqued as merely UCD by a different name, lacking the original political and activist contexts:

> It is a far cry from earlier work in the field, where Participatory Design not only sought to incorporate users in design, but also to intervene upon situations of conflict through developing more democratic processes. (Bannon et al., 2018, p. 2).

There are instances of PD applied in the design of DMIs. A PD-based methodology was proposed for the design and evaluation of Theremin-based controllers by Geiger et al. (2008), and PD techniques were applied in the development of audio-haptic interfaces for visually impaired sound engineers and musicians by Metatla et al. (2016). A participatory approach to music interaction design based on conceptual metaphor theory was also introduced by Wilkie et al. (2013). Finally, we note that our own work presented here uses HCD methods that fall under the PD umbrella but without any specific political motivation; therefore we present our approach as HCD and refrain from characterizing it as full PD in deference to the aforementioned objections raised by Bannon et al.

3.2.3 Design frameworks

HCI research has contributed a number of different frameworks for the design and evaluation of new DMIs, While not exhaustive, we highlight a few that help to inform our own specific design approaches.

A theoretical framework by Bongers (2000) based on early HCI approaches organized musical interaction as a two way process of *control* and *feedback* described across three categories: *performer-system*, *system-audience* and *performer-system-audience*. This was followed by an explanation of the techniques and technologies (in particular the various sensors to capture different types of performance gestures) necessary to realize the proposed interactions. Wanderley and Depalle (2004) proposed a design framework for gestural control of sound synthesis comprised of four main elements: *gestures*, *sensors*, *mapping* and *sound production*, which also included *feedback* from the instrument back to the performer.

Around the same time, Jordà (2004a, 2004b) introduced several interrelated concepts of musical instruments and practice (*efficiency*, *apprenticeship*, *learning curve*, *diversity*, *freedom* and *control*) towards formulating a conceptual framework that could address diverse needs of different performers appropriately. A separate theoretical framework was subsequently proposed by Overholt (2009) that focused on human-centered design approaches in the combined areas of music performance, HCI and digital technology.

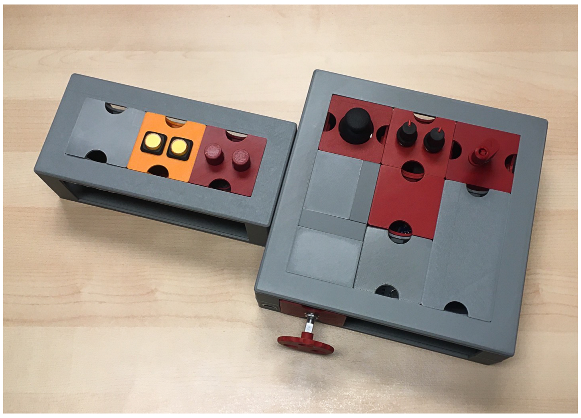
O'Modhrain's framework for the evaluation of DMIs (2011) takes a unique approach, prioritizing the various stakeholders involved in the development of a new instrument, including audience, performer/composer, designer, and manufacturer. Another HCI-based evaluation framework is specified by Young and Murphy (2015), emphasizing established, rigorous and flexible techniques to ensure complete and in-depth device appraisals. Finally, Morreale et al. (2014) created the Musical Interfaces for User Experience Tracking (MINUET) framework to serve three purposes: reduce design space complexity, specify criteria for design success, and to guide evaluation procedures. The framework divides the design process into two stages. The first establishes design objectives and the second designs the appropriate interaction to meet the established objectives. It establishes a user-centered design approach framed by *people*, *activities*, *contexts* and *technologies* derived from Benyon et al. (2005), embracing more embodied and participatory methods found in the second and third waves of HCI research.

3.2.4 Novel approaches to idea generation and prototyping

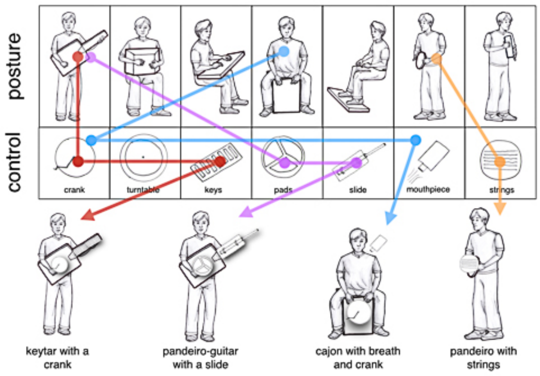
While these frameworks may be helpful in formulating a conceptual design approach, they are generally not oriented towards specific design tools and methods. For our own design work, we wish to develop effective strategies for developing new instruments that will be appealing for musicians to incorporate into their own artistic practice. In particular, we look at two user-driven approaches to generating ideas for new designs: a physical DMI prototyping toolkit and a design workshop methodology.

Probatio

Probatio is a system developed by Calegario (2019) that is comprised of a set of physical modules and accompanying methodology for exploring ideas and developing proof-of-concept DMI prototypes. It is meant to address a few important issues that arise in DMI design: for one, it provides functional constraints to limit the endless possibilities and increased complexity that arises from the separated user input and sound production components of DMIs, which can lead to "creative paralysis" (Magnusson, 2010). For another, it can help speed up and eliminate bottlenecks for iterative design, facilitating rapid design and evaluation cycles. The Probatio hardware consists of several control blocks, each featuring a different type of input control (ie., buttons, slider, crank, etc.), and different bases and structural supports that can accommodate variable configurations of the control blocks. The hardware is engineered so that the blocks attach magnetically and electrical connections are made automatically. Control signals are then mapped to sound synthesis software, making the prototype instantly playable as soon as one or more blocks are connected. An example Probatio prototype is shown in Figure 3.2a.



(a) A prototype constructed with a Probatio base, structural support and several control modules.



(b) Morphological chart suggesting new prototypes by combining features of existing instruments. Drawings by Giordano Cabral.

Fig. 3.2 The Probatio toolkit, version 1.0, by Calegario et al. (2020).

The methods that guide the use of the Probatio toolkit are based on Calegario's concept of *instrumental inheritance* in which aspects of existing instruments such as physical structures, playing techniques and specific types of input controls can be explored in different combinations and configurations, yielding entirely new instruments. A morphological chart (Cross, 2000), shown in Figure 3.2b, assists the designer in this process, presenting different postures and controls that can be constructed with the Probatio hardware.

Magic machines and design fiction

Another compelling approach to idea generation and prototyping for DMI design comes with "Magic Machine" workshops developed by Andersen (2017). The workshops "make use of the notion of technology as a ‘magical unknown’ as the starting point for a range of workshop techniques that begin with material exploration” (Blythe et al., 2016, p. 4971). In them, participants are prompted to make non-functional low-fi prototypes out of generic crafting materials like cardboard, wood, string, and glue. Once finished, they present their creations, demonstrating their use in imagined scenarios.

The use of low-fi and paper prototyping is a well established approach to early stage design, and a number of different techniques and methods exist (see Sefelin et al. (2003) for a short overview). The Magic Machine workshops are also based on the concept of design fiction, where problems can be explored through the development of imaginary scenarios and “fantasy prototypes” (Sterling, 2009). Importantly, the artefacts that are generated (the non-functional prototypes) are not overly meaningful in and of themselves, and the ultimate aim is not solve any given problem. Rather, the processes of creating and engaging with the “magical unknown” serves “to give temporary body to concerns and questions [and] to consider the potential reality of a world in which such a thing might exist” (Blythe et al., 2016, p. 4971).

Andersen has run the workshops is a variety of of contexts for both adults and children, including workshops for the design of new (imagined) musical instruments. The workshop was also utilized by Lepri and McPherson (2019) in a study that explored diverse values and priorities of different music cultures, backgrounds and contexts.

Towards design for performance

The Probatio toolkit and Magic Machine workshops present dynamic methods for early ideation stages of DMI design that we are interested in applying to our own work. The workshops offer a creative approach for generating ideas free from technological or practical constraints, while Probatio provides a clearly defined set of tools to construct and test prototypes within an established set of constraints. The next section reports on our own workshop that was styled after the Magic Machines workshop. It includes additional details about Andersen's methods and our own customizations to orient the activities to address our specific goals and inquiries. Later in the discussion (Section 3.6) we consider how our own methodology can be complementary to the well-structured Probatio approach to ideation and functional prototyping, and if and where the two can overlap.

3.3 The Design for Performance workshop

In this section we introduce the Design for Performance workshop, where expert musicians envisioned and crafted fictional musical instruments. The structure draws from a variety of general methods from UCD and PD that have been mentioned so far: design workshops, non-functional and low-fidelity prototyping, iterative design, and design fiction. The workshop was envisioned as part of a multi-stage design study, with additional phases of the project to follow (See Chapter 4 for the workshop results applied in the design of new DMIs, and Section 3.6.2 for a discussion on current limitations and future work.)

The workshop structure is based on Andersen's Magic Machine workshops but is revised to direct the outcomes towards the generation of design specifications that could be applied to the development of new performance-ready DMIs. Table 3.1 provides a side by side comparison of the the Design for Performance and Magic Machine workshop activities (in particular Andersen's musical instrument design workshops (2017, pp. 30-53)) and notes variations between them. In Section 3.3.4 we describe each activity in detail.

It is important to note that the intended outcomes of the Design for Performance workshops differ from those of the Magic Machine workshops, which are specifically oriented towards building diverse design knowledge and complex understandings "about

Activity	DP	MM	Description	Variations
Introduction	X	X	Introduce workshop and set out rules	
Prompt	X	X	Draw the imagined sound/music you wish to create.	MM: The prompt is drawn in permanent marker on hand. DP: Prompt is drawn on index card.
Build	X	X	Create non-functional instrument prototypes from provided crafting materials	
Present	X	X	Each participant presents their instrument with demonstration and explanation.	DP: During presentations, the facilitator takes note of defining elements of the instrument and adds them to a whiteboard underneath category headings.
Discuss (1)	X	X	A short discussion follows each presentation to explore the instrument and its design.	DP: Presenter and other participants suggest additional elements to be added to the whiteboard.
Evaluate	X		Participants dot-vote the elements they find most compelling in the design of a new instrument.	DP only.
Discuss (2)	X		A group discussion discussion is held to reflect on voted elements and the prospects for their application in design.	DP only.
Document		X	Each instrument is photographed and documented.	MM only. (In DP, photographs are taken during presentations.)

Table 3.1 Comparison of activities for the Design for Performance (DP) and Magic Machine (MM) workshops, noting any significant differences between the activities.

technology, rather than of technology" (Andersen & Wakkary, 2019, p. 1). Our approach seeks to find a middle ground between theoretical knowledge and functional design, connecting the diversity and creative freedom fostered by the Magic Machine activities with a holistic design ecology from ideation to finished product. In this way, the Design for Performance workshop is envisioned as a design tool that can elicit preliminary ideas from a group of expert practitioners and translate them into tangible elements that designers can work with. This may be especially valuable in the DMI design space, where idiosyncratic approaches and highly personalized designs are common, and widespread adoption of new DMIs is limited.

A detailed schedule and script (included in Appendix C.1) was drafted based on Andersen's recommendations to run the workshop at a quick pace and keep a tight timeline. This was found to be an effective strategy to alleviate any potential anxieties or fears of failure that participants could experience during the creative and open-ended design activities (Andersen, 2017).

3.3.1 Crafting materials

The main activity of the workshop is for participants to design fictional musical instruments out of provided materials, and the type of materials used can have a large impact on the outcomes of the workshop.

Through several incarnations of the Magic Machine workshops (that have utilized an array of different crafting materials, from wood and paper to gumdrops) Andersen and Wakkary (2019) provides recommendations and rationales for the selection of materials. Importantly, generic and potentially absurd or impractical qualities of the materials chosen are essential to the activity. In being tasked with building something concrete out of ill-suited materials, the participant is freed from working within practical constraints or following known traditional methods. Furthermore, Andersen emphasizes that any material has the potential to influence the design outcome: particular objects or shapes may suggest typical or obvious uses, which should be avoided. And in the case of musical instrument design, materials may have sound-producing properties that a participant may want to apply in their design. However, Andersen specifies that materials should not be utilized for their acoustic qualities. In this way, the prototypes are explicitly *non-functional* and the design activity is oriented towards the imagining of abstract features and novel forms without concern for feasibility or technical implementation.

Again, as our goals differed from those of the Magic Machine workshops and we were interested in in tangible design outcomes, we were open to more conventional designs and included some items that might be predictable in their use. For example, each participant was given a large posterboard from which structural shapes could be fashioned, while index cards, colored tape and magic markers would make it easy for participants to draw in graphical user interfaces (GUIs) and other features typical of DMIs.

For the Design for Performance workshop, we selected a wide range of basic items purchased from a dollar store. Materials included:

- posterboard
- index cards
- sticky notes
- string
- wire
- rubber bands
- popsicle sticks
- plastic mesh
- paper plates
- plastic cups
- magic markers
- tape
- glue
- paper clips
- scissors
- utility knives

3.3.2 Pilot

Before the official workshop was held, a pilot test was carried out to run the full workshop from start to finish. Six master's students who were enrolled in a seminar about musical interface design participated. The session was facilitated by the first author with help from an assistant.[3] The workshop was attended by two colleagues of the facilitator (a music technology Ph.D. student and visiting professor) in order to observe and give feedback.

The full workshop was run according to the preliminary schedule that had been designed. Afterwards an informal discussion was held with the participants and observers to get feedback and take suggestions for any improvements that could be made. All generally agreed on the activities and format, while details for minor changes were noted and incorporated into the final structure and script.

While not a focus of this specific study, an interesting contrast between the pilot and official sessions is noted in that the pilot participants were all well-versed in DMI design research. On the other hand, the participants who took part in the official workshops were selected for their experience as active performing musicians and not required to have any preexisting knowledge of DMI design (though some did have some design experience as well). We can envision potentially different outcomes between designers and non-designers. As the pilot study was constructed to test and rehearse the workshop design, and not for data collection and analysis, no further investigation was made around this at the present. However, it suggests a compelling direction to explore for future workshops.

3.3.3 Participant selection

Research ethics and participant consent

Before recruitment began, the Design for Performance workshop was reviewed and approved by the Research Ethics Board Office of McGill University (certificate included in Appendix D). This approval requires that studies involving human participants follow specific guidelines for research ethics, to ensure safe handling of data and participants'

[3] The assistant, Collin Wang, was a master's student supervised by the last author.

right to privacy and informed consent. While the participants' names, personal information and gathered data would be anonymized, the proceedings would be photographed and video and audio recorded for later analysis and documentation. Participants would be asked permission to use their likenesses (photos, videos or audio) to be used in public disseminations, including this report. Individuals choosing to opt out would still be welcome to participate fully in the workshop and with their recorded presence removed from any publicized documentation.

Criteria and recruitment

As the workshop was focused on the design of DMIs for use in live performance and intended to be held with expert musicians, we identified three main criteria for prospective participants:

1. They should use, or at least be familiar with, digital, electronic or computer-based instruments for musical performance.
2. They should maintain an active practice, performing in public on a regular basis (at least five times per year).
3. Their performance practice should be related to electronic, electro-acoustic or other musical styles in which DMIs are typically used.

A call for participation was circulated through the following local mailing lists that were likely to reach individuals matching our criteria:

- McGill University Music Technology Area Graduate Students
- Université de Montréal Music Faculty Students
- Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT) Members and Students

- Eastern Bloc New Media and Production Centre [4]
- Montréal Contemporary Music Lab[5]

Interested parties were invited to complete an online prescreening questionnaire. Recruitment lasted for two weeks and 25 responses were received. Fifteen individuals who met the criteria were invited to participate, divided into two sessions. Five declined or did not respond, leaving a total of ten participants. To accommodate schedules, the workshop was divided into two sessions, with three participants in session A and seven in the session B. Profiles of each participant, including the background information reported on the prescreening, are included with our results in Section 3.4.1.

3.3.4 Workshop activities

The workshop sessions were held on consecutive days in a large conference room at CIRMMT, a multidisciplinary research center located at McGill University. The first author acted as the facilitator and was assisted by the same master's student who assisted the pilot session.

Efforts were made to create a comfortable and convivial atmosphere for the participants. The area was spacious and well lit with natural light, and snacks were put out. Tables were arranged together so that participants sat around the outside facing each other. The crafting materials were spread out on a separate table and covered with a cloth when the participants arrived.

Introduction

Before starting the workshop activities participants were asked to read and sign an information and consent form that outlined how the workshop would run and explained

[4] https://easternbloc.ca
[5] https://www.labomontreal.com

their rights as participants. Permission was requested for video and audio recording the sessions, as well as for taking photos, to which all participants agreed.

The workshop then formally began, and the facilitator introduced themselves and the assistant, giving additional context and background about the workshop and related research. Then participants went around the room and introduced themselves and gave a short summary of their musical practice, as well as any interest or experience they had in instrument design. Finally, the facilitator presented five guidelines to establish the intended mood for the ensuing activities:

1. There is no right or wrong.
2. The activities are short, so move quickly.
3. Be honest, respectful, and supportive to yourself and the other participants.
4. Make sure everybody can be heard.
5. Be creative, enjoy the process and have fun with it!

Activity 1: Prompt

With introductions and administrative affairs concluded, a prompt activity was given. Participants were asked to think of the music that currently make or would like to make, and then instructed to “draw the music” on an index card in front of them with a permanent marker. They were given two minutes to complete the activity, after which the workshop moved directly on to the next activity. The given prompt is an adaptation of the Magic Machine version, in which the drawing is done in permanent marker on the participant’s own hand. (However in pilot testing, the participants were unanimously opposed to drawing on their hands, so it was moved to an index card instead.)

Andersen stipulates two important functions that the prompt activity serves: First, it provides the specific context for the workshop focus. In this case, the focus is on designing new musical instruments, therefore drawing the participants’ attention to making music in novel and unexpected ways (as suggested by the inherent absurdity of *drawing* music) serves as a primer for the task at hand. Second, the short activity serves as a preliminary task to complete, “an initial goal. . . that tests competence and establishes confidence, acting as an on-ramp to an experience” (Andersen & Wakkary, 2019, p. 5). This eases the transition into to the more substantial design activity that follows, as one creative task has already been completed. Furthermore, any pressures or anxieties that may arise around perceived value or quality in participants’ creative outputs are minimized by the short time frame they are given to create their drawings.

Activity 2: Crafting non-functional prototypes

This is the main activity of the workshop, where “the content of the prompt must be translated into an imagination of the device that produces it” (Andersen & Wakkary, 2019, p. 5). As discussed in Section 3.3.1, non-functional instrument prototypes are built from rudimentary crafting materials, which moves the focus away from producing high resolution or even technically feasible designs. Instead, the participants are asked to envision and craft a purely fictional instrument that they would want to use, and the materials (and especially their unsuitability for functional instrument design) allow the participant to operate freely and instinctively without concern for implementation or technical constraints.

The following instructions were given to introduce the activity:

- Using the provided materials, you are asked to build an instrument with which you could play the music that you drew.
- Bear in mind that you are building *non-functional* prototypes. Your instruments do not need to sound and, specifically, you should not select or utilize materials for their acoustic properties, nor should you be concerned with technical feasibility.

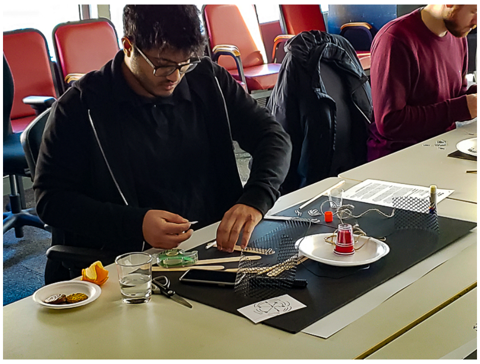
To assist the participants in developing their ideas into tangible designs, we introduced an informal list of eight considerations to refer to while building their instruments. The considerations, listed in Table 3.2 are divided into two categories: *high-level* operational qualities and general characteristics that could describe the instrument's intended use, and *low-level* essential features and fundamental components of the design. While some of the considerations can be classified as functional and non-functional requirements (as defined by requirements engineering (Glinz, 2007) and commonly employed in systems design), it is important to point out that these elements not specifically drawn from existing literature, but instead were empirically chosen based on our own prior knowledge and experience in DMI design, and intended to provide helpful points of reference through the activity. The considerations were presented along with their descriptions before the activity began, then written on a large whiteboard while the participants worked.

Category	**Consideration**	**Description**
Operational qualities and usage	Functionality	How does the instrument function?
	Playability	How do you play it?
	Musicality	What does it sound like, and how does it facilitate musicality?
	Context	Where and how will this be used? (types of venues, solo or in groups, etc.)
Design features and fundamental components	Physical form and ergonomics	What are the instrument's defining physical characteristics, life size, shape, orientation and posture for the performer?
	Interaction methods	What kind of controls and user inputs does it have?
	Sound production	How is the sound produced? (ie., synthesis, sampling, live audio processing)
	Feedback	What kind(s) of feedback will the instrument provide to the performer?

Table 3.2 DMI design considerations given for the non-functional prototyping activity.

(a) Session A.

(b) Session B.



(c) Participant P04 in Session B.

Fig. 3.3 Participants crafting non-functional instrument prototypes in Activity 2.

The participants were initially given 25 minutes to complete the activity (pictured in Figure 3.3), though extra time could be allotted if desired. In both sessions, five extra minutes were added, making the total length of the activity 30 minutes.

Activity 3: Presentations

Next, each participant gave a short presentation and demonstration of their instrument prototype. They began by showing their index card and explaining the music that they had drawn. Then they introduced their instrument, giving a short demonstration of how it was played, and a description of what it was and how it worked. Following suggestions made after the pilot test, the participants were encouraged to explain the links between the “music” on their index cards and the instruments, which helped to orient the presentations on the imagined outcomes, rather than the technical details of the fabricated designs. Presentations were allotted five minutes, three for the individuals to present and two for group discussion.

In a departure from the Magic Machine workshop design, an additional element was included during the presentations. While the participants described their instruments, the facilitator listened for “key elements” of their designs. Key elements may include essential features, attributes, characteristics that can help to define the instrument. As elements were identified, they were written on sticky notes and posted to the whiteboard, clustered around the eight considerations that had been given in the previous activity. During the presentations and ensuing discussions, the presenter and other participants were encouraged to suggest additional elements which were also added to the board. This method of identifying design elements with sticky notes is common in design research (Fischel & Halskov, 2018). The sticky notes were also color coded by participant to allow us to attribute key elements to individual designs (Reichelt, 2014), although ultimately a detailed comparative analysis was beyond the scope of this study.

Activity 4: Dot-voting

The identification of key elements and posting them to the whiteboard was intended to set up a transition in the workshop and allow the group collectively to consider aspects of the designs that would be appealing to incorporate into a fully functional instrument. To facilitate this turn, participants were then asked to dot vote for the elements that they most strongly favored (as shown in Figure 3.4).

Dot voting is a common activity in design workshops and collaborative sessions to collaboratively prioritize items from a large set (Gibbons, 2019) and focus attention for discussion and decision making (Gray et al., 2010). Each participant is given a number of stickers to place by the items of their choosing. When they are finished, the votes are calculated and presented to the group for further action. Various recommendations exist for the appropriate number of votes per participant (Gray et al. (2010) recommends five; Gibbons (2019) recommends 25% of the overall number or elements to be voted on; another online resource (Lam, 2019) recommends the formula: $votes = items \div voters \div 2$), which given the number of items and participants in our workshop would equal between 4 and 13 votes per person. Considering these methods and feedback from the pilot workshop, each participant was given 10 votes.

As we will discuss in the presentation of results, the dot voting exercise was less oriented around ranking of essential design elements and more concerned with facilitating a discussion around individual and shared priorities for bringing a new instrument to life. The voting activity was completed quickly and the workshop moved on to a final discussion.

Fig. 3.4 Session B participants dot voting for essential design elements in Activity 4.

Fig. 3.5 Session A participants conclude the workshop with a group discussion in Activity 5.

Activity 5: Group discussion

The workshop concluded with an open discussion (shown in Figure 3.5) with the facilitator and participants about the identified key elements and prospects for utilizing them and additional aspects of the instrument designs in the development of new DMIs that they would want to use in their own practice. In the discussion, the facilitator also provided information about future steps for the project including the anticipated design of functional instrument prototypes. Ten minutes were allotted for the discussion. The workshop length was planned for 90 minutes, though session B, with seven participants, ran longer and was completed in just under two hours. At the end, the participants were thanked and the workshop concluded.

3.4 Results

3.4.1 Participant profiles and output

In addition to the basic background information collected in the prescreening questionnaire, the self introductions at the beginning of the workshop provided additional insights about the participants' own musical and DMI practices. Profiles of the ten participants are shown in Table 3.3.

In their self-introductions, participants were also asked if they had previous experience with designing digital musical instruments, which is included in Table 3.4. While this was not a criteria for participation, the participants exhibited varying ranges of personal experience with DMI design. Six of the participants reported at least some previous experience, including P04 and P05 who come from engineering backgrounds and have significant technical knowledge and experience in this area. This is consistent with previous surveys (Magnusson & Hurtado, 2008; Morreale et al., 2018; Morreale & McPherson, 2017) that have highlighted the overlap between DMI design and practice (discussed in 2.3.1). While not a specific focus for this study, we were interested to see if there were recognizable design trends between performers who were also designers and those who were not. We can also envision a future Design for Performance workshop that investigates the differences between participants explicitly.

It should be noted that three of the participants are known by the authors. In particular, P09 is a harpist whose interest in electroacoustic performance has led to two collaborations with the first author before and after this workshop. These projects are presented in Chapter 5. Given the limited size of the local community involved in DMI practices and its overlap with the research community, we had anticipated that prospective participants might be familiar to us but determined that this should not disqualify them from participation if they met the defining criteria.

Design outputs

Table 3.4 presents the design output for each participant: their "draw the music" index card (as described in the presentations) and the instruments the designed. Figure 3.6 shows the participants presenting their instruments. Given the abstract nature of the "draw the music" task and its express purpose to provide an on-ramp and context for the creative activity to follow, it is unnecessary to discuss the output of the cards themselves and instead focus on the instruments that the participants created.

To relate the instruments to existing DMI research, Table 3.4 also categorizes them according to their similarity to existing instruments, based on Miranda and Wanderley's classification of gestural controllers (2006):

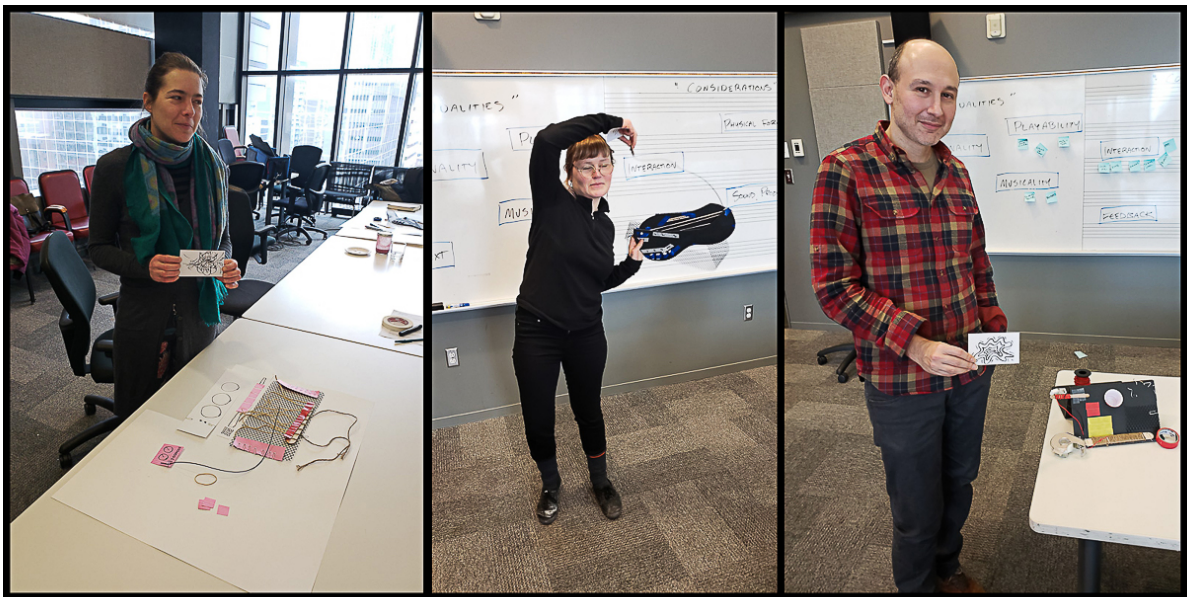
- ***Augmented*:** existing instruments extended by the addition of extra sensors which allow the performer to control additional sound and other performance parameters (such as the control of live visuals).

ID	Years experience	Performances / year	Use DMIs	Design DMIs	Instruments played	Musical style and description of practice
Session A						
P01	14	21-50	Always	some	synths, radios, DIY instruments	experimental improvisation; transmission-based, in situ solo and group performance
P02	23	21-50	Rarely	no	vocals, guitar, synthesizers	rock, noise, drone, free improvisation
P03	30	5-20	Often	no	guitar, piano, keys, modular synth, misc. electronics, other stringed instruments	Electronic, World music, Experimental, Brazilian; sound and FX for film
Session B						
P04	18	5-20	Often	yes	piano, guitar, drums, T-stick and Sponge (DMIs)	Classical, orchestral, prog rock, metal and blues; more recently into electronic music
P05	20	5-20	Always	yes	synths, vocals, guitar, DIY instruments	Electronic, experimental, pop
P06	13	5-20	Always	some	sampler, synths	Electronic, ambient improvisation; typically plays house parties and dive bars; beat-making (electronic/hip-hop)
P07	10	21-50	Always	no	guitar, bass, controllers, laptop, Max (software)	Contemporary music, noise, electronic; composer
P08	16	5-20	Always	some	drums, guitar, bass, vocals, piano, laptop, controllers, Ableton Live and Max (software)	live electronic music mixed with real instruments: “Think Radiohead.”
P09	16	21-50	Often	no	harp, augmented harp, vocals, laptop, controllers, Ableton Live	classical, contemporary, electro-acoustic, free improvisation
P10	17	5-20	Often	yes	vocals, guitar, harmonica, Myo (biosignal/motion controller), DIY instruments	Ska, folk and electroacoustic; incorporates movement, martial arts and theatre performance

Table 3.3 Profiles of the workshop participants, from prescreening questionnaire data and self-introductions.

ID	"Draw the music" description	Instrument presentation	Instrument classification
Session A			
P01	gestures and organic aspects	modular combination of different sensor inputs that could be mapped and remapped in realtime	alternate instrument
P02	many layers of textures: "shifting sands of many different sounds [and] melodic lines"	a device for FX processing and cross modulating vocals and guitar	instrument-like
P03	layers and textures, slowly going from soft to more powerful	a collection of different types of sensors for the performer to interact with sound in many different tactile ways	alternate instrument
Session B			
P04	audiovisual performance of multicultural music inside a 360° dome representing the world	digital/acoustic hybrid acoustic instrument with features of traditional world instruments	instrument-inspired
P05	representation of sound propagating through the air, similar to Chiladny plates (Rossing, 1982)	resonant physical structure to excite many different sound processes	alternate instrument
P06	circles and orbits, improvising drones and long and short samples shifting over time	multifunction workstation: sampler, sequencer, piano keyboard, dual displays	instrument-inspired
P07	drops in the water, ripples moving outwards and overlapping	stringed instrument held with feet; strings stretched, pulled, plucked, and manipulated	alternate instrument
P08	"any time I hear or feel sound", music coming from inside body	Ondes-Martinot inspired MIDI controller (ring-continuous control)	instrument-inspired
P09	harp strings, sound source that is distributed into a living system	interface to augment a harp. indirect acquisition of harp sound and manipulation	augmented instrument
P10	vertical layers: low basses, middle light and fast, high clear like clouds	hyperactive, need to move, two objects tethered to swing around like nunchucks.	alternate instrument

Table 3.4 Design output of the ten workshop participants: description of the "draw the music" index cards, their musical instrument prototypes as described in the presentations, instrument classification and previous experience with DMI design.



(a) Session A: P01–P03 (left to right)

(b) Session B: P04–P10 (clockwise from top left)

Fig. 3.6 Participants present their instrument prototypes in Activity 3.

- ***Instrument-like***: instruments with interfaces modeled closely after existing instruments, but that may be mapped to different functions or sound and musical outputs.
- ***Instrument-inspired***: Instruments with interface features that are derived from or inspired by existing instruments, yet are significantly altered from the original.
- ***Alternate***: Instruments that are not directly modeled on or necessarily inspired by existing instruments.

Half of the instruments can be classified as alternate instruments. While each was entirely unique, the various forms show the strong influence the materials played on the resulting designs, with each instrument prioritizing physical shapes and textures as the focus of the design. For example, P05 created a resonant physical structure built of many different types of materials (Figure 3.6b, top center). The structure would be excited by touching, tapping, rubbing or plucking different elements, which would generate audio signals to drive multiple different sound processes.

Four of the remaining five instruments can be identified as either instrument-like or instrument-inspired, taking various elements from existing instruments and repurposing them in different ways. A noticeable trend among this group was to combine the functionalities of several instruments into a single instrument, either to be able to play multiple parts simultaneously like P06's multifunction performance workstation (Figure 3.6b, top right) or to mix them together in creative ways like P02's instrument that would mix and cross-process vocals and guitar (Figure 3.6a, center).

There was one augmented instrument designed by P09 (Figure 3.6b, bottom center). This participant is an expert instrumentalist with an advanced degree in performance on her instrument, the concert harp. She has been performing electroacoustic music using harp and various external controllers and was clear in her needs and priorities as a performer, which was reflected in the pragmatic approach and practical utility of her design. (As previously mentioned, P09 and the first author are active collaborators whose work is the subject of the following chapter.)

In Andersen's Magic Machine workshops, the physical objects that are produced are design artefacts. Instead they may serve to evoke inspirations for discussion and conversation within the workshop group, or "serve as simple vessels for notions and ideas, which are somewhat or completely beyond, what is represented in the model" (Andersen, 2017, p. 63). This holds true for the Design for Performance workshops as well, and therefore the physical prototypes themselves were not analyzed in depth. Instead the key element identification and dot-voting activities, followed by the post-workshop thematic analysis of the presentations provided a rich understanding of the participants' designs.

3.4.2 Key elements, dot voting, and discussion

In this section, we examine the output of the remaining workshop activities: the key elements compiled during presentations, results and implications of the dot voting activity, and the group discussions that concluded the sessions.

Key elements

As described in Section 3.3.4, during the instrument presentations the facilitator, along with the suggestions of the presenter and other participants, identified key elements of the instrument designs and posted them on a whiteboard. We intentionally refrained from giving a strict definition for what constitutes a "key element" in hopes of drawing out intangible aspects of the designs in addition to more obvious and concrete elements. Given the short format of the presentations (three minutes to present and two minutes for discussion), this was not an exhaustive list, however with the active participation of the whole group we attempted to capture most of the essential elements of each instrument. The full list is included in Appendix C.2 showing the elements corresponding to each participant's instrument, as identified from the color-coded sticky notes.

36 elements were recorded for the three instruments in Session A and 70 elements identified for the seven instruments in Session B, for a total of 106 (averaging 10.6 elements per instrument). As the elements were posted during the presentations, they were clustered around the eight considerations the participants had been given at the start of instrument prototyping exercise (see Table 3.2). These weren't intended to be strict categorizations: the classification of some elements was ambiguous; furthermore the eight considerations chosen informally (as discussed in Section 3.3.4), intended to serve primarily as aids for the participants during the prototyping activity. However, they did provide a basic structure that helped to reveal where the attention of the designs was focused. Figure 3.7 shows the distribution of elements across the eight considerations.

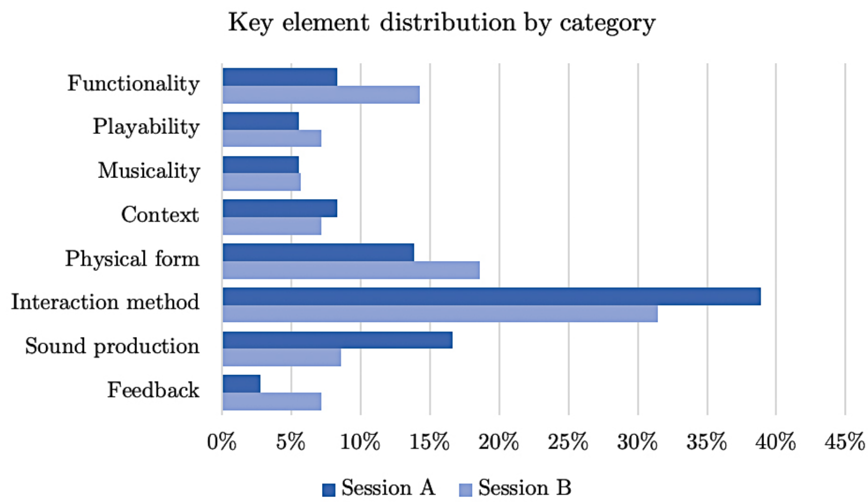


Fig. 3.7 Distribution of key elements by category (design considerations), shown as percentages of total elements identified. For Session A, N=36; for Session B, N=70.

The most common category was *interaction methods*, with roughly one third of all elements related to how the performer would interact with the instrument, naming specific types of controls (like knobs or keys) or describing techniques for playing the instrument (touching, bowing, moving, etc.). While both controls and playing techniques were classified into one category here, it is worthwhile to note that they are not strictly orthogonal. A DMI design study by (Marshall et al., 2009) had found that musicians tended to use the same control with different interaction techniques and playing strategies. Nonetheless, the frequent mention of both physical controls and instrumental technique highlights the embodied connection between a performer and their instrument that has been a strong theme in DMI research (Emerson & Egermann, 2020; Magnusson & Hurtado, 2007) and third wave HCI (S. Harrison et al., 2007)). On the other hand, the prevalence of this category may also be due in part to the structure and pace of the presentations, where describing these elements (along with physical form, which was the second most frequent category) gave the most succinct description of an instrument in a short time.

Another insight from the categorizations is that overall, the more abstract "operational qualities and usage" considerations of *functionality*, *playability*, *musicality*, and *context* received far less attention than the more concrete "design features and fundamental components" of *physical form*, *interaction methods* and *sound production* (though the fourth category *feedback* was the least identified of all). Again, we refrain from reading too much into this, because the more objective elements may have simply provided the quickest and most direct way to describe the instruments.

Dot voting and group discussion

Following the presentations, the participants dot voted for the elements that they would most want to be incorporated into a new instrument design. Table 3.5 shows the top dot voted elements from each session and Appendix C.2 shows the votes for all elements.

In planning the workshop, we imagined the key element identification and dot voting

Session A		Session B	
Element	**votes**	**Element**	**votes**
playful unreliability	3	synthesis	5
textures	3	audiovisual experience	4
modular	3	pressure sensor	4
organic	2	plucking	4
move while you play	2	MIDI output	3
blending	2	portability	3
radio	2	strings	3
touching	2		

Table 3.5 Prioritized key elements as ranked by the dot voting activity. In Session A, elements receiving more than 1 vote are shown, and in Session B, elements receiving more than two votes are shown.

steps could serve two possible functions. First, it could indicate areas of consensus (or disagreement) between the participants' designs that could inform the discussion around prospects of employing elements into functional instruments. Second, we hoped that the process on its own might suggest clear directions to orient our future functional designs.

In Session A the closing discussion followed the dot voting with conversations around several of the prioritized elements. There was a high amount of agreement despite the individual instruments being very different. In particular, the participants valued modular instrument designs that could facilitate mixing and rerouting of signals, and allow the instruments to be flexible for use in a variety of ways.

Additionally, the quality of *playful unreliability* was popular, where an instrument might behave in non-deterministic or unexpected ways, leading to novel sounds and new ways of performing. This seemingly runs counter to one of the findings of Magnusson and Hurtado's survey (discussed in Chapter 2, Section 2.3.1), in which many respondents were intolerant of this quality in digital instruments. However the underlying assumptions aren't necessarily the same. The viewpoints of our workshop participants, who are active in improvisation and experimental performance, are consistent with Chadabe's

(1984) description of *interactive composing*, in which the performer "shares control of the music with the information that is automatically generated by the computer, and that information contains unpredictable elements to which the performer reacts while performing" (Chadabe, 1984, p. 23). Thus the difference lies in the performer's understanding and expectation of an instrument. If the unreliability is intentional, it can be coopted into their performance; if unintentional, it is more likely viewed as a flawed or malfunctioning instrument.

In Session B, the discussion was relatively short as the session was nearing the two-hour mark and there was a sense that the participants were ready to leave. In addition, as there were so many elements on the board and a wide variety of elements receiving votes, it was difficult to facilitate a conversation around the distinct elements or specific design ideas. However, a comment by P07 provided a valuable observation:

> *I'd say that you can sum [an instrument] up with keywords, but sometimes what makes it special or good are all the keywords together. If you take some of the words that were thought by different brains [and put them together in a single instrument], it can turn out like Frankenstein.*

The quote elucidates the challenge of moving from the individual and idiosyncratic ideas of the participants (as expert performers and end users), to tangible design specifications that can drive instrument designs. Our intent was for the sessions to serve as a space to freely generate ideas which, as seen in the creativity of the designs, was successful. However a systematic understanding of the participants' designs failed to materialize through the dot voting and discussion activities. We can suggest two reasons for this. First, the real time identification of key design elements during the fast-paced presentations may not have captured the full essence of the instruments, especially more nuanced or less pronounced elements, and (as reflected in P07's comment) the connections between them. Second, though not explicitly intended in the workshop design, the ensuing activities (key element identification, voting and discussions) were largely organized in a top down manner, structured around the the eight pre-defined considerations given during the workshop activity.

3.5 Thematic analysis

To better understand the workshop results, an exploratory thematic analysis was conducted using the methodology presented by Braun and Clarke (2006), which we had previously employed for the qualitative analysis of an online survey (see Section 2.5). The goals of the thematic analysis are to organize and describe a data set in rich detail, and the methods are flexible to accommodate a variety of approaches. We chose an inductive approach, similar to the constant comparison method found in grounded theory (Strauss & Corbin, 1994), in which the data set is coded from the bottom up, and avoids fitting it to any preexisting framework.

Our analysis included the following steps:

1. Presentations of the ten participants were transcribed from the video recordings.
2. A round of open coding was performed on the transcribed presentations, where all codeable incidents were identified and assigned preliminary codes.
3. In a second round of coding the incidents were compared to one another to identify similarities and relationships between them, yielding the final set of codes.
4. The codes were then sorted into themes, which were in turn reviewed and refined, then defined and named.

The initial round of open coding was performed using Microsoft Excel, while the rest of the analysis was completed with NVivo[6], qualitative data analysis software. NVivo contains a powerful set of features that are particularly useful to develop a

[6] https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/

rich understanding and and deep insights out of qualitative data, such as the ability to synchronize video and audio files to text transcripts, and to link the data set to different *nodes* (emerging codes and themes) in a searchable database. This underlying structure made it possible to explore the data from different perspectives throughout the process, which helped us determine our complete list of codes and themes.

In all, 152 incidents were coded across the ten presentations, yielding 56 individual codes categorized across eleven themes. The full list of codes and themes, along with their mentions by participant, is included in Appendix C.3.

3.5.1 Design specifications

To move from open exploration in the workshops to tangible design implementations, we examined the six most common themes (which were mentioned by at least half of the participants) and formulated five of them into a set of design specifications. In Table 3.6, we list each theme with its description, a representative participant quote, and resulting design specification.

No design specification was formulated for the *performance environment* theme. As we will discuss the following section, the specifications would be applied to the design of instruments using an existing instrument framework, which carries its own set of constraints especially in terms of size, available materials and fabrication methods. While the design of large-scale audiovisual environments was appealing to several workshop participants and offers possibilities for future designs, it is beyond the practical scope of our current project.

3.6 Discussion

The Design for Performance workshops were developed as a strategy to generate novel ideas for new DMIs, using methods from contemporary HCI and participatory design,

Description	Quote	Specification
Interaction styles and input control		
Embodied physicality; materials, shapes and textures for unique tactile interactions; strings, movement and position sensing, as well as standard input controls.	"I bring in different types of textures that you can touch. Touching is an important part of it." (P03)	Combine conventional and novel interface elements that prioritize embodied, physical, and material-oriented interactions.
Signals, connections, and mapping		
Flexible, user-definable signal routing and input mapping; Eurorack-style patching, touchscreen and hardware signal matrixes, configurable wireless networks.	"There could be some kind of tactile matrix that you could change to get different sensors." (P01)	The instrument should feature flexible audio and control signal routing and mappings.
Sound production and processing		
Sampling, mixing, and layering sounds; processing external audio; synthesizing and modulating audio signals; exciting resonant acoustic objects for signal generation.	"The idea is to get a physical structure that is resonant by itself . . . then just one stroke, one gate, propagates one signal all over the other instruments." (P05)	Generate sound via external audio input and resonant acoustic features; sample, synthesize, mix, modulate and process audio signals.
Extending (or inspired by) existing instruments		
Referencing specific features, functions and playing styles of other instruments.	"This is like the poor man's version of [the Ondes Martinot], in that the original instrument is really impractical and it's really weird and old technology." (P08)	Mix familiar elements of existing instruments with novel methods of interaction and sound production.
Versatility		
Versatile, multipurpose instruments that can be used in different ways and contexts; multifunction controls and interchangeable modules.	"I wanted something that makes singing, while playing guitar, while doing lots of stuff to your voice, plus your guitar, easier." (P02)	The instrument should feature multiple modes or modules of operation that allow for a variety of playing styles.
Performance environment		
Large-scale performance environments, audiovisual elements, video projections, immersive spaces and audience interaction.	"So I am imagining I'm playing in a dome-like structure, with the world map projected on to it." (P04)	*none*

Table 3.6 Six themes generated from the workshop analysis with description, exemplar quote and resulting design specification.

which prioritize qualitative and situated approaches to design and evaluation. By bringing in expert musicians, we aimed to leverage their tacit knowledge and experience of real-world performance practice in hopes that their input could direct the design of instruments that would be appealing and viable to be taken up into musical practice. The choice to use of design fiction as a primary methodology was made for two reasons. First, by removing technological constraints and considerations, the participants were allowed to freely build non-functional prototypes with a focus on their musical practice, without worrying about the feasibility of implementing their designs into functional instruments. Second, the activity, as well as the "draw the music" prompt before it, situated the participants and designs in a fictional narrative of their own imagining. The playful aspect of the activities - the inherent absurdity of drawing music, and the "arts and crafts" approach to building an instrument - urged the participants to be creative and unconventional in their endeavors.

From a designer's point of view, this approach to capturing ideas generated by musicians, especially those that are highly creative and not bounded by the limitations of technical feasibility, can help to stave off potential creative paralysis, bringing in fresh ideas and a better understanding of priorities for performance.

3.6.1 Tools for design

A large part of the methodology designed for this project was adopted from Andersen's Magic Machine workshop playbook. Regarding the prospects for these methods to be used by other researchers, Andersen and Wakkary proposes that "the multiplicity of highly personal and interpretive content might serve as an additional and complementary resource to design and HCI workshops, which can then in turn be analyzed, annotated or simply challenge designers" (2019, p. 12). Our work here aims to apply the unique and imaginative approach of of design fiction to collaborate with expert musicians to generate creative new ideas and elements for the design of new instruments.

HCI has informed several well-structured approaches to DMI design, which were reviewed in Section 3.2. With the Design for Performance workshops we aim to align our methods with current and emerging HCI concerns, especially focusing on embodied interaction, phenomenology and qualitative methods of analysis. We find this approach to be complementary to trends in musical interface design which may combine formal engineering and technical know-how with creative practice, and where the lines between functional design and musical composition may become blurred.

The path from idea generation to the creation of functional playable instruments is similar to Calegario's Probatio (2019), in which an entire design cycle is formed. For Probatio this is achieved in a rapid succession, often in a single workshop session where ideas can be generated and directly explored in hardware, which allows for instant testing and evaluation, and rapid iteration. For this project, we envision the similar progression, but occurring on a longer time frame (including the Design for Performance workshop and subsequent iterative instrument designs), and generating high fidelity prototypes that ultimately can be suitable for use in artistic practice.

The Design for Performance workshop is intended to be one element of a larger design ecosystem. We envision an iterative design sequence in which multiple workshops can be held to evaluate and refine the resulting instrument designs, similar to the method employed by Absar and Guastavino (2015), where a sequence of three panels iterated on the development of auditory feedback to assist navigation of a visual information system. An iterative process like this could also employ the Probatio toolkit as a step in the design cycle: Ideas generated from the non-functional prototype designs could be explored in low-fidelity functional models with the Probatio hardware before moving towards the design of high-fidelity prototypes that would be viable for real world use.

3.6.2 Limitations and future work

It will be useful and instructive to run this workshop multiple times with different musicians. In reviewing the design of the workshop, two aspects stand out that merit rethinking. First, the key element identification and dot voting activities did not contribute significantly to our understanding of the instrument prototypes or the participants' design priorities. In future iterations, these activities could be redesigned, if not eliminated altogether. Second, session B ran around 1/2 hour longer than session A, and the closing discussion of session B was brief as the participants were anxious to leave. Thus, if the workshop is run again, it will be idea to limit the size to five participants or arrange the sessions so there is ample time for a more robust final discussion.

COVID-19 and the ongoing suspension of in-person research

In our own work we have applied the design specifications that were drawn from the workshop to the development of three new DMIs, which are intended to embody several of the aspects that emerged from the workshop participants' designs (which is the subject of the following Chapter). Future workshops were planned to present the prototypes back to the participants for evaluation and feedback. Unfortunately, at the time of writing they have been indefinitely postponed as the COVID-19 pandemic has forced the temporary closure of university research laboratories and suspension of in-person research until the health risks are alleviated.

While COVID-19 represents a serious and ongoing situation around the world, we remain optimistic that it will be brought under control in due time. As such, while it is disruptive to our immediate applied research plans, we look forward to continuing our design research in-person with participants when it is safe. Additionally, while we haven't applied it this particular situation, there are a variety of tools and methods available to conduct DMI workshops and evaluations remotely through videoconferencing and asynchronous activities (such as recording and uploading practice sessions). However, this requires a thorough evaluation of potential methods and ramifications of this approach, and is not planned for this particular project.

Generic vs. idiosyncratic design

The comment by P07 in the closing workshop discussion brings to mind the idea of specificity in design. The participants each created an instrument that was personalized for their own needs and practice, and by combining elements of several different instruments into a single design (the Frankenstein instrument), the essence of any single one may be lost.

On one hand, we are motivated to orient our designs to address areas of concern for general performers. This is shown through our analysis of the workshop designs and presentations, which found many design elements that were shared by several of the participants. This presents the opportunity to design instruments that could be used by different performers across different contexts, possibly improving an instrument's chance for long-term and widespread adoption. On the other hand, P07's comment speaks to the idiosyncrasy that characterizes field of DMI design, especially where design and performance roles commonly overlap.

While this issue is not covered in depth here, our continued work explores both angles, first through the design of multiple DMIs intended for a nonspecific user and encapsulating several elements of the participants' designs (Chapter 4), and then though a focused collaboration with a single performer to develop bespoke interfaces for their unique musical practice (Chapter 5). Ultimately, it may not be an all or nothing proposition, and there is benefit in considering both views together. Performers operating in similar contexts may benefit from designs that emerge from the ideas of many, yet at the same time require more specific and individualized needs to be met.

3.6.3 Conclusion

Here we have reported on a novel approach to generate ideas for the design of new DMIs based on a design workshop methodology that employs design fiction, allowing workshop participants to freely imagine and craft non-functional instrument prototypes. The workshop design is adapted from Andersen's Magic Machine Workshops (Andersen, 2017) and is informed by theories for DMI development based on previous design frameworks and HCI literature. In particular the approach emphasizes the tacit knowledge of the participants, in our case, expert musicians, towards the development of new instruments that would be appealing for performers to take up into real-world use.

We began by reviewing previous research around DMI design, including motivations for the design and use of new instruments, and various design frameworks that have been proposed. Then we introduced the Design for Performance workshop, which we ran with 10 participants divided into two sessions. We have presented the methodology and results, which included thematic analysis of video-recorded participant presentations and discussions. We found that several design aspects were shared across many of the participants' designs, which we used to develop a list of design specifications.

As a continuation to this project (which is presented in Chapter 4), we have applied these specifications to the design of three new instruments that are intended to embody many of the desirable aspects presented by the workshop participants. We also envision future workshops, not only to design new instruments, but also to present our current and ongoing designs for feedback and continued iteration.

Beyond the generation of practical design specifications based on the outcome the workshop that we ran, we also present this research as a methodological contribution of a unique and creative approach to early design stages of idea generation and non-functional prototyping that can serve as the initial steps towards the development of high quality, functional and finished prototypes. These methods, while developed for

DMI design, are appropriate for a wide range of applications with within and beyond the creative arts.

Chapter 4

Reinventing the Noisebox: On the Technical Design of Three Novel DMIs

This chapter is based on the following published research article. It has been adapted to include additional content connecting it to the previous chapter and to eliminate redundant material.

- Sullivan, J., Vanasse, J., Guastavino, C., & Wanderley, M. M. (2020). Reinventing the Noisebox: Designing Embedded Instruments for Active Musicians. *Proceedings of the International Conference on New Interfaces for Musical Expression*, 5–10.

Abstract

This paper reports on the user-driven redesign of an embedded digital musical instrument that has yielded a trio of new instruments, informed by early user feedback and design workshops organized with expert musicians. Collectively, they share a stand-alone design, digitally fabricated enclosures, and a common sensor acquisition and sound synthesis architecture, yet each is unique in its playing technique and sonic output. We focus on the technical design of the instruments and provide examples of key design specifications

that were derived from user input, while reflecting on the challenges to, and opportunities for, creating instruments that support active practices of performing musicians.

4.1 Introduction

In the previous chapter, we presented the Design for Performance workshop, where participants crafted imaginary instrument prototypes in a design fiction activity. The analysis that followed identified novel concepts for new instruments, desirable features and other intangible elements that were encapsulated into the following five high-level design specifications towards the design of instruments fit for use in the participants' performance practices:

1. Instruments should combine conventional and novel interface elements that prioritize embodied, physical, and material-oriented interactions.
2. Instruments should feature flexible audio and control signal routing and mappings.
3. Instruments should generate sound via external audio input and resonant acoustic features; sample, synthesize, mix, modulate and process audio signals.
4. Instruments should mix familiar elements of existing instruments with novel methods of interaction and sound production.
5. Instruments should feature multiple modes or modules of operation that allow for a variety of playing styles.

In this chapter we describe the development of three new DMIs developed from these specifications. The instruments are based on an existing platform for embedded DMIs called Noiseboxes. They share a set of basic attributes including their standalone design, digitally fabricated enclosures, and common sensor acquisition and sound synthesis architectures. However each of the new instruments is unique in its playing

	Advantages	Disadvantages
Design from scratch	• Start with a blank slate • Allow full participation by users in the design process	• Time and resources spent re-engineering core components • Could lead to impractical or unbuildable designs
Utilize preexisting framework	• Establish useful constraints • Leverage tested and reliable tools, methods and expertise • Rethink previous designs towards long-term, professional use	• Limits user participation later in the design process • Places limits on creative freedom

Table 4.1 Advantages and disadvantages of designing from scratch versus building off a preexisting instrument framework.

technique, sonic output and signature features, which were driven by the ideas presented in the workshops.

4.1.1 Recycling technology

The choice to employ ideas generated from the workshop into an existing instrument framework versus designing from the ground up represented a tradeoff, balancing a number of advantages and disadvantages for each option, which are listed in Table 4.1. Most importantly, while designing from scratch would allow for complete creative freedom throughout the process (and potentially the capacity to most fully recreate some of the workshop designs), building off the existing platform would leverage an established, well-tested set of design methods, tools and core technologies, and impose practical design constraints in terms of size, interaction capabilities, and materials, while still remaining open and flexible to support new creative designs.

Another aspect of our choice to utilize a preexisting framework (the third advantage listed in Table 4.1) reflects one of our fundamental design objectives. We are motivated to develop new instruments that are viable for, and appealing to, experts and professional musicians, and can support long-term use and engagement in real world musical practice. As discussed previously (in Chapter 3, Section 3.2.1) DMIs are frequently designed within specific research contexts and not necessarily intended for artistic use. This has been the case with the Noisebox series of instruments that were designed as research probes for various projects. By linking the creative ideas generated from the workshop of expert musicians to our previous design research, we see the opportunity to reorient our focus towards the development of performance-ready instruments intended for use in applied artistic practice.

4.2 A brief history of the Noiseboxes

The original Noiseboxes were conceived out of practice-based research and development of *embedded acoustic instruments*, defined by Berdahl (2014) as an instrument that is self contained with an onboard processor and direct sound output. While many previous DMIs have had embedded sounds (such as the Buchla Lightening), the distinguishing characteristic is the programmability of the processor versus the limited functionality of an embedded sound card. Each Noisebox carries out its own computation with a Raspberry Pi or similar single-board computer and produces sound via onboard amplification and mounted loudspeakers, while integrated sensors provide user control of sound synthesis parameters.

The instruments are fully standalone with the inclusion of an internal rechargeable battery. One of our original aims with the Noisebox design was to imbue a digital instrument with some inherent qualities of conventional acoustic instruments that may be missed on a DMI. For one, onboard sound production and battery power make for immediate playability with no need for connections, configurations or additional hardware to get started. For another, a standalone instrument combines input device and sound production into one cohesive unit, reversing a defining attribute of DMIs (the decoupling of control from sound production (Miranda & Wanderley, 2006, p. 1).

4.2.1 Technical design

Two distinct versions of the Noisebox were developed, yielding multiple copies of each. The first version (top center and right of Figure 4.1) utilized the Satellite CCRMA framework for embedded instruments Berdahl and Ju, 2011, comprised of a Raspberry Pi for sound synthesis, onboard mapping and general system functions, an Arduino Nano microcontroller for sensor acquisition, and a custom Linux (Raspbian) distribution. Mapping and audio programming was done in the Pure Data,[1] an open source visual programming language for audio and multimedia applications.

Sonically, the instrument functions as a "drone box". It is comprised of a polyphonic FM (frequency modulation) synthesizer with embedded sensors mounted on the laser cut enclosure to control the number of voices and their frequencies. An internally mounted inertial measurement unit (IMU) modulates various timbral parameters with the instrument's movement and orientation. An enhanced model was also produced that included delay and reverb effects and sound presets that could be interpolated.

A second version (bottom center and left of Figure 4.1) of the instruments was constructed the following year. The instruments functioned similarly to the v1 instruments, and also included a base model and an enhanced model equipped with additional effects. However the underlying architecture was redesigned to use an early version of the *Prynth* framework for embedded instruments (Franco, 2019).[2] Similar to Satellite CCRMA, Prynth uses a Raspberry Pi as the processing base, but utilizes purpose-designed printed circuit boards (PCBs) with an integrated Teensy 3.2 microcontroller

[1]https://puredata.info/
[2]https://prynth.github.io/

Fig. 4.1 The Noiseboxes, v1 & v2 *(Clockwise from top middle)*: v1 initial prototype, v1 finished, v1 with additional controls and audio FX, v2 with additional controls and FX, a quartet of v2 instruments.

for sensor acquisition, and uses the SuperCollider[3] open source programming language for onboard audio processing and mapping (Wilson et al., 2011).

The move from Satellite CCRMA to Prynth offered a few distinct advantages. The custom Prynth software and hardware allows for simple connection and setup of analog sensors that can be immediately accessed in the main instrument code. Another key feature of Prynth it runs a web server that can be accessed through any network-connected browser. This provides convenient access to system setup and configuration options, as well as a SuperCollider code editor for direct programming of the instrument.

4.2.2 User feedback

For the second version of Noiseboxes we ran a small pilot study that explored how performers appropriate new instruments and develop personalized playing styles. Following the protocol of a previous study conducted by Zappi and McPherson (2014), we gave four participants an instrument to take home for one month. After two weeks they returned individually to report on their progress and give a short demonstration performance with the instruments. At the end of the month they returned as a group to give another performance, this time with a small invited audience in attendance. Feedback was collected from the participants and audience members through interviews, questionnaires and a round table discussion.

While much of the feedback – and study – concerned the participants' engagement and development with the instrument, some key issues with the instrument design were identified that would disqualify it from real-world use. Overall sound quality was lacking, mostly because of the inexpensive small onboard speakers but also due to component failure in one of the instruments. Participants and audience members alike recommended more interesting sound synthesis, greater variety of sounds, and better user controls for

[3]https://supercollider.github.io/

(a) The Keybox. (b) The Stringbox. (c) The Tapbox.

Fig. 4.2 CAD renderings of three new instruments.

sound parameters. [4] Performers reported noticeable latency between user input and sound, which made the instrument feel unresponsive and difficult to control. Finally, while the "retro" aesthetic of the instrument was appreciated, the sharp corners of the laser cut acrylic enclosure and location/placement of controls made the instrument uncomfortable and difficult to play.

4.3 Reinventing the Noisebox

With our new instrument designs, we wanted to reinvent the Noisebox, not only to rectify of the issues identified with the previous versions but also to explore novel instrumental designs, features and functions. The result is three new instruments that combine feedback and lessons learned from the original designs with new ideas from our workshop participants, and crafted using improved and refined methods and tools for computer-aided design (CAD) and fabrication (Figure 4.2).

The new instrument designs were guided by the five original design specifications that emerged from the Design from Performance workshops presented in Chapter 3.

[4]While beyond scope of the discussion here, it is interesting to note that this seems to be a common finding in DMI research, and may be connected to a perception about the potential of electronic and digital instruments as opposed to their acoustic counterparts (Magnusson & Hurtado, 2007). Fyans and Gurevich (2011) found that spectators assess skill as a largely embodied phenomenon; capabilities of acoustic instruments are implicitly understood, but for electronic or digital instruments it is more speculative (either suggesting "infinite" potential or alternately lacking any frame of reference to judge skill or assess potential).

Fig. 4.3 The Keybox.

We begin by introducing each of the designs in detail, after which, in Section 4.4.1, we review the explicit links between workshop output and instrument designs.

4.3.1 Instrument 1: The Keybox

Our first instrument in this series is a radical departure from the largely inharmonic noise-based timbres of the past versions. The Keybox (pictured in Figure 4.3) is a two-oscillator polyphonic subtractive synth featuring a Moog-style low pass filter, amplitude envelope, effects section, and looper with external audio input. It is equipped with an onboard OLED display, four multifunction rotary encoders, 8 buttons and a 20-note piano-style capacitive touch keyboard. Whereas the previous Noiseboxes were best at producing dense swarming chaotic drones, the Keybox is immediately easy to play, control and understand, while the multifunction encoders, buttons and display provide access to a host of parameters for deep modulation and sound design.

The Keybox utilizes the same computing hardware as its predecessor, utilizing a Raspberry Pi 3 Model B+ for audio processing and general system function, and a

Teensy 3.2 microcontroller for sensor acquisition. However the software framework has been redesigned from the ground up, addressing two limitations we experienced with the previous Prynth-based instruments. First, while the Prynth framework is designed for automatic acquisition of analog sensor data, connecting digital sensors (such as the IMU for acquiring motion data and the capacitive touch sensors for the keyboard) is non-trivial and requires extensive modification of the existing Prynth code and external libraries to configure correctly.[5] Second, latency (the time delay between input gesture and sonic result) was an ongoing issue with the previous Noiseboxes. In an early prototype of the Keybox running the Prynth framework, we were able to alleviate some of it through code optimizations but we still regularly encountered latency between 20ms and 70ms for note-based interactions, above the generally accepted threshold for acceptable latency of 10ms, as suggested by Wessel and Wright (2001).

Because we were not dependent on some of the primary features of Prynth like the browser-based coding environment and GUI-based configuration panels, and our use of specialized sensors had already demanded significant customization of the firmware, we opted to forego the Prynth software framework and write our own lightweight code that would accommodate both analog and digital sensors while further reduce latency. In the new system, sensor data is encoded on the Teensy using the *Consistent Overhead Byte Stuffing* (COBS) protocol (Cheshire & Baker, 1997). This formats the data in an extremely small and efficient format for transmission over the hardware serial bus to the Raspberry Pi, where it is directly received and parsed by SuperCollider which handles all of the control mapping and audio synthesis. The improvement has been significant, with no noticeable latency when playing the keyboard.

The onboard display functions separately from the rest of the instrument processing.

[5] Digital sensor integration was a known limitation with the previous Prynth-based Noiseboxes we built, which were meant to use digital IMUs. For those we had replaced the IMUs with a simpler analog accelerometer.

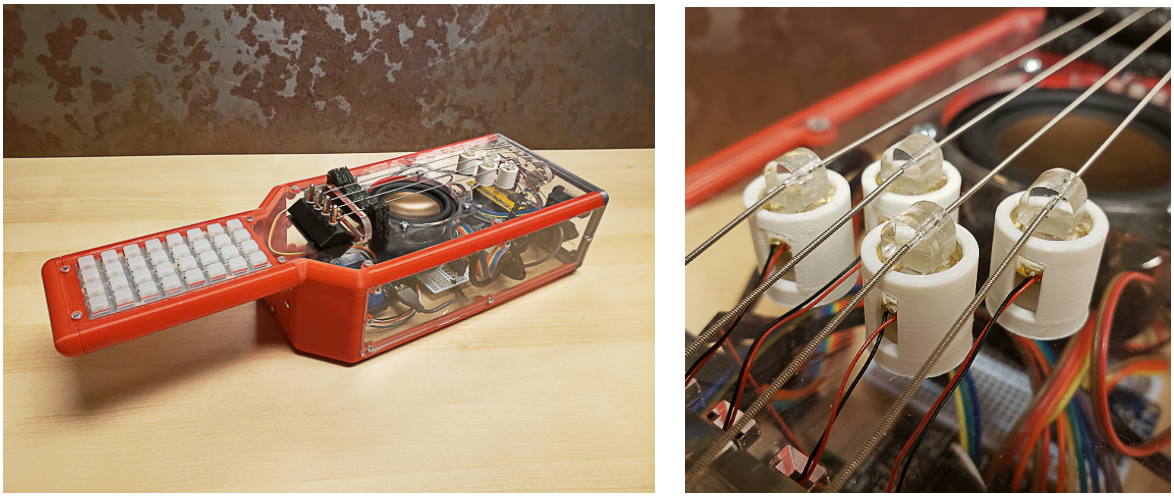
When parameters change, new data is sent as OSC (Open Sound Control) messages from SuperCollider to a Python script which updates the display. The display can move between several pages of grouped parameters with the two red buttons to its left. Each page displays eight parameters, mapped to the four rotary encoders and four buttons to the right of the display.

The fabrication of the Keybox and the other new instruments have been refined as well. The enclosures are constructed from a combination of 3D printed frame assemblies and laser cut panels. While the instruments are mostly true to their "box" names, our updated fabrication materials and methods permit rounded, smooth edges for a more ergonomic feel, and allow for the possibility of alternate shapes, angles and more freeform designs.

While the Keybox is finished and playable at present, we continue to make incremental enhancements. In its current form it lacks direct sound output, but an updated version of the enclosure will include onboard amplification, which is a feature of the other instruments. Additionally, we have installed an IMU that will map movement of the instrument to user-selectable sound parameters.

4.3.2 Instrument 2: The Stringbox

The Stringbox (pictured in Figure 4.4a) is a digital synthesizer inspired by the form and function of a ukulele. The primary function of the instrument is a physically modeled string synthesizer that can be played in traditional guitar (or ukulele) fashion. Four strings provide an excitation source through plucking or picking (or alternately by bowing, rubbing, scraping, etc.) A 4x8 matrix of soft elastomer buttons sit on the short neck of the instrument that can be pressed as fingerings on a fretboard to determine the pitch of the corresponding string's note. A simple implementation of the Karplus-Strong synthesis algorithm (Karplus & Strong, 1983) provides a string-like sound, and the instrument can be played as one would play a ukulele.



(a) The Stringbox. (b) Detail of the pickup assemblies.

Fig. 4.4 The Stringbox.

Alternately, a separate mode can fully reconfigure the instrument, and while the physical and visual similarities may remain, it becomes totally different. In this mode, the 4x8 grid can function as a sequencer, with different pages to determine sound sources and synthesis algorithms, sequences and arpeggios, while the strings can be manipulated by the user to modulate the corresponding audio track. This flexibility highlights a unique quality of DMIs, that one design can be made into different instruments. The choice of different interaction strategies can been plotted on Malloch et al.'s model of music interaction and performance contexts discussed in the previous chapter (Section 3.2, Figure 3.1), in which the Stringbox can alternately function in the skill/signal or rule/sign domains.

The core hardware of the Stringbox is the same as the Keybox. A Teensy 3.2 receives sensor data, encodes it with the COBS protocol and sends it to SuperCollider running on a Raspberry Pi for audio synthesis and processing. The string pickups shown in Figure 4.4b) are made from small piezoelectric elements sandwiched between rigid discs of laser cut acrylic and mounted in a flexible 3D-printed housing. The pickup design is based on the approach developed by J. Harrison et al. (2018), where string excitation is carried to the coupled piezo, which outputs a corresponding voltage that is passed to an analog input of the Teensy. Two types of data are extracted from the piezo input: an event trigger with corresponding velocity (as with the initial pluck of a string), and a continuous data stream resulting from the vibration of a plucked string or sustained excitation (as in the case of a bowed string or other string interaction).

An onboard speaker gives the player an option for direct sound output, while audio can also be routed through a parallel audio output jack. An embedded IMU allows for further modulation of sound parameters though the movement of the instrument. While the hardware is finalized, additional features are planned for the instrument including additional synthesis models and deeper functionality of the sequencer module.

Instrument 3: The Tapbox

The third and final instrument in the series is a digital percussion instrument (pictured in Figure 4.5). Each face of the rectangular instrument consists of a discrete panel that "floats" on rubber washers attaching it to the instrument frame. Five of the faces are equipped with large piezoelectric elements held flush to the inside of each panel, each mapped to a different voice of the embedded synthesizer. The instrument can be played by drumming, tapping, knocking and rubbing the various surfaces of the instrument and exciting the different synth voices. The final face is equipped with two small speakers, USB ports for charging and reprogramming purposes, and a volume/multipurpose slider.

An IMU is embedded within the instrument which, in addition to modulating synthesis parameters based on movement, serves a particular function. There are two synthesis modes mapped to the instrument which can be selected and mixed based on the absolute orientation of the instrument.

In its normal upright state, signals from the piezoelectric elements are each routed

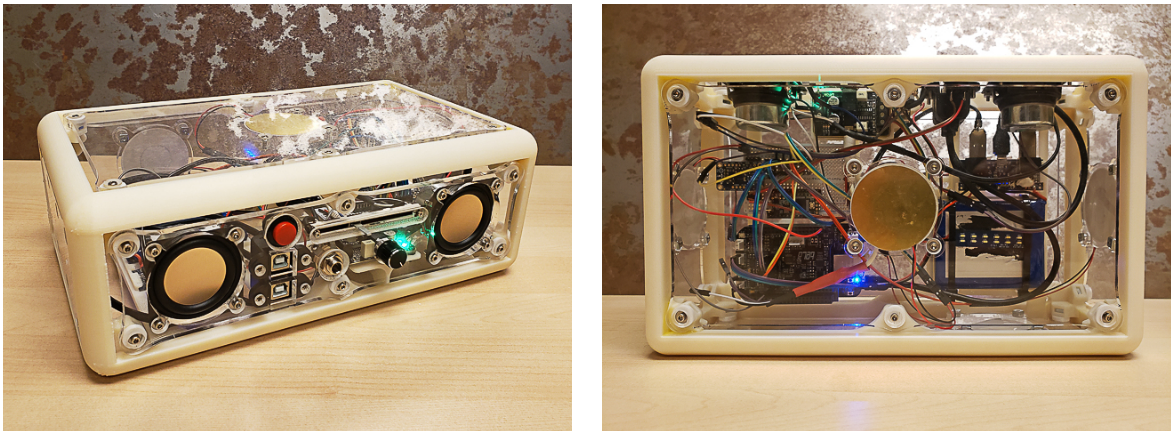


Fig. 4.5 Side and top views of the Tapbox.

to a physical model of an N-segmented tube. This produces a unique bell-like tone for each interaction. Rotation and movement of the instrument changes the parameters of the virtual tube segments, modulating the frequency, duration and timbre of the tones.

When the instrument is rotated into an upside-down orientation, the controls are mapped to a synthesized drum set, with each face a trigger for a different drum or cymbal. As with the first mode, movement and rotation can modulate the drum sounds in different interesting ways. Additionally, with the instrument held near the midpoint between the two, the modes are cross-faded proportional to the angle of orientation.

The synthesis method for the first mode processes audio directly from the piezo-electric element, whereas the second uses a layer of feature extraction to trigger sample playback when an onset (strike or slap, etc.) is detected. These two methods are extreme ends of a continuum, and any combination of feature extraction and audio signal can be mapped to synthesis parameters.

The technical design and hardware of the Tapbox is a slight departure from the architecture of the Keybox and Stringbox, as it is built on the Bela[6] platform (McPherson & Zappi, 2015) which runs on a BeagleBone Black single board computer. Percussion

[6] https://bela.io/

tasks demand considerably lower latency than other more legato instrumental gestures. Selected for its exceptionally low latency and readily accessible audio rate signal acquisition in comparison to other embedded hardware platforms (Meneses et al., 2019), the Bela proved to be the ideal platform to bring this instrument to fruition.

Interestingly, the physical construction of the Tapbox revealed an unforeseen issue: the shape, size and color of the two speakers mounted on one panel are similar to the round piezoelectric elements on all other sides (see Figure 4.5: the speakers are shown on left, while the top panel with piezoelectric element is shown on right). In preliminary tests users mistakenly tapped directly on the speakers thinking they were the elements. There are a variety of simple ways to address this in future builds (e.g., use a different size/shape/color of speaker, or incorporate a protective speaker covering), however this is an interesting design issue that was not obvious to foresee in advance even with highly detailed and accurate digital prototypes.

As with the other instruments, we continue to explore ways to improve the Tapbox. We are experimenting with various preparations of the panels, applying several materials to bring a diversity of textures into instrument play. Rippled hot glue, felt, tree bark and glued pebbles can decorate the sides of the instrument that provide the performer with an array of surfaces to hold, rub, or strike. On the flat felt, hand slapping is effective; on the pebbles rubbing like a güiro is a possible playing technique.

4.4 Discussion

4.4.1 From Design specification to implementation

The three instruments represent a synthesis of our own accumulated knowledge and experience in embedded instrument design with the imaginative ideas and recommendations of expert musicians. In Table 4.4.2, we reprise the five design specifications that came from the Design for Performance workshops in the previous chapter (listed in Section 4.1), and show the the detailed implementations across the three instruments.

The specifications informed the designs at many different levels. Some were applied at the universal level to all instruments. For example, the modular software design was motivated by the fifth specification **versatility**. This entailed developing a single codebase used by all the instruments, where the unique features of each (like the various synthesis/effects units and different input devices) were constructed as modules that connect in a fixed framework with signals flexibly routed to meet the particular needs of the instrument.

The specifications also inspired creative design choices for particular features on the different instruments. For example, interest in physical and tactile interactions (#1, **interaction styles and input control**) and resonant objects and acoustic sound production (#3, **sound production and processing**) led to the development of two novel systems that utilize piezoelectric sensors to interact with physical models of acoustic sounds (Stringbox and Tapbox). The fourth specification of **extending or being inspired by existing instruments** was applied to all three instruments in a variety of different ways that are unique to each instrument.

4.4.2 Future work

With the instruments completed, an important next step will be to put them into the hands of musicians for testing and evaluation. We aim for a longitudinal approach, which will allow musicians to keep an instrument for several weeks or even months. While less common than other more short term methods of evaluation, this approach has been successfully used in DMI design and offers several benefits. It can be valuable in understanding changes over time such as frequency of use, users' attitudes towards the instrument, or development of playing technique and skill) (Gelineck & Serafin, 2012).

Table 4.2: Each of the five design specifications are listed with their precise implementations across the three new instruments.

	Keybox	**Stringbox**	**Tapbox**
1. Interaction styles and input control: Combine standard controls with with novel interface elements that prioritize embodied, physical, material-oriented interactions.			
standard input controls	All instruments feature a number of standard input controls, including buttons, knobs and sliders.		
physical and tactile interaction		Strings for plucking, bowing, tapping, scraping, etc.	Panels detect touch, tap and other tactile interactions Experiments with prepared surfaces
movement position and sensing	All instruments are equipped with motion tracking sensors and software to map movement to effects parameters.		Orientation-based interpolation of dual synthesis modes
2. Signals, connections and mapping: The instrument should feature flexible audio and control signal routing and mappings.			
signal routing (see Modularity below)	Audio passes through discrete processing modules	Signal routing matrix planned for the grid interface	
mapping		Dual modes remap controls to different parameters	Complex mapping of motion data to control multiple parameters simultaneously
3. Sound production and processing: Generate sound via external audio input and resonant acoustic features; sample, synthesize, mix, modulate and process audio signals.			
external audio input	Keybox and Stringbox are equipped to receive an external audio input for realtime sampling and looping.		
resonant objects and acoustic sound production		Replicating acoustic sound production with strings, piezoelectric pickups and physically modeled string synthesis	Entire instrument as "sounding object" with surfaces mapped to sounds
mixing and layering sounds	Synthesized and external sounds can be mixed and processed together	Planned matrix signal routing mode	Movement and orientation mixes between two synthesis modes

Table 4.2: Each of the five design specifications are listed with their precise implementations across the three new instruments (cont.)

	Keybox	Stringbox	Tapbox
synthesis	2-oscillator subtractive synthesis	"Guitar-like" mode uses physical modeling to synthesize strings.	Dual synthesis modes: drum machine (subtractive synthesis) & pitched percussion (physical modeling)
sampling	Live looper and delay to record, sample and overdub external and synthesized audio	Sequencer mode designed for samples and external audio input	
4. Extending, or inspired by, existing instruments: Mix familiar elements of existing instruments with novel methods of interaction and sounds production.			
reproduce features	Piano-style keyboard	Guitar strings and pickups	
playing style		Play like a guitar with strings and 4x8 grid for note selection	Playing style inspired by Latin American percussion instruments (cajon & pandeiro)
functions	Classic keyboard synth functions		808-style drum sounds
5. Versatility: The instrument should feature multiple modes or modules of operation that allow for a variety of playing styles.			
combining functions	Synth / live looper / FX processor	Dual modes: "guitar-like" and sequencer	dual synthesis modes: drum machine and pitched percussion
flexible and multipurpose controls	multifunction knobs and buttons	multifunction grid controller	
modularity	Modular software framework with discrete components for audio input, synthesis, effects processing, mixing, and audio output		

It can also help to measure long-term engagement, which we found in previous work to be a key factor in the success of new DMIs (see Chapter 2, Section 2.5.3). Additionally, it can allow for study of the instrument outside of controlled settings (for example, in the lab or at a workshop) and evaluated through real-world musical practice (Elblaus, 2018). This is highly relevant for our own research, which is aimed at developing instruments expressly for active and professional musicians.

Furthermore, designing an instrument is a difficult task, and one that is seldom done in one try. The designer and researcher Buxton famously said that *artistic spec* was the most demanding and exacting design specification to achieve, more so than *military* or *standard spec* (1997). Thus we anticipate additional iterative design cycles to continue improving the instruments. As mentioned in the previous chapter (Section 3.6.2), the designs of these three instruments had been planned in sequence with a series of workshops, in which the instruments would be presented back to the Design for Performance workshop participants for evaluation and further design input. However, with the suspension of in-person research activities due to the ongoing COVID-19 pandemic, the additional workshop sessions remain indefinitely suspended.

4.4.3 Crafting a design methodology

In addition to the practical aims of this work, which are practice-based and committed to designing and building professional-level DMIs, we are also interested in developing a structured approach to guide our own practice and offer to other researchers and designers. We do this while accepting that DMI design is often a highly personalized endeavor and, consistent with prevailing attitudes in NIME and HCI, there is no one correct path to follow. However, through our study of the design literature and utilization of innovative tools and methods, we are working towards a unified methodology that consists of tools for design (presented in Chapter 3, Section 3.6.1) and tools for prototyping, presented here.

Tools for prototyping

The creation of functional prototypes is facilitated by a technical instrument framework has been developed and refined through the previous Noisebox instruments and the three new instruments presented here. Drawing from existing frameworks for embedded instruments, it includes the use of readily available hardware that comprise a generic instrument base: a Raspberry Pi or similar single board computer that can run the SuperCollider programming language and an Arduino-compatible microcontroller for sensor acquisition.[7] The enclosures are designed in CAD software with the aid of several standard templates and conventions, and fabricated using conventional rapid prototyping methods of laser cutting and 3D printing. A single software framework has been developed in SuperCollider that forms the basic core instrument, and the particular instrument functionality (including input acquisition, mapping and sound generation and processing) can be written as individual modules that can be added to the framework and flexibly routed.

4.4.4 Closing remarks

This chapter has reported on the technical design of three new DMIs that implemented design specifications drawn from design workshops that we held with expert musicians. The three instruments presented here represent a dedicated focus on the development of new digital musical instruments that will be both appealing and robust for long-term, engaged use in real-world performance practice. We believe that our user-driven approach may ultimately lead to greater uptake and longer term use than many DMIs currently experience.

Our work here is only one part of the equation towards bringing DMIs into more active performance practices. For one, there is a distinction to be made between commercially available instruments which benefit from industrial-production technologies and non-commercial DMIs designed and constructed using readily available maker tools

[7] If the Bela system is used, as was with the Tapbox, the hardware requirements are slightly different: a BeagleBone Black replaces the Raspberry Pi and additional Bela hardware is required; additionally the microcontroller is not required in most cases.

and technologies. Furthermore, it is vital to acknowledge the important role that community-building plays in the development of performance practices around new instruments.

However, with this and related work, we hope to promote design processes involving performers to best meet their needs in terms of DMI use and performance within and beyond NIME, with new tools and new techniques to support ever-evolving musical practices.

Chapter 5

Designing Musical Interfaces for Professionals: A Case Study of the Augmented Harp

5.1 Introduction

The previous two chapters reported on two connected projects that explored methods to conceive of and develop novel digital musical instruments that would be viable for use in real-world applications by expert musicians. The approach utilized theories and methods from established DMI design and HCI research, applying creative ideas generated from user workshops to the design and production of functional and robust DMI prototypes. The finished instruments are assumed for use by "typical" expert DMI users, defined by criteria used in selection of participants for that study: active musicians that perform regularly in public, play music typical of DMI use (including but not limited to electronic, electroacoustic and experimental styles), and that regularly use digital instruments, interfaces or related technologies in their practice.

The choice to design for a general user was a conscious response to observed trends in DMI research, where novel instruments are seldom adopted into widespread use (see Chapter 2, Section 2.1 for a discussion). Based on the input of expert musicians that participated in our previous design workshop, the instruments were designed to accommodate a range of performance situations and styles, implementing multifunctional capabilities that mixed conventional and novel elements together. In this scenario, details regarding the specific use contexts are not identified (for example, whether playing solo or in groups, or if the instrument is used with or alongside others in a musician's performance setup).

In this chapter, the focus shifts to the development of bespoke musical interfaces designed for a professional musician. This shift in focus reflects a more common approach found in DMI research, in which the design of instruments is tightly coupled with the performer. In some cases the designer and performer may be the same person, as was found in previous surveys by Magnusson and Hurtado (2008) and Paine (2010); in our case the role of design is shared between the designer and performer.

This co-design approach presented in this chapter carries with it some important implications. First, the work represents a long-term collaboration between me and a musician to develop performance tools tailored to the unique needs of their practice. Second, in contrast to the creative designs of our previous instruments which were inspired by the artistic imaginings generated from design fiction workshops (as discussed in Chapters 3 and 4), the interfaces developed for this project are built to accommodate the particular demands of the performer and prioritize qualities intended to ensure their viability for long-term and professional use. These qualities were identified in a previous survey and presented as a set of design considerations (in Chapter 2, Section 2.6.1). Finally, the ultimate aims of the designed interfaces are purely musical. Where the development of our previous instruments was at least partially carried out as theoretical research in design and HCI, my work here is focused on the practical development of new DMIs that will be directly integrated into a performer's real-world live performance.

Taken together, the two design approaches that are presented in this thesis - the first informed by group workshops and applied to instruments for general users (Chapters 3 and 4), and the second focused on one to one collaboration (in this chapter) - are intended to explore diverse approaches to design, and each exhibit their own strengths and weaknesses. Ultimately, there may be opportunity to combine approaches, where design workshops and early prototyping with musicians can lead to dedicated collaborations with skilled designers and instrument makers, that can extend unique ideas into tangible instruments.

5.1.1 The concert harp: A case study

The design focus of this chapter is the concert harp. Specifically, it concerns augmentation of the concert harp to allow a harpist to perform a solo electroacoustic concert that combines traditional harp playing with realtime digital audio sampling, effects processing and control of live visuals. The work comes out of a long-term collaboration between professional classical concert harpist Alexandra Tibbitts and myself that has spanned over four years. It encompasses two distinct projects, however they are presented here together as they are closely connected and show an evolution of knowledge and practice in the area of harp augmentation, and more generally design for professional performance.

The impetus for our collaboration came with a performance Tibbitts and I gave together of the "Concerto Techno", a piece for harp, live electronics and orchestra by composer and harpist Caroline Lizotte (n.d.) that mixes elements of contemporary classical and electronic house music. One aspect that stood out in particular was the clear separation of roles: the harpist playing a conventional concert harp (albeit with the use of occasional extended techniques like the use of found objects to play percussive passages on the body and tuning pegs of the instrument), while the accompanist performs the electronic elements.[1] During rehearsals and after the performance, we were interested in mixing these roles, especially for the harpist. This lead to our motivation to develop our own performance tools that would allow Tibbitts to move towards more experimental and technology-driven modes of performance and development of new original music.

If our experience performing together sparked the initial interest in collaborating, it was one of Cook's "Principles for Designing Computer Music Controllers" that provided the basis of our research inquiry: "Some players have spare bandwidth, some do not" (Cook, 2001, p. 3). The concept of *bandwidth* in this context refers to the available physical – and also cognitive – capacity to carry out multiple tasks simultaneously. In Cook's paper he uses the trumpet as an example of "spare bandwidth": simply speaking, a trumpet can be played with as little as one hand and the mouth, leaving the other hand, fingers, legs and feet free and potentially available for other tasks. But the concert harp is played with both hands and both feet, requiring a full-body physical engagement to command the large instrument. In Cook's terminology, the harpist has very little spare bandwidth. This poses unique challenges for the design of musical interactions, and was a continual point of reference and consideration across the two projects. It is important to note, however, that Cook's principle is a bit of an oversimplification of the concept. Pressing, whose research has dealt with cognitive processes in improvisation and musical complexity, emphasizes that cognitive limitations impose greater restrictions that do physical limitations (1990), ergo the concept of "bandwidth" is necessarily more complex than simply measuring available physical affordances and could also be extended to processes of learning and development. This point is revisited later in the

[1] In our performance, and commonly in Lizotte's own performances of the piece where a live orchestra is not feasible, the sampled orchestral parts are triggered by the accompanist.

chapter, where reflection on the system design versus the needs/expectations of the composition is given.

Chapter structure

In Section 5.2, we review related work that provides the basis for our own work in this chapter at three distinct levels: practice-based DMI research that combines design and artistic performance, design for professional contexts, and lastly, the design of augmented acoustic instruments, including previous investigations of harp augmentation. Two research-performance projects are then presented. Section 5.3 introduces the first, “Gestural Control of Augmented Instrumental Performance”, in which a study of movement in harp performance informed the design and implementation of a system for augmenting a harpists’ natural playing motions with gesture-based control of computer effects and processing. Section 5.4 then introduces the “The Bionic Harpist” project, in which custom performance interfaces were developed for the concert harp for control of digital audio and visual effects in a solo live performance. In Section 5.5, we reflect on the methods that guided the design process, and the collaborative approach that the projects used. We conclude by enumerating lessons learned throughout the projects that we hope can be of use to other designers, and discuss prospects and plans for continued work and collaboration.

5.2 Related work

5.2.1 Practice-based research

As has been pointed out previously in this thesis, the field of DMI design is highly interdisciplinary (see Chapter 2, Section 2.2 for a discussion). For a discipline that is deeply rooted in technology, engineering and computer science, many practitioners are highly involved in artistic practice as part of a practice-based research paradigm, or at the very least as a recreational outlet for their more academic pursuits. Regarding NIME research, Dahl states that "we cannot divorce our design practice from its application in musical performance, for it is through performance that our ideas, embodied as design prototypes, become testable" (2016, p. 76). As opposed to the work of previous chapters that applied more theoretical design approaches, the value of directly linking design research with real-world artistic practice emphasized. Here a short introduction to practice-based DMI design research is given.

In HCI, music interaction design has a place of special significance, and requires special consideration of a number of factors, such as the lack of clearly defined goals in certain types of performance (during improvisation, for example) along with varying notions of virtuosity and personal expression in musical performance (see Dobrian and Koppelman (2006) and Malloch and Wanderley (2017) for discussions). In the design community, these unique considerations can be framed as "wicked problems", which describe complex tasks for which few established guidelines are available and criteria for success are not well defined (Buchanan, 1992). Practice-based research, in which the iterative development and evaluation of tangible design artefacts is a central activity, has been identified as a valuable method for engaging wicked problems that cannot be easily addressed by engineering or scientific means alone (Zimmerman et al., 2007). In this way DMI design research (especially that which includes aspects of artistic practice) can also be helpful to study broader issues in HCI that extend beyond DMI design itself.

There is ample evidence of practice-based DMI research combining both scientific and artistic activities in the field. An informal survey of early NIME proceedings by Gurevich (2016) cited "practice-based research" as the first (and probably largest) of five general categories of papers that appear. One year after Gurevich's survey, Cantrell (2017) outlined five main areas of intentional practice in NIME that include *practical* *research* and *artistic performance*, as well as *hacking/making* which is described as occupying a "liminal space" between the first two areas. Further evidence is found with musical performance and artistic programs that are standard and well-established components of annual music technology conferences like NIME, SMC, ICMC and several others.

Personal and collaborative design-performance practices

There are numerous examples of individual research practices where instrument design and musical performance are fundamental elements as well. The Hands, a DMI designed by Waisvisz (1985) in 1985, endures as a classic example of dedicated design research that was used in Waisvisz's live performances for decades (Torre et al., 2016). Cook's design principles (2001), to which he added more in (2009), are elicited through autobiographical accounts of his own instruments developed for his own artistic practice, as well as for the practices of others like Dexter Morrill (Morrill & Cook, 1989).

In his commentary on Cook's principles, Wanderley (2017) highlighted the important personal performance experience that informs Cook's designs, suggesting that this type of practice is complementary to that of more technical designers who instead choose to collaborate with artists as part of the design process. The collaborative approach was explored in depth with the Digital Orchestra Project by Ferguson and Wanderley (2010), a three-year project that brought together designers, composers and performers in an interdisciplinary setting. The project resulted in a number of new instruments and works developed in the context of long-term, artistically driven collaboration, and some of the instruments have continued to be used in professional performance contexts well beyond the duration of the project.

Design and artistic collaboration is also a central focus for Elblaus (2018), who argues that DMI design research is an act of crafting experiences and translating between domains (musical, technological, design, etc.). Using theories of Sonic Interaction Design (Franinović & Serafin, 2013) and embodied aesthetics, Elblaus presents several instruments as case studies for how design artefacts (the DMIs) operate as catalysts for exploration and transformation across and between both design and artistic spaces.

5.2.2 Design for professional contexts

Fewer points in literature address the specific requirements or design strategies for instruments to be successful in professional contexts. From Chapter 1, Section 1.2.2, three criteria were given to define "professional" performance practice: making music is a part of the individual's livelihood; the individual's musical activities are professional in nature (e.g., performing, touring, recording, as well as other required non-musical activities); and the activities, equipment and other aspects of the musician's practice meet professional standards and expectations.

In a previous work (Sullivan & Wanderley, 2018) we conducted a systematic review of conference proceedings related to DMI research to investigate how the field has addressed pragmatic concerns of instrument fitness (in particular issues of stability and reliability) for performance contexts. A secondary finding of that work was that, while musical performance was discussed in nearly all of the reviewed papers, professional practice was mentioned infrequently, leading us to conclude that designing specifically for professional use has historically not been a strong motivation in the field.

There are instances of professionals involved in the evaluation of new designs, though frequently their participation is not necessarily related to evaluating systems for professional use. For example, a study by Stowell et al. (2009) used professional drummers to provide high quality performances in the evaluation of a novel beat tracking tool. In studies by Johnston (2011), professional musicians were recruited to test and provide informed and authoritative feedback on sound-controlled virtual musical instrument prototypes that explored a novel concept of conversational interaction. In cases like these, professionals have been regarded as experts (in terms of skills and knowledge), but the particular demands of their professional practices are not considered in the evaluations.

A notable exception to this trend is the work of Hattwick (2017), who investigated the topic of design for professional artistic productions through several collaborations involving hardware developed and used for large-scale international public expositions. Similar to Cook's design principles, Hattwick presents a framework based on his own personal design experience and approaches, addressing the following design aspects: *functionality*, *aesthetics*, *support for artistic creation*, *system architecture*, *manufacturability*, *robustness* and *reusability*. A number of corresponding design principles are proposed for each aspect.

One unique consideration of Hattwick's framework is the context from which it was developed, which primarily involved the development of purpose-built hardware for use in specific experimental performances and interactive intermedia installations. The Prosthetic Instruments, designed with Joseph Malloch (Hattwick et al., 2014) represent perhaps the most "typical" DMIs. The instruments consist of different "prosthetics" worn by dancers in an interactive dance performance. They are equipped with touch and motion sensors, as well as lights, and function as both wireless controllers and aesthetic objects that are part of the visual performance. For the *Ilinx* project, Hattwick et al. (2015) developed a wearable vibrotactile garment for visitors to don and navigate an immersive, multisensory environment. A third hardware system designed by Hattwick is the VibroPixels (2017), a scalable wireless tactile display system comprised of small individual actuator devices that can be flexibly placed and reconfigured, allowing for use in distributed applications. The VibroPixels were developed for the *Haptic Field* artwork, an immersive multimodal art installation similar in concept to *Ilinx*, developed with artist-researchers Chris Salter and TeZ (Salter, 2017). While many of the principles offered in Hattwick's framework have been formulated in response to the particular requirements of the multidisciplinary projects that they were designed for, nearly all of them are relevant to the design of musical DMIs for use in more conventional musical applications including the instruments and interfaces we present here.[2]

There are, of course, other aspects of professional performance that could be considered. For one, as discussed in Chapter 2, Section 2.5.3, theoretical work on long-term user engagement by Wallis et al. (2013) focused on *intrinsic* motives for amateur music-making, contrasting *extrinsic* motives that may drive professional performance such as the need for financial compensation, schedules and professional obligations. It could perhaps be of interest to investigate how these extrinsic factors relate to engagement in professional contexts, though it is beyond the scope of this current research.

Summarizing the discussion, we find that practice-based approaches to design are common in DMI research and are often linked to artistic production, whether applied as a method for evaluation or personal enjoyment. From a research perspective, researchers like Elblaus (2018) and Ferguson and Wanderley (2010) have demonstrated the benefits of long-term and collaborative integration with artistic practice as a vital tool in design research. While there has been less research around the specific needs of professional performers, Hattwick (2017) has offered a set of principles for the design of hardware and software intended to meet the demands of professional artistic production and based on his own applied research. We bear these in mind as we introduce our own work and methods, and return to it in our closing discussion in Section 5.5.2.

[2] Interestingly, while the hardware developed by Hattwick and colleagues was designed in the specific contexts of particular projects, in each case was repurposed for other applications: versions of the Prosthetic Instruments were later used as interactive sculptural elements at an artist residency in Greece; the *Ilinx* technology was used the project "Musicking the Body Electric" by Bhagwati et al. (2016); the VibroPixels continue to be developed by Hattwick and have been used in a variety of research and artistic applications including a haptic metronome for conducting contemporary classical music (Ignoto et al., 2018).

5.2.3 Augmented instruments

To contextualize our designs that will be introduced in the following sections, a short review of augmented digital musical instruments is presented here. One of four categories of DMIs defined by Miranda and Wanderley (2006) (see Chapter 3, Section 3.4.1 for a description of each category), augmented instruments consist of conventional (typically acoustic) musical instruments whose functionalities are extended by the addition of extra sensors, allowing the performer to control parameters of other sound or related processes. Importantly, the instrument can still be operated in its default manner and the additional controls exist as an additive layer of functionality on top.

There is a rich tradition of augmenting common traditional instruments in various ways. Trumpets have been a frequent target of augmentation, with versions by Morrill and Cook (1989), Impett (1994) and Thibodeau and Wanderley (2013). In fact, Thibodeau and Wanderley identify no fewer than 12 augmented trumpets (and 5 augmented mouthpieces) that preceded their own designs! Additional examples include Touchkeys, an augmented piano by designed by McPherson (2012), augmented violins by Bevilacqua et al. (2006) and Overholt (2005),[3] and two different approaches to augmented nylon string guitars by Meneses et al. (2018).

One other augmented instrument deserves a mention as it also serves as an exemplary example of long-term, practice-based research with a solid foundation in artistic musical practice. The Hyper-Flute, designed and played by Palacio-Quintin (2008) is an acoustic flute fitted with several additional sensors that provide controls for a digital effects and processing suite running in Max[4] on a laptop. Palacio-Quintin has been performing

[3]Despite Overholt's self-categorization as an augmented instrument, it could be argued that it more accurately belongs in the "instrument-like" category of instruments specified by Miranda and Wanderley (2006) as the instrument was custom designed and built from the the ground up. However, Overholt also highlights that the instrument retains the original functionalities of a conventional (electric) violin which is a primary characteristic of augmented instruments.

[4]Max is a visual programming language for audio and interactive media developed and maintained by Cycling '74. https://cycling74.com.

with the Hyper-Flute since it was first designed in 1999 with only minor updates and maintenance during that time.

5.2.4 Towards an augmented harp

There has historically been relatively little research on the harp as a basis for an augmented instrument. This may be due to its scarcity of spare bandwidth, making it potentially less suited for augmentation than other instruments like the trumpet or flute. It could also be related to the instrument's long history and formal traditions, though this has hardly slowed the augmentation of other traditional instruments like those mentioned previously.

Perhaps the most recognizable connection of harp to new interface design and extended performance is the laser harp, an instrument-inspired controller that projects an array of laser light beams that bear some resemblance to the strings on a harp. The interface is "played" by interrupting the light beams with the hand, while sensors measure the distance at which the light is broken for additional gestural input. Its original invention has been credited to Geoff Rose in 1977, while a 1981 version created by Bernard Szajner, Yan Terrien and Phillipe Guerre was equipped with MIDI and made and made famous in performances by Jean Michel Jarre ("Laser Harp", n.d.; Wiley & Kapur, 2009).[5]

Control strategies for extended harp performance

In the area of extending harp performance, we can look at the work of harpist and researcher Monaghan (2019). Her work has explored techniques and implications of electronic and experimental music practices in contemporary Irish traditional music.

[5]Several laser harp versions have been manufactured based on similar principles: http://www.laser-harp.com/, http://www.harpelaser.com, http://www.kromalaser.com, to name a few.

Monaghan has documented a variety of different methods and technologies for augmenting harp with gestural control, each which offered its own advantages and disadvantages.

An early approach employed a microphone attached inside the sound cavity of the harp to use the direct audio as an input signal. With computational analysis of the signal in both the time and frequency domain, this approach can yield low-level parameters of the signal such as fundamental frequency, spectral envelope, the frequency, amplitude and phase of the partials making up the spectrum. Additional analysis can also produce higher-level parameters relating to the perceived timbre of the sound (Traube et al., 2003). This method of indirect acquisition of instrumental gesture can be highly effective at parameterizing performance data while remaining unobtrusive for the performer. However, a fundamental issue with this approach is found when applied to polyphonic and multitimbral instruments like the harp, where it is difficult to isolate single notes for accurate analysis.

Monaghan and Tibbitts have both experimented with attaching small MIDI[6] controllers (specifically Korg nanoKONTROL2 and nanoPAD2[7]) to the soundboard of the harp near the performer's hands to provide access to a discrete set of controls for manipulating electronics while playing. However, both were ultimately unsatisfied with the outcome. For Tibbitts, the fixed placement of the controls did not integrate well with the physical structure of the harp, making the controls difficult to operate accurately and not well integrated with natural performance movements.

A motivation to leverage natural playing gestures independently led both Monaghan and us to a prototype MIDI harp built by Camac Harps.[8] During the early stages of our collaboration we arranged a residency at the Camac studio in Paris to explore the

[6]Musical Instrument Digital Interface, a music technology protocol for connecting hardware and software that has been the de facto industry standard since its inception in the 1980s. https://www.midi.org/

[7]https://www.korg.com/caen/products/computergear/

[8]https://www.camac-harps.com/en/

instrument and experiment with different techniques for its use in performance. While the residency was informative, we found that the MIDI harp was not well-suited for generating expressive continuous control signals that we were interested in exploring, nor was it available for longer term use.

Ultimately, both Monaghan and our team would arrive at similar systems for gestural controllers to augment harp performance: small wireless motion acquisition devices worn on the back of the hands instead of attached to the instrument. More recently, another system gestural control of harp was introduced by Di Donato et al. (2019) which also uses wearable motion acquisition devices, in their case Myo armbands.[9]

5.3 Gestural Control of Augmented Instrumental Performance

This section presents the first collaborative design project by Tibbitts and me, which was carried out with two others: music technology researcher and hardware designer Ólafur Bogason, and composer Brice Gatinet.

While gestural control of music has been extensively explored, a standardized model for performers has yet to emerge. This is not surprising, as the notion of gesture in music is a broad topic (Wanderley & Depalle, 2004), and there are many different objectives, approaches and technologies that have been applied (Jensenius, 2014). The widespread availability of inexpensive sensing technologies and programmable microcontrollers (Medeiros & Wanderley, 2014), not to mention a variety of commercially available low cost motion tracking systems like the Nintendo Wii, Leap Motion and Microsoft Kinect provide accessible means of interfacing motion data with live performance. This has made implementation of motion sensing a viable option for many

[9]Myo was a wearable wireless controller equipped with both motion and electromyography (EMG) sensors that can sense muscular movements. In (Di Donato et al., 2019), the devices were only used for motion acquisition and EMG was not used. As of October 2018, Myo's parent company Thalmic Labs ended production of the device.

performers.

For this project, we were interested in designing a lightweight gestural control system that could augment live instrumental performance. While our primary focus was the harp, our aim was to develop tools that would be flexible enough to be used with any instrument and integrate easily into common live performance workflows. Most importantly, it would be simple for a performer to set up and configure without requiring extensive technical knowledge to operate. Given these parameters, we devised a small wireless device that could attach unobtrusively to either the performer or instrument, accompanied by an OSC-based software interface for connection to other audio applications.

Because of the large size of the harp and the relative lack of spare bandwidth for the performer, any system of gestural control would need to be integrated into the natural playing movements of the harpist. These factors were explored through a motion capture study of harp performance. From it we devised basic strategies to inform the design of our gesture control system.

Utilizing an exploratory, user-centered approach, the project tested these strategies through the development of hardware and software that culminated in the creation of a new live work for solo concert harpist and gesture controller.

5.3.1 Harp gesture study

To better understand the movements of harp performance and how they could be integrated into a gestural control system, we began the project with a motion capture study. Our particular focus centered on the concept of spare bandwidth, and the differentiation of instrumental (sound-producing) and ancillary (non-sound-producing, or *accompanist*) gestures (Cadoz & Wanderley, 2000). We hypothesized two general methods of mapping gestures to musical parameters. On one hand, the organic movements of harp playing could be used, allowing the performer to transmit gestural control data naturally without altering their technique. Gestures, both instrumental and ancillary, could be mapped to events and processes as specified in the composition and realized with computer-based audio processing and effects. On the other hand, isolating ancillary gestures might present an opportunity for a performer to explicitly control other parameters without interfering with their harp performance.

The protocol for our motion capture study was adapted from the work of Chadefaux, Le Carrou, Fabre, and Daudet (2013), who had previously studied musician/instrument interaction in the case of the concert harp. Their study yielded high-level kinematic descriptors of harp performance posture and dynamics, as well as a detailed analysis of hand and finger mechanics of harp plucking (Chadefaux, Le Carrou, & Fabre, 2013; Chadefaux et al., 2012).

Excerpt selection

Four short excerpts of well known orchestral works were chosen for the study: two from Tchaikovsky's *Nutcracker Suite: Waltz of the Flowers*, Berlioz's *Symphonie Fantastique Mov. II*, and Debussy's *Danse Sacré*. The excerpts were taken from the first few bars of each piece, with the Tchaikovsky passage divided into two. The duration of the excerpts ranged from under 15 seconds to one minute.

The pieces are well known and part of the standard harp repertoire. They were chosen in hopes that the participating harpists would already be familiar with them, allowing them to play freely and comfortably with the most natural motions. Additionally, the excerpts contain a wide variety of dynamics and technical passages. As we regarded the analysis with an eye to map performance gestures to control of other parameters, it was important to see a broad range of techniques.

Participants

Eight highly skilled harpists participated in the study. Six were graduate students pursuing degrees in harp performance, including Tibbitts. One was an undergraduate, also pursuing a degree in harp performance, and the last was a faculty member and harp instructor. The participants averaged 13 years of private study and 14.5 years experience playing in orchestras. All participants reported that they practice every day. Everyone had experience performing the Tchaikovsky and Berlioz pieces. Five of the eight had performed the Debussy piece, though the other three were familiar with the selected excerpt and had no trouble playing it.

Experimental setup

The study took place in a motion capture laboratory at CIRMMT, shown in Figure 5.1. A Qualisys motion tracking system[10] was utilized, comprised of twelve infrared cameras placed around the perimeter of the room or suspended from a grid on the ceiling. Reflective markers were fixed on the participants and harp which were recorded by the cameras and translated into 3-dimensional motion data. For marker placement, the *Plug-in Gait model*[11] was utilized with the right shoulder marker removed where the harp rests during performance. Markers were also placed on the harp to track its movements.

A force plate was placed underneath the harpists' stool, which captured the amount and angle of downward force applied by the seated harpist, however, this data was not used in the analysis presented here. Additionally, video and audio was recorded with an HD digital video camera. All data was synchronized to the same SMPTE timecode to aid the later analysis.

[10]https://www.qualisys.com/
[11]http://www.idmil.org/mocap/Plug-in-Gait+Marker+Placement.pdf

Fig. 5.1 The motion capture laboratory setup at CIRMMT, showing a participant play one of the excerpts while Tibbitts (right) observes.

Participants were instructed to play each excerpt one time in four different styles: *normal*, *deadpan*, *expressive*, and *immobile*. This follows similar protocols used in previous musical gesture studies of clarinet (Wanderley et al., 2005), piano (Massie-Laberge et al., 2019; Thompson & Luck, 2012), and concert harp (Chadefaux, Le Carrou, Fabre, & Daudet, 2013). The first three styles relate only to musical expression, and explicitly do not infer any instruction or restriction on movement. Conversely, the last, *immobile*, is a movement constraint and does not pertain to musical expression. Our intent was to observe both uniform and unique gestural features between participants and between the different playing styles. The participants were given no further instructions and left to interpret the different styles as they saw fit.

Analysis

Because the gesture study was just one component in the overall project, our analysis was limited to a summary overview using a mix of quantitative and qualitative methods. The motion capture data was recorded and processed with the Qualisys Track Manager software. Processing included identification and labeling of markers according to the Plug-in Gait model, cleaning and gap-filling data where needed, and constructing a 3D model of each performance. The processed dataset was exported for analysis in

MATLAB and video files were generated of the 3D animations.

In MATLAB, the data was further processed using the Motion Capture Toolbox (Burger & Toiviainen, 2013), which provides a set of functions for processing and analyzing motion data. A marker reduction process was performed to translate sets of markers into discrete components for analysis. The coordinate system was translated so that the coordinate axes matched those of our proposed gesture space (as oriented by the harp): X axis extending right and left from the harp strings, Y axis extending horizontally forward and backward, and Z axis extending vertically.

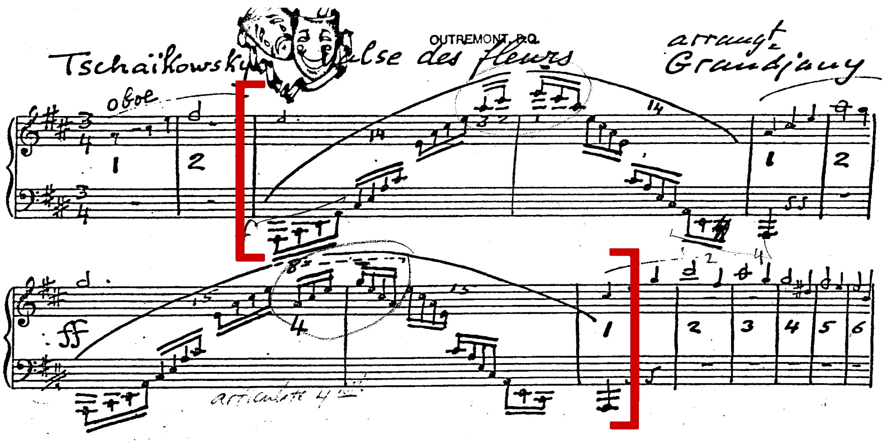


Fig. 5.2 First excerpt: Tchaikovsky *Nutcracker Suite: Waltz of the Flowers*, opening arpeggios.

Dynamic time warping (DTW) was employed to allow us to compare excerpts across participants and styles (Verron, 2005). To demonstrate, Figure 5.2 shows the score of of the first excerpt, the two opening arpeggios of Tchaikovsky's *Waltz of the Flowers*. First, the following dynamic events were chosen to warp to: the plucking of the first note (green vertical line), highest note (cyan line) and last note (blue line), and the muting of the strings at the end of the last note (red line). This yielded eight "warp" points, four for each arpeggio. Using digital audio editing software, the warp points were identified in each performance (for each participant, in each style) and exported as SMPTE timecodes. In MATLAB, the timecodes were used to align the motion data

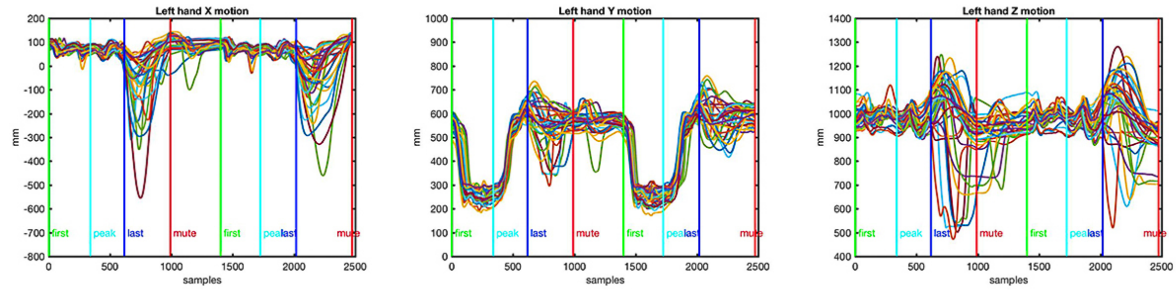


Fig. 5.3 Left hand movement of all participants, all styles, playing the the opening arpeggios of Tchaikovsky's *Nutcracker Suite: Waltz of the Flowers* (first excerpt).

to a fixed reference, which was the first participant's *normal* excerpt. This allowed for the comparison of movement trajectories across participants and styles making it easy to identify both common and unique gestures.

Figure 5.3 shows one such analysis, of the left hand movement on the X, Y, and Z axes for all participants playing all styles. The vertical lines indicate the warp points, and the phrasing of the passage is especially evident on the Y axis as the hand moves towards the body in the ascending half of the arpeggio and back out on the descending notes. Then between the blue and red lines, the last note is played and left to ring out until the hand returns to mute.

This example shows the type of high-level information we were able to extract from the data and apply to the design of our gestural control system. On one hand we see clear movements that directly relate to the music being played: the hand deliberately moves along a single axis when playing ascending and descending lines in a controlled and predictable manner. We can see this as an opportunity for a reliable mapping if the composer has a desired parameter they wish to control during this type of passage. On the other hand, looking at the segment where the notes are sustained (between the blue and red vertical lines), we observe different behaviors between the axes. On the X and Y axes, while there is variation in amplitude, the direction and shape of the motions are relatively consistent. But on the Z axis, the directions and shapes are varied as well.

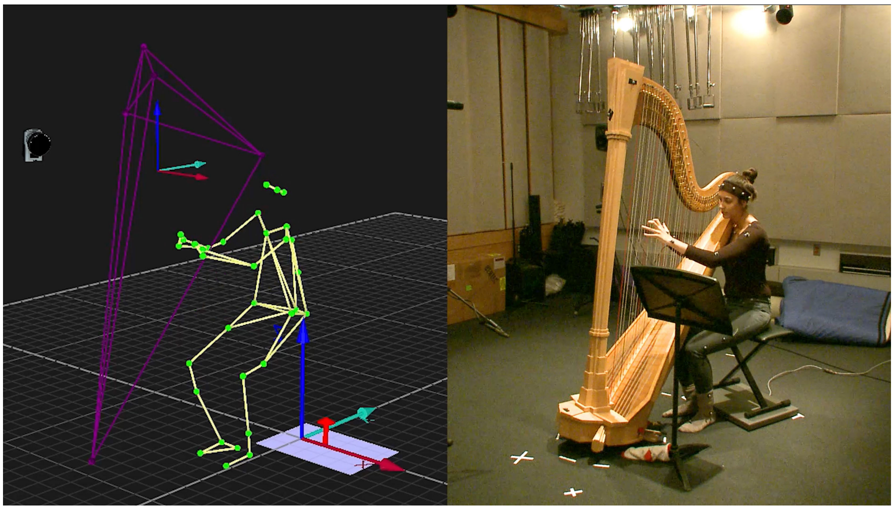


Fig. 5.4 Image taken from analysis video, showing 3D animation synchronized with video recording.

This ancillary gesture is freely interpreted by the performer and can be exploited as an opportunity for the performer to take control of another process without interfering with the instrumental harp performance.

Additional qualitative analysis was done simply by observing the videos of participants to note general characteristics of performance, noting potential implications for mapping strategies. Figure 5.4 shows the split screen analysis videos, with the 3D animation synchronized to the video-recorded performance. One observable trait pertained to movement of the harp. We had hypothesized that movement of the harp could be a compelling motion to map, however visual analysis showed that the overall movements of the instrument are quite small and tightly linked to the physical mechanics of playing. Thus in practice the actual movement is not well suited as a control signal.

5.3.2 Controller design

From the motion capture study and initial research, we arrived at a plan for the use of small self-contained wireless devices that could be worn on the performer or fixed on the instrument. A software interface connected the controller data to commonly

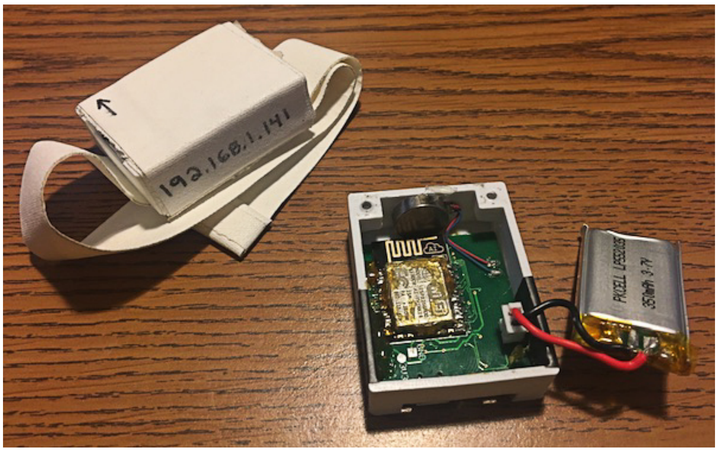


Fig. 5.5 Inside and outside of the prototype gesture control devices.

used digital performance software that would allow for flexible mapping of the signals to musical parameters.

The motion controllers we used were research prototypes developed by our collaborator Ólafur Bogason and his team at Genki Instruments.[12] Shown in Figure 5.5, the devices are comprised of a custom PCB to which is connected a small microprocessor, motion tracking sensor, two LED (light emitting diode) lights, haptic motor and driver, internal battery connector and charging circuit, and on/off switch. The unit is powered by a 350mAh 3.7V lithium polymer rechargeable battery and housed in a matchbox-sized 3D printed enclosure with tabs to attach an elastic strap. The top of the enclosure is minimally translucent so light from the LEDs is visible from the outside.

Wireless Communication

The core of the unit is an ESP8266 microprocessor with firmware written in the Arduino programming language. The ESP8266 was chosen because of its capabilities for 2.4 GHz (802.11 b/g/n) WiFi transmission, I^2C digital digital serial communication support and general purpose input/output pins. The devices communicate bidirectionally with the

[12] https://www.genkiinstruments.com/

host computer over UDP (user datagram protocol), sending streaming motion data out while receiving messages to control the onboard haptic motor and LEDs. All data is formatted and sent via OSC messages.

Gesture Acquisition

The MPU-9250 integrated motion tracking device is a Magnetic, Angular Rate, and Gravity (MARG) sensor module equipped with 3-axis accelerometer, gyroscope, and magnetometer (Bachmann et al., 2003). An on-board processor performs sensor fusion to produce a stable measure of device acceleration, angular rate of motion, and orientation which is output as OSC-formatted motion data in quaternions, roll/pitch/yaw (Euler angles), and individual 3-axis outputs for the accelerometer, gyroscope and magnetometer.

Added Functionality

Along with their primary motion tracking capability, the devices are equipped to provide basic visual and haptic feedback to the user. One LED provides device status information, while a second is user programmable. The haptic unit consists of a single coin-style eccentric rotating mass (ERM) motor, paired with a DRV2605 haptic driver by Texas Instruments. The driver was selected for two particular features: first, it possesses a digital waveform sequencer and trigger, and is loaded with a library of 123 different haptic effects such as short and long pulses, hums and buzzes of various intensities, transition ramps of different lengths and more.[13] Second, the device can communicate with the driver via digital I^2C bus. Control of the LED and motor (including the various waveforms) is available from the user interface.

[13]The complete waveform library can be found on p. 63 of https://www.ti.com/lit/ds/symlink/drv2605l.pdf.

5.3.3 Graphical user interface

The main objective of the graphical user interface (GUI) was to provide a simple set of controls to integrate motion data into a live performance workflow and communicate with the device. The interface was built in Max, and is designed to function in three primary ways: (1) integrated as part of a larger Max performance patch, (2) as a Max for Live device in Ableton Live[14], or (3) as a standalone application that can communicate with other devices via OSC.

The main control panel is shown at the top of Figure 5.6 and is comprised of four main sections (clockwise from top left): motion data acquisition and calibration; device settings, including device addressing and preset storage and recall; device LED and haptic controls; and data output and visualization.

The software interface exists as a Max abstraction equipped with outlets to apply the motion data to parameters elsewhere when used inside of a main Max patch. With the abstraction open, all of the interface controls are accessible on screen. Additionally, OSC routings are included along with appropriate inlets and outlets, so the interface can be controlled remotely via OSC messages even while the GUI is not displayed. An alternate standalone version was implemented as well, with network connectivity via UDP for use with other networked OSC-compatible applications.

Max for Live

To further simplify use of the system and make it available for use in Ableton Live, one of the most popular and widely used music performance software applications, the GUI was ported to a Max for Live device. The device contains the exact the same functionality as the Max interface. The front panel contains a subset of the controls for

[14] Max for Live is an addition to Ableton Live that allows Max programs to be run as modules inside of Live. https://www.ableton.com/en/live/max-for-live/

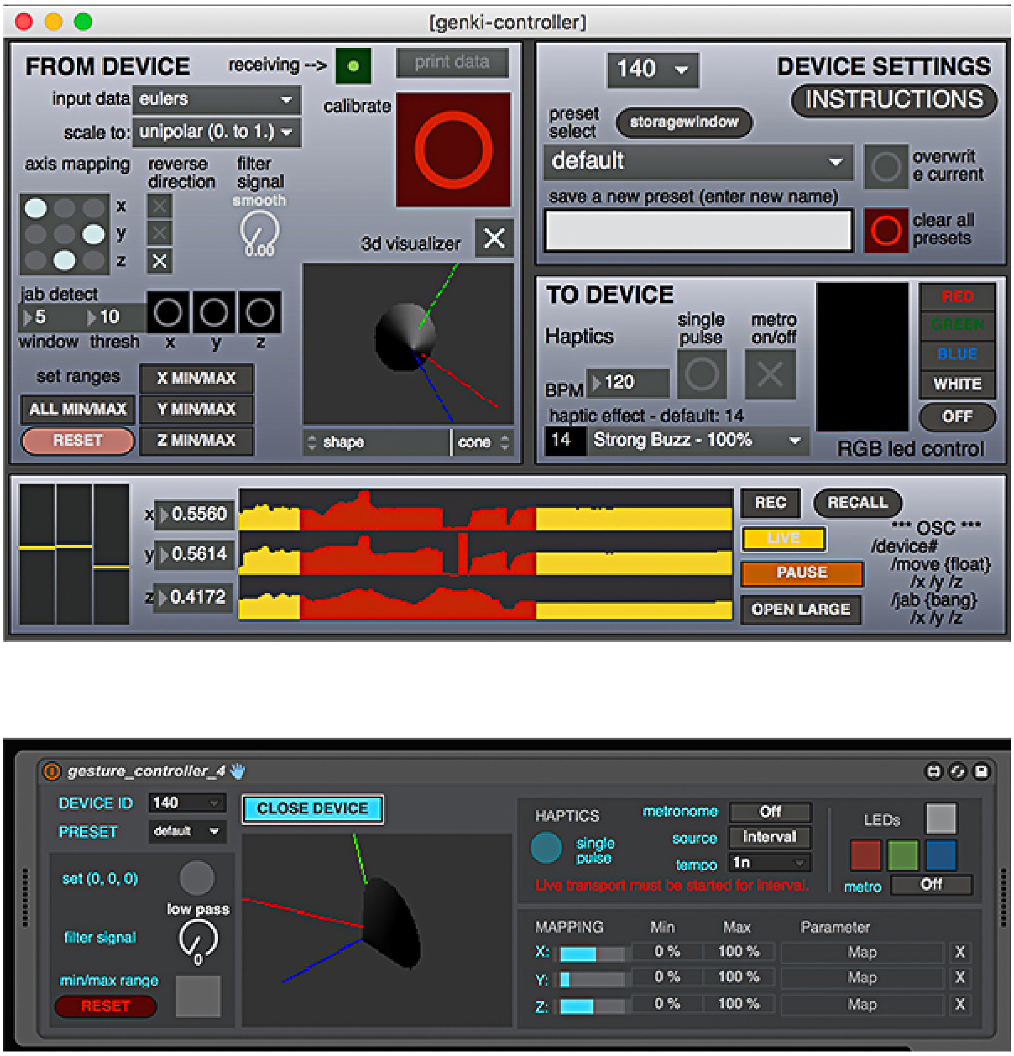


Fig. 5.6 Top: User interface for Max and stand-alone use. Bottom: Max for Live device.

basic operation, while the full control panel can be opened with an onscreen button. Additionally, the device leverages built-in features that help to streamline the workflow. Output from the motion data can be directly scaled and mapped to any parameter in Live, and device's LED and haptics can be synced to Live's global tempo and transport controls.

Motion data processing

Several parameters are available to give the user control over the incoming data, including controls for coordinate rotation and translation. In practice, we found the two most important controls to be the "calibration" and range controls. The calibration function (while not technically a true device calibration) sets the $X/Y/Z$ axes to zero when the "calibrate" button is pressed, orienting the device to a known "home" position. If the controller measurements begin to drift (which was often an issue in rehearsals), the user can recalibrate on the fly to restore confidence in the measurements. To create a usable range of motions, a range function was implemented which allows the user to define minimum and maximum limits of their motion on each axis.

Preliminary experiments using machine learning were also carried out using MUBU, a library of Max objects for the multimodal analysis of sound and motion data, including a suite of machine learning tools (Françoise et al., 2014). However, promising developments were offset by the addition of significant complexity for the performer and ran counter to our stated goal of achieving simple and lightweight system. As a result, we carried on with our $X/Y/Z$ control system, favoring simplicity and ease of use over advanced functionality.

5.3.4 Implementation into artistic performance

The final objective for the project was to bring everything together in a new creative work and performance. This was done in collaboration with composer Brice Gatinet, who prepared a work for solo harp and gesture-controlled electronics to be performed by Tibbitts.

Gatinet's composition *...prends-moi, chaos, dans tes bras...* is a reflection on mounting refugee crisis and asylum seekers in recent years affecting the Middle East and Europe. The title comes from the translated collection of Arabic poems written by the Syrian poet Adonis, and is based on three different materials: the choreographed motions of a harpist's musical gestures; narration of a Sumerian creation poem; and a transcription of *Hurrian Hymn no.6*, a Mesopotamian song, known as the first written piece of music (ca. 1400 B.C.E.), discovered in the 1950's in the Ugarit, Syria.

The work requires amplified harp, gesture controller, voice microphone, foot-switch, and four speakers. Audio from the harp and voice is processed through several effects modules by GRM Tools.[15] Parameters are mapped to the movement of the controller, allowing the performer's gestures to modulate the sound in real-time. The piece is implemented in a Max patch with interchanging audio effects and a foot switch used to toggle between various scenes of effects and mappings. To perform the piece, effects are applied to their desired axis (e.g. *pitch* controlling granulation and *roll* controlling delay) in order to blend between multiple effects.

Development

The work was developed over three stages. First, the functionality and range of the controllers were freely explored through improvisation sessions, enabling the performer and composer to investigate relationships between musical gestures and sound. In the second stage, a basic gesture vocabulary was defined to fine-tune the tracking of the controller for skilled control over effects parameters. In the last stage, the score and Max patch was finalized for concert setup and performance.

In the exploration phase, different effects and mappings were auditioned to match various performance motions that had been identified in the motion study. The biggest challenge for Tibbitts was to understand the responsiveness of the controller and refine her movements accordingly. Naturally, a harpist's arm and hand movements are not

[15]GRM Tools is a well-known suite of audio plug-ins developed at the Groupe de Recherches Musicales, a music research collection founded by Pierre Schaeffer. https://inagrm.com/

fixed on a singular axis; therefore the performer must take care to understand how each respective movement affects the processing.

While gaining familiarity with the system, it was natural for Tibbitts to react to sounds generated by the controller. However, this was not the controller's intended purpose. With dedicated practice and increased understanding between movement and control, a personalized gesture vocabulary was more freely developed and integrated into the natural movements of instrumental harp performance.

Through the rehearsals, the composition took form with a bottom-up approach where Gatinet's writing explored the relationship between the instrument and controller. While various complex mapping strategies were rehearsed, ultimately the choice was was to use direct one gesture-to-one axis mappings, which provided the best results and were more directly controllable by Tibbitts during instrumental passages.

Performance

Tibbitts gave two initial performances of the piece. The first was for her final recital at the Université de Montréal, where she was completing her master's degree (shown in Figure 5.7).[16] The second performance was included in a mixed concert of new music. While the first performance went off without a problem, issues with WiFi connectivity led to dropouts of the controller in the second performance. Tibbitts was able to continue through the piece with minimal disruption, however the actual manipulation of electronics processing was intermittent in some sections.

Following the initial performances, Bogason continued to work on the hardware design as Genki Instruments moved towards producing a commercial gesture controller based on the initial prototypes we had been working with. In addition to the WiFi dropouts experienced during the second performance, we had experienced other techni-

[16] Video of the first performance can be seen at https://vimeo.com/291366942.

Fig. 5.7 Premiere performance of "...prends-moi, chaos, dans tes bras...", Université de Montréal, April 2017.

cal issues during rehearsals. One issue in particular was difficulty in achieving accurate and reproducible calibrations, which were critical to ensure that the performer could control the effects parameters effectively. Over the following year most of the issues were resolved through software updates and upgraded hardware.

A year after the initial performances, we gave an updated performance at the International Conference on Live Interfaces (ICLI) in Porto, Portugal using the latest controller prototypes provided by Genki Instruments. There were no technical problems and the performance went off without issue. One important technical development was the move from WiFi-based communication to MIDI over Bluetooth, which in our experience provided much better connectivity and reliability in performance. In the time since, Bogason and Genki finalized the Wave controller and it was commercially released in 2019.[17]

[17]https://genkiinstruments.com/products/wave/

5.3.5 Reflection and indications for future work

In assessing the project after the performances, we were able to reflect on some of the challenges and successes we experienced, and identify areas for potential future development.

Gesture Vocabulary

While the motion capture study provided a blueprint for the design of gestures for our system, in practice the selected gestures emerged through experimentation during rehearsals and were focused on achieving specific compositional and musical objectives. Therefore it is hard to directly correlate the motion analysis results with the selected gestures. However, the general principle of applying both instrumental and ancillary gestures taken from natural harp performance movements guided the overall process.

Furthermore, in a later interview with Tibbitts, she reflected on the tension between creating a new set of gestures versus adapting the naturally occurring gestures of harp performance. Gatinet's composition primarily used the former approach, for which gestures often felt at odds with her instrumental performance, preventing her from executing either as well as she would have liked. In the future, as she continues to work with the Genki Wave gesture controller, Tibbitts likens the integration of gesture control into her performance to the use of *word painting* in Renaissance music (Reese, 1959), in which music was composed to reflect the literal meaning of the underlying lyrical or story elements. In this way, movement would move in harmony with the music, instead of against it.

Learning and Performing

A final reflection on both the challenges of working with this system come from a learning perspective. Performers develop a specific relationship to learning their primary instrument. Controlling a new device that modifies the sonic result of the instrument profoundly disrupts that relationship. The first exploratory rehearsals allowed Tibbitts to investigate her own response to the potential of her gestures on the sound. The freedom of movement, when she was in full control of the effects, allowed her to develop virtuosity and precision. But as parts of the composition became fixed it became difficult for her to embed the gesture, score, and her interpretation into one sound result. Gatinet's approach asked Tibbitts to trust what she was hearing and be able to make nuanced adjustments to correct. Unsurprisingly, however, this proved to be hard to achieve, especially where required gestures moved contrary to her natural harp performance movements. To help with this, we briefly experimented with providing visual feedback by adding an iPad in front of the performer that displayed the gesture-controlled parameters. However, that became just one more element for the performer to keep track of and was ultimately removed.

The large quantity of information to be managed and additional movement constraints when the controllers are in use require a significant retraining and recalibration of the relationship between instrument and player. Returning to Pressing's assertion that cognitive limitations may supersede physical limitations (1990), future work may consider complementary research in the areas of performer-instrument interaction, embodied cognition, and musical pedagogy to develop strategies for the performer to learn and adapt to the new augmented performance paradigm.

5.4 The Bionic Harpist

The second project began approximately a year after the ICLI performance. Even more than the first, this project was pragmatic in its scope and ultimate goals. Following the Gestural Control project and the resulting composition and performances, Tibbitts was motivated to begin creating her own original music and build a personalized performance system that she could fully be in control of. While she had continued to experiment with the new Genki Instruments Wave gestural controller, her professional electroacoustic performances mainly used the Korg nanoKONTROL2 and nanoPAD2 MIDI controllers. However she was interested in acquiring custom hardware that could more tightly integrate with the ergonomics of her harp.

For me, the second project followed the Design for Performance workshops (Chapter 3) and overlapped with the design of three new Noisebox instruments: the Keybox, Stringbox and Tapbox (Chapter 4). Through the development of those instruments, along with previous experience with the harp gesture controllers and other DMI design work, I was refining a systematic approach to quickly prototype functional and reliable hardware, with a clear understanding of preferred methods, techniques and components to achieve optimal results.

Furthermore the workshops, which Tibbitts had also participated in, provided motivation and strategies for us to approach the design of a completely novel harp control system with confidence that we could develop a successful solution.

The duration of the project was approximately five months, and four key areas of work were identified:

- Phase 1: Ideation and prototyping
- Phase 2: Hardware fabrication
- Phase 3: Evaluation and testing
- Phase 4: Artistic development, rehearsal, performance

Design specifications

While we began with largely blank slate about the system we wanted to design, we both had certain criteria based on our collective experience and lessons learned from the previous project. These were articulated as a set of preliminary design specifications:

1. The system should be comprised of one or more control interfaces that can be mounted on the harp, as opposed to a free-handed, motion-based system.
2. The hardware should mount on the harp in a non-permanent, non-destructive manner.
3. Any hardware system should not obstruct the performer's full range of natural performance movement, nor should it interfere with the natural acoustic properties of the harp.
4. The system should be fully compatible with common audio and multimedia performance software and use industry standard protocols for communication and data transmission.
5. The system must be robust, reliable, and easy to set up and use.

The specifications differ from those developed out of the Design for Performance workshops in Chapter 3, and reflect two of the main advantages to the collaborative style of work we engaged in: first, the specifications are limited in scope to this particular context, accommodating unique considerations like the form, size and material of the harp, and the individual needs of the performer's live show. Second, after completing a previous project together, we intimately knew some of the pain points and important items that needed to be addressed that would allow for robust and successful use in real-world application.

5.4.1 Ideation and prototyping

The first few sessions were devoted to exploring ideas and developing a working concept of what a system might look like. We began with whiteboard sketches and lists of potential components, sensors, techniques and materials. A useful prototyping workflow was established for this phase that involved three components (shown in Figure 5.8), namely sketching, touchscreen prototypes and detailed CAD design. Once a viable sketch of an interface was drawn, it was converted into a functional touchscreen interface running on a tablet using touchOSC, a cross-platform MIDI and OSC control utility.[18] The tablet, an iPad Mini, was small and flat enough to put on the harp and audition various placements, and could be used to control Tibbitts' Ableton Live setup in the same way that the final controllers would. This made for a lo-fi but fully functional controller prototype that could be conjured and trialed in a few short minutes. The third part of this workflow was the creation of 3D mockups from sketches using the CAD software Fusion 360 by Autodesk[19] which could produce a high resolution image of the proposed design with precise measurements, and would ultimately render the digital files for fabrication.

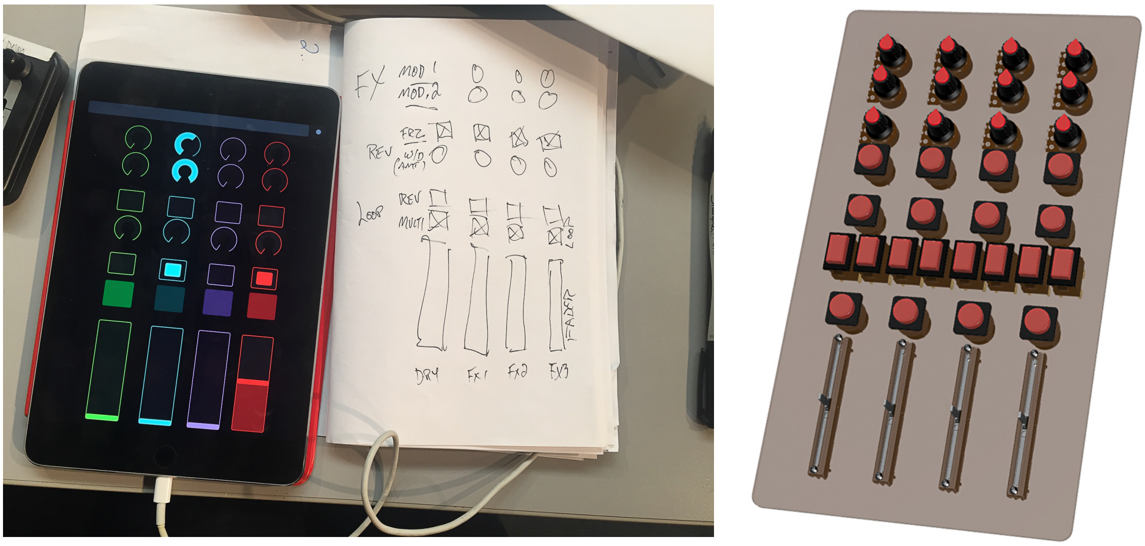
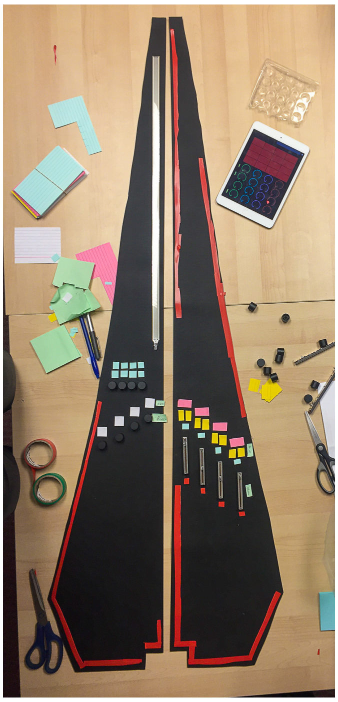


Fig. 5.8 Early prototyping workflow. Left: Sketches are converted to functional interfaces using touchOSC running on an iPad Mini. Right: Sketches are modeled in CAD software for high quality visual inspection.

Another valuable method used in this phase was non-functional prototyping, as had been done in the Design for Performance workshop. Panels were measured and cut to

[18] https://hexler.net/products/touchosc
[19] https://www.autodesk.ca/en/products/fusion-360/

match the dimensions of the harp soundboard which was our main target for applying a control surface. Then using basic crafting materials like colored paper, electrical tape and rubber knobs, panels could be laid out in full size. Figure 5.9 shows a laid out panel and its ensuing conversion to a 3D model.



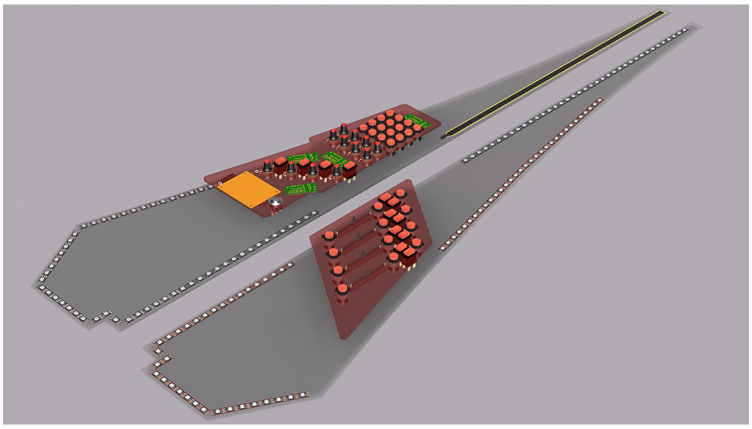


Fig. 5.9 Left: Non-functional prototype of interface panel layouts. Right: 3D model of the same panels.

The importance of this fast-paced lo-fi and digital prototyping can't be overstated. For example, after arriving at a desirable configuration (shown in Figure 5.9), extra care was taken to draft a detailed 3D model for possible production. However, Tibbitts had also created simple cardboard cutouts of the interface panels and began experimenting with placement on the harp. During that process a few issues became clear. First, as the panels were originally laid out, most of the controls were beyond her comfortable reach. Second, with the interfaces parallel to the soundboard, it would be impossible to see the controls during performance. However, as Tibbitts experimented with moving the cardboard interfaces around and positioning them at different angles, it quickly became

Fig. 5.10 Lo-fi cardboard prototypes allowed us to quickly identify unforeseen issues with positioning of interface panels and suggested alternatives that were converted into 3D designs.

apparent that tilting the interfaces slightly up would bring them into easier reach and allow the controls to be seen. The angled placement and resulting 3D model are shown in Figure 5.10. Our prototyping strategies allowed us to identify errors in our design well before fabrication started and pointed us to the proper solution.

5.4.2 Fabrication

Once the layout and positioning was settled, the final hardware design was created in Fusion 360. The final 3D model is shown in Figure 5.11, along with the finished hardware.

The design consists of two isomorphic interface panels that attach to the soundboard of the harp. The shape of the controllers is matched to the shape of the soundboard and they are inclined at a 15° angle. The controllers are positioned at a natural point of rest for the harpist's hands with the left controller placed slightly ahead of the right

Fig. 5.11 Finished CAD model and fabricated controllers.

so that all controls are easily within reach.

Controls

The selection and placement of controls were chosen to accommodate the live performance environment that Tibbitts was developing with Ableton Live. The basic performance setup is as follows: a microphone captures the acoustic harp sound and is brought into Live, where it is routed to multiple tracks. Each track contains its own unique processing chain as well as the ability to sample, loop and freeze the audio. There are global effects tracks as well that each audio track can reach with send and return busses. Finally, there are additional tracks that contain samples and other prerecorded material that are triggered at various points throughout performance.

Given this setup, the controller configurations use the metaphor of a mixing board channel strip containing buttons, sliders and knobs. The two controllers are similar, however each is unique and designed to the specific requirements and ergonomics of Tibbitts' performance. Control signals are sent as MIDI messages and received in Ableton Live where they can be flexibly assigned. In Tibbitts' configuration, some of the mappings are permanently fixed to Live parameters, while others are dynamically assigned and morphed during the course of performance. The 4x4 grid of buttons on the right controller contain multicolor LEDs providing visual feedback, and are primarily used for moving through a piece to advance scenes, trigger sequences, and change controller mappings.

Electronics and software

Prcoessing for each controller is handled by an ESP32 microprocessor. The ESP32 is similar to the ESP8266 that we used previously for the gestural controllers, but with added Bluetooth capabilities. After struggling with connectivity issues using WiFi in the last project and seeing good results with the Genki Instruments Wave, Bluetooth was an appealing option for wireless communication, and MIDI was a good choice for easy integration with music software. Research by Wang et al. (2019) provided a generally favorable evaluation of implementing MIDI over a Bluetooth Low Energy (BLE-MIDI) connection, citing near universal compatibility with modern hardware and operating systems[20], and acceptably low levels of latency (measured at 7.5ms for a minimal BLE MIDI configuration and 19.1ms for custom configuration that more closely matches real world conditions[21]). Therefore we chose to use BLE-MIDI for our project.

There a total of 48 input controls on the two controllers. 32 are analog buttons and potentiometers and require a discrete analog input pin on the microcontroller to be read. (The remaining 16 are the 4x4 matrix of buttons, which use a dedicated digital I^2C connection.) The ESP32 microcontrollers have limited number of analog input pins (only 6 on the boards we used) therefore six 4051 multiplexer ICs (integrated circuits) were used, each of which buffer eight analog inputs to be read on a single analog pin. This process was facilitated greatly by the Muxi PCBs designed by Ivan Franco's open source Prynth framework[22] for embedded musical instruments, which we customized for use here.

Each unit runs on a single rechargeable 600mAh 3.7V lithium polymer battery which, despite its small size, is capable of powering the device for several hours at a time. The microcontroller is equipped with a power management circuit including battery charging, so the controllers can be directly charged with a USB micro cable and standard 5V power source.

The devices were programmed in C++ using the Arduino IDE and libraries for

[20]BLE-MIDI is natively supported on MacOS and Linux, though Windows 10 requires an additional bridging application.

[21]While 10ms is held as the maximum threshold for acceptable latency in music performance (Wessel & Wright, 2001), this is typically oriented towards note-level interactions. For our applications, where controls are used for higher-level and less time-critical parameters, we have found 20ms to be acceptable.

[22]https://prynth.github.io/create/framework.html

specific functionality, most importantly Bluetooth and BLE-MIDI. This also included the necessary coding to implement and read the multiplexed analog signal acquisition. The code is also written with an eye towards continued development, with definable arrays to specify the number, type and MIDI address of input controls, as well as additonal parameters to control basic aspects of the functionality like sampling rate and filtering of the control signals.

Physical construction

The fabrication and construction of the hardware enclosures was similar to that of the new Noisebox instruments presented in Chapter 4. All physical elements were rendered digitally in Fusion 360 to model precise placement of components, measurements and so on. Once all aspects were finalized, assets were exported as files for fabrication. Rigid frames for the controllers were 3D printed out of PLA (polylactic acid, a biodegradable plastic compound commonly used in 3D printing) that included mounting points for the top control panel and microcontroller and battery underneath. The top panels were cut from translucent acrylic using a laser cutter with cutouts for all of the controls to fit.

Two strategies were used to attach the controllers to the harp in a non-permanent, non-damaging way. The primary method employs acrylic panels that lay over the soundboard of the harp above and below the controllers (visible in Figure 5.11). The harp has a wooden molding that runs around the soundboard on each side fo the strings that holds the fitted panels in place, and the controllers fit between the two panels on either side, keeping it from falling down while at rest or when tilted back during performance. Because the soundboard is a primary element of the acoustic structure of the harp it vibrates (resonates) as the harp is played. To prevent the panels and controllers from buzzing, the undersides are covered with felt, and the edges of the panels are wrapped to avoid direct contact with the wood.

For a more secure method of non-invasive attachment, we devised a system of magnetic brackets that could be mounted inside the harp that would line up with magnetic points on the controllers and panels, as shown in Figure 5.12. However, we encountered two issues with this system. First, the tight interior cavity of the harp and internal bracing made it difficult to shape the brackets to provide a good coupling point with the controllers. Second and more importantly, once adequate brackets were created and the system put into place, the controllers and brackets vibrated audibly while playing, despite layers of felt being applied to all contact points. After several trials and various proposed remedies, we haven't yet found a viable solution for this, though it will be revisited later. In the meantime, Tibbitts continues to perform with the system without the magnetic mounts, without issue.

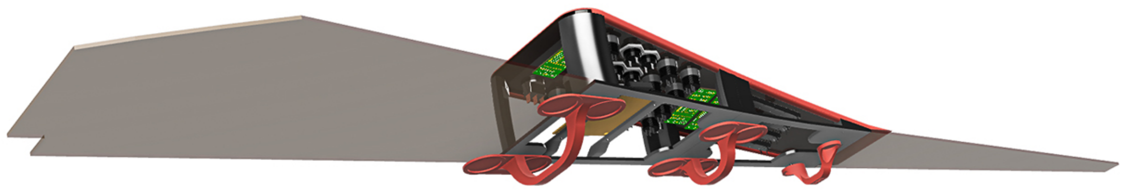


Fig. 5.12 Underside of LH panel showing magnetic mounts

5.4.3 Evaluation and testing

Because of our multiple approaches to prototyping in the earlier project stages, evaluation was ongoing throughout. Once the controllers were fully assembled, only minor changes were needed and the system worked as expected. Furthermore, given this was a research-creation project, the real evaluation and testing ground was its implementation into actual artistic performance. Two main performances have provided important milestones for the evaluation and completion of the project. First, an initial debut of the controllers occurred with Tibbitts' solo performance at the live@CIRMMT: CIR-

Fig. 5.13 Alexandra Tibbitts performs as the Bionic Harpist. Left: live@CIRMMT: CIRMMT Composers concert. Right: MUTEK International Festival.

MMT Composers concert at McGill University in February 2020. This coincided with the recent completion of the hardware, and first public test run. Second, Tibbitts gave a full audiovisual performance as part of the MUTEK international electronic music and digital arts festival in Montreal in September 2020. Images from both performances are shown in Figure 5.13 and are discussed further in the next section.

5.4.4 Artisic development, rehearsal, performance

While my focus (and the primary focus of this chapter) was oriented towards technical development of the required hardware and software, throughout the project Tibbitts was working concurrently to develop her own original performance style and material. This entailed not only writing and rehearsing new material, but also learning and practicing advanced techniques for audio manipulation, processing and sequencing using Ableton Live, developing complex mapping strategies to allow her to control everything in real time, and experimenting with the digital controller prototypes we were creating.

The first concert was very much a trial run, as well as an opportunity to give a public exposition of the controllers. Except for some small software updates, we agreed that the controllers were finished in their current state, and Tibbitts would continue to use them without further modification or development for the next performance.

In the leadup to the second performance at MUTEK, Tibbitts had a residency at Avatar, an artistic research and development center in Quebec, where she developed a large-scale solo performance. Tibbitts worked with additional collaborators to create a performance that included not only music, but also synchronized control of live visuals to be projected in the 360° immersive space of the MUTEK venue.[23] Both shows were a success, and Tibbitts continues to rehearse with the controllers while planning for future shows.

5.5 Discussion

5.5.1 Interview

After the conclusion of the Bionic Harpist performance at the MUTEK festival, I interviewed Tibbitts to discuss our recently completed project as well as our past project, and to reflect on our long-term and ongoing collaborative work. A summary of our conversation is provided here.

On Gestural Control of Instrumental Performance

For the first project, Gestural Control of Augmented Instrumental Performance, our aim was to develop and test a system for easy integration of gestural control into a harpists' playing. The motion capture analysis provided a basic understanding of instrumental and ancillary gesture in harp performance, and was a good starting point for developing

[23] The concert was held in the Satosphère, a large dome featuring 360° projection and spatialized sound system at the Société des arts technologiques. https://sat.qc.ca/en/satosphere

a gesture vocabulary that could be used for electroacoustic performance. However, regarding the creative use of the controllers, Tibbitts felt that their full potential wasn't achieved. This was in part due to the compositional approach used by Gatinet and Tibbitts, in which explicit gestures were required during performance that conflicted with the harpist's natural movements.

> In terms of an aesthetic for the [composition], it was very open ended and that was more for me and the composer to work on. . . I was asked to really use the controller to create new gestures for performance, and I learned new ways of playing the harp through that, so it wasn't all for nothing in that aspect. But I wanted to focus more on the natural ancillary gestures of performance, and how can we use that information to map effects in a more, I want to say, *holistic* approach.

The other part of this issue highlights Tibbitts' own creative development. By the end of that project she was clear with her own style and aesthetic, and well on her way to building her own original performance.

On The Bionic Harpist

Our second project was more clearly defined and less exploratory in scope than the first. Despite remaining open about the possible design outcomes, we began with a tangible goal and basic design specifications to focus our efforts. The early prototyping was highly productive, and Tibbitts' experience from the Design for Performance workshop provided both tools and creative confidence to elucidate her ideas:

> It gave me that artistic license to start thinking of [design], because you kind of demystified that idea of what it is to build. This process of crafting gave

> me a way of expressing what I needed, and made me feel like it was possible to do.

In the interview, Tibbitts also reflected on the dual roles of design and artistic performance:

> There was a lot of learning about how to be an artist, while also creating the tool that I want to make my art with. So it set up a lot of challenges and, challenges are great, and a lot of risk taking. And so I felt like I spent this last year learning a lot of the foundations behind what it is to create and what my voice is trying to go towards.

5.5.2 Reflections on designing musical interfaces for professionals

Both projects have provided clear insight on some of the particular demands of designing instruments and interfaces for professional musicians. In Section 5.2.2 we discussed Hattwick's framework for designing hardware systems for professional artistic productions. While it wasn't strictly applied in the development of these projects, we can highlight principles that were key to our successes, as well as some that could have averted frustrations. For each of Hattwick's seven design aspects, we provide one principle, followed by a short summary of its relevance to the project. A ✓ indicates a success and × indicates frustration.

For Gestural Control of Instrumental Performance:

- ✓ **Functionality**: *Reuse existing systems when possible.* Original gesture controllers were adapted from ongoing research by our collaborator, sparing us from building our own.

×/✓ **System architecture**: *Be aware of wireless details.* Initial prototypes experienced WiFi connectivity issues during performance, later versions (and Bionic Harpist controllers) successfully used BLE-MIDI instead.

× **Robustness**: *Repairability vs. replaceability.* Some units failed and were not repairable due to non-reversible assembly (glued components, etc.).

For The Bionic Harpist:

× **Aesthetics**: *Form and fit are important, and subjective.* An advanced prototype was in development before a simple check showed that the interfaces were poorly positioned for the performer.

✓ **Supporting artistic creation**: *Pay attention to your collaborators' process, and be prepared to provide prototypes with the appropriate functionality.* Iterative design process and diverse prototyping methods provided rapid response, feedback and updated designs.

✓ **Manufacturability**: *Use appropriate manufacturing techniques.* Accumulated experience from previous projects provided refined methods for robust builds.

✓ **Reusability**: *Keep an eye towards future applications.* Device firmware is written to accommodate new controller designs with different types of controls and layouts by updating a set of descriptive parameters.

These are just a few that resonated with our own work, to which we could add a few others, such as the importance of early lo-fi prototyping and digital modeling and design methods to speed the efficiency of the development process. For us this meant that, by the time the actual manufacturing began, there was little left to chance and building multiple hardware prototypes wasn't necessary.

5.5.3 Limitations and future work for the Bionic Harpist

There are also certain limitations to the system we have designed, and outstanding issues to address. First, we intend to revisit the magnetic mounting system in search of a permanent and secure method to attach the controllers that won't compromise the acoustics of the instrument. Second, communication between the device and a computer is unidirectional, and the analog controls aren't equipped to provide feedback beyond what their physical state indicates. While this is less of an issue with sliders and knobs, it is a problem for the 20 analog buttons which can be programmed as on/off toggles. While a current workaround has been to utilize the 4x4 grid equipped with multicolor LEDs for tasks that need to convey information about their state, a future plan will be to implement bidirectional MIDI communication, and upgrade the controls to types with programmable visual feedback, such as buttons with LEDs and rotary encoders with LED indicators. A further potential step may be to implement a small OLED display similar to that of the Keybox (Chapter 4, Section 4.3.1).

Another important consideration that hasn't been discussed yet is touring, which for many professional musicians constitutes an essential part of their livelihood. Given the large size and weight of a concert harp (around 1.85 meters tall and 1 meter deep, and 36 kilograms[24]), most touring harpists rely on an instrument being provided for them when they arrive for a performance. The controllers and panels we designed for the project were measured and fit to Tibbitts' own harp. Future research will investigate how to design the controllers so that they can be easily attached to other harps with different dimensions.

We have already begun plans for an updated version of the controllers that will address some of the shortcomings listed above. Additionally, as we now have a stable and reliable base to build off of, it presents an opportunity to experiment with more

[24] https://en.wikipedia.org/wiki/Pedal_harp

novel and adventurous designs. From a research perspective, considering our own lessons learned along with those of Hattwick and others in the field, we can continue to refine and share an efficient and replicable design methodology for instruments intended for professional performance.

5.6 Conclusion

This chapter has investigated the unique demands and requirements for the design of DMIs and interfaces that are intended to be put to use in professional musical practice. We began with a review of related work in three distinct areas: practice-based research including collaborative and arts-based DMI design practices, DMI design for professional contexts, and research in the area of augmented instrument design. The main contributions lie in the presentation of two applied design projects carried out in collaboration with a professional concert harpist. Taken together, the projects represent a progression of practice-based research that has refined approaches to artistic collaboration and technical design methods, resulting in the development of professional-grade musical interfaces.

The first research-design project investigated gestural affordances of harp performance. We conducted a motion capture study to analyze motion in harp performance, then applied the findings to development of a system for gestural control of digital audio effects and processing. The system consisted of wearable hardware controllers and a software GUI to connect it to common music performance applications, and was used successfully in multiple international performances.

The second project was dedicated to the design of purpose-built controllers that could non-invasively attach to the harp, allowing the performer to access controls for a sophisticated live audiovisual performance system, that has now been used in professional performances including a high profile solo set at a major electronic music festival.

This work varies from the previous chapters in two ways. First, these projects represent a long term collaboration with a professional musician, and the design decisions we have made reflect this partnership and orientation towards artistic practice. Second in contrast to the previous projects we have presented, which were primarily oriented towards building theoretical knowledge in the area of DMI design, and more generally HCI, here were have focused on pragmatic approaches to develop new DMIs that can be successfully taken up into professional artistic practice.

In the final chapter of this thesis we will reflect back on the earlier theoretical work, to link the design considerations we proposed from our initial survey in Chapter 2 through the design workshops and experimental instrument designs in Chapters 3 and 4, to the practice-based instruments developed here.

Chapter 6

Conclusion

The aim of this thesis was to investigate how active and professional musicians engage with novel digital musical instruments, and to explore methods of design for the production of instruments that active professionals would be willing to take up in their own practices. The motivation for this work comes both from previous research in the field which has shown that DMIs suffer from low rates of adoption into real world artistic practice (often limited to a single user, which is commonly the designer themselves), as well as my own personal observations as a former touring musician and current DMI designer.

Several interconnected studies have been carried out across three phases to better understand the needs of performers and to design technology for them. The work presented here has taken an open-ended, human-centered and practice-based approach, applying methods drawn from HCI, UCD and participatory design for the design and technical development of new instruments, as well as the qualitative analysis of survey and workshop data.

The first phase (Chapter 2) surveyed musicians about their practice, the instruments they use, and their views on taking up new DMIs into their own musical practice. These were presented as a set of design considerations intended to give designers practical information about musicians who use novel technologies in their practice, especially active and professional musicians who require the most from their instruments. The second phase (Chapter 3) investigated methods of DMI design, focusing on strategies to leverage tacit knowledge of performers in the generation of creative ideas and design specifications used in the development of new instruments (Chapter 4). The third and final phase (Chapters 4 and 5) focused on the design and manufacture of tangible hardware and software instruments. While the instruments in Chapter 4 continue to be developed and iterated upon, those in Chapter 5 have already been successfully put to professional artistic use.

This progression represents a culmination of the research presented here, which has moved from gathering knowledge about the field to developing and implementing a user-driven design methodology, generating ideas for new instruments with musicians, building them, and then putting them to use in professional settings. In doing so, the results provide contributions field in the following ways: theoretical, through the active examination and extension of existing theories on design, user engagement, and performance with DMIs; methodological, through the development and formalization of tools for design and prototyping, as well as analysis; and practical, in the presentation of new instruments, along with technical details and information for other designers.

The following sections of this chapter are structured as follows. In Section 6.1 methods and results of each study are summarized. Section 6.2 presents contributions of this thesis based on the main research questions posed at the outset. Limitations of the current research and indications for future work are discussed in Section 6.3. Finally, in Chapter 6.4, we offer our closing remarks.

6.1 Summary of methods and results

6.1.1 A survey on DMI performance

The first phase of this dissertation was to build a knowledge base around performance with new instruments (Chapter 2). In particular, the objective was to investigate who exactly uses novel technologies, how practices differ between different types of performance communities, and to identify shared values and priorities that performers have for the DMIs they use or would want to use in their practice. To do this, an online survey was conducted which was open to all musicians, whether or not they actively use DMIs. The survey contained mostly open-ended questions organized into four sections: demographic information and musical background, information about performance practice, descriptions and opinions of currently owned DMIs and similar performance technologies, and perspectives on the uptake, continued use (or retirement) of DMIs. 85 responses were received, including 62 respondents who actively use DMIs and similar instruments (including commercial digital instruments, computers, controllers, miscellaneous electronics, etc.) in their performance practice.

The responses were analyzed in three steps. Steps one and two used methods of thematic analysis proposed by Braun and Clarke (2006), an approach similar to grounded theory (Strauss & Corbin, 1994) but more flexible in its application. Step one used a bottom-up approach to organize responses about participants' currently used instruments into three groupings: recurrent quality attributes, requested features, and instrument issues. The second step entailed a top-down analysis of participants' perspectives on uptake and continued use of DMIs based on theories of long- and short-term user engagement found in the literature. An exploratory third step of analysis crosstabulated the themes identified in the first two steps across two primary performance attributes, musical style and frequency of performance, to highlight different characteristics between different performance communities and to suggest a methodology for continued research in this area.

The results of the survey have been summarized as a set of considerations for designers to take into account when developing instruments intended for use in active performance practices, which are offered as one of the main contributions of this thesis and are listed in Section 6.2.

6.1.2 Early stage, user-driven DMI design

Following the initial survey of the field of DMI use and performance, the rest of my dissertation research is practice-based with a focus on developing and implementing human-centered approaches to DMI design. This began with a workshop designed to generate creative ideas for eventual development into new DMIs (Chapter 3). The Design for Performance workshop was held with ten expert musicians divided into two sessions, who built non-functional prototypes of imagined musical instruments that they would want to use for their own musical practices. The workshop was adapted from Kristina Andersen's Magic Machine Workshops (2017), based on the concept of design fiction in which "the deliberate use of diegetic prototypes to suspend disbelief about change" (Sterling, 2013, as quoted by Blythe, 2014). In short, through the design of fictional instruments, participants were free to engage with the possibilities of what could be, not only in terms of instruments but also in terms of novel ways of performing.

While the immediate outcome of the workshop was the physical instrument prototypes and identification of key design elements that were collected during the sessions, the analysis that followed provided a more complete and nuanced understanding of the design activity and emergent design aspects. The same exploratory, bottom-up method of thematic analysis that was applied to the survey results was applied to videorecorded workshop sessions, in which the participants presented their prototypes, highlighted important aspects of their designs, and engaged in group discussion around instrument design. The result of the analysis was an organized collection of design elements mentioned by the participants organized into 11 identifiable themes, the most popular of which were encapsulated into tangible design specifications.

This methodology is intended to leverage tacit knowledge of expert performers in the design of new instruments. It is hoped that the designs and resulting specifications embody important aspects of real-world performance, freed from concerns of what is or isn't technically feasible. Furthermore, asking participants to engage in activity that is fiction-based and contains elements of absurdity and levity (one participant commented that they hadn't done arts and crafts since kindergarten) opens up possibilities for highly unique and imaginative design ideas that might not otherwise be arrived at.

6.1.3 Applied design and integration into professional performance

The third and final element of this dissertation is the applied design of DMIs and their prospects for use in professional performance practice. This work was carried out in two separate contexts, however some of the methods used, especially for the technical design and manufacture, are interrelated.

The first context (Chapter 4) represents a direct continuation of the Design for Performance workshops that had resulted in a set of high-level design specifications. These specifications guided the design of three new DMIs, based on a series of instruments called Noiseboxes that I had previously designed. The results then are a combination of the embodied performance knowledge from the expert musicians who participated in the workshops and my own personal knowledge and experience in the technical design of DMIs. While the new instruments share an underlying architecture for embedded instruments (including onboard processing and sound production), each represents a distinct and novel design with a unique set of functionalities. The instruments have yet to be integrated into real world use, as planned evaluation sessions with participants have been suspended due to health risks related to COVID-19, which is ongoing at the time of writing. However, the ultimate aim for these instruments are to present them to musicians for long-term evaluation in applied real-world performance practice.

The second context of applied design has taken place through development and integration of hardware interfaces to augment the concert harp for solo electroacoustic performance (Chapter 5). This work has spanned two distinct projects both carried out in collaboration with a professional harpist. Each resulted in the manufacture of performance-ready hardware and software that was, and continues to be, successfully used in professional, real-world performances. The first project concerned the investigation of movement in harp performance as a basis for a gesture control system. A motion capture analysis provided information about instrumental and ancillary gesture in harp performance, and a system comprised of wearable wireless controllers and software interface was developed. The work culminated in the composition of a new electroacoustic work for harp and the controllers which was performed several times. The second project involved the design of isomorphic controllers that physically attach to the concert harp and connect wirelessly to live performance software. This system has now also been used in professional performances and is now integrated into the harpist's core performance setup.

The two applied design contexts (the Noisebox-inspired instruments of Chapter 4 and harp augmentations of Chapter 5) represent different conceptual approaches and scenarios. The conceptual approach for the first is a direct application of the exploratory idea generation methods developed in Chapter 3, while the approach for the second is artistically motivated, carried out in close collaboration with a professional performer. Importantly, the former represents design for general DMI users: several expert musicians contributed ideas, which resulted in three different prototypes which have been designed to accommodate a variety of different performance contexts. On the other hand, the latter was focused on a single context, that of harp performance, and the final design (the augmented harp controllers) are bespoke creations for my collaborator.

Many of the same materials and methods are shared across the different contexts, including iterative low fidelity and digital prototyping approaches to design, development of modular reusable software components, and rapid prototyping techniques including 3D printing and laser cutting for hardware fabrication. These techniques are summarized as practical contributions in the following section.

6.2 Contributions of knowledge

This dissertation contains multiple contributions of knowledge towards the design of highly playable DMIs that can support active and professional use in performance. The original research questions that were posed in Chapter 1 are reprised here, followed by the main contributions made in response to each. Finally, a fourth contribution comprising general DMI design strategies is presented.

1. How do active and professional performers across diverse communities of practice engage with new instruments?
2. Can designers effectively leverage the embodied knowledge and experience of performers through applied design activities?
3. How can ongoing collaboration with active musicians support the development of new DMIs that are optimized for long-term professional use?

6.2.1 Professional engagement with new instruments

The survey of musicians provided a broad understanding of DMI use in active and professional practice including factors for, and attributes of, instruments that would be put to use in real-world performance contexts. They are summarized here are as a set of considerations for designers. (The full list of considerations is listed in Section 2.6.1.)

1. The ability to handle complexity, accommodate the unique requirements of its user, and suitedness for appropriation are important qualities for instruments to be successful in long-term practice.

2. Sound quality, affordability, and look and feel contribute to performers' overall favorable impression of an instrument.

3. Performers consistently show interest in acquiring instruments that provide improved features, controls and new sounds.

4. Performers exhibit great loyalty to their instruments. Even though reliability is a persistent concern, performers often prize their instruments and will put up with minor issues to continue using them.

5. Several instrument qualities contribute to both short- and long- term engagement with DMIs: including ownership and novelty (through deep customization or acquiring new instruments), complexity and challenge (through elaborate and highly personal setups), and immediacy, incrementality and reliability (for functional, long-lasting operation and minimizing obstacles to their use).

6. These considerations may need to be accounted for in different ways depending on who the designer is designing for. Two obvious differentiations are frequency of performance (contrasting between amateur and professional practice) and musical style, though there are many others that may be considered.

6.2.2 Leveraging embodied knowledge in design

With the Design for Performance workshops, a workshop is presented to fully engage knowledgeable performers in the early stages of instrument design. With the nonfunctional prototyping and design fiction approach, musicians are able to freely ideate and express their ideas without concern for technological feasibility or constraint, allowing them to extend and explore concepts, shapes, materials or interactions, that can be more closely aligned with their own embodied practice than would be translated or envisioned by a designer alone.

Methodologically, the workshops are simple and repeatable, and require little overhead to carry out. While the version that was run here included in-situ activities to capture and highlight important design elements, ultimately the thematic analysis provides a more thorough interpretation of the creative workshop activity, providing a path from fictional designs to tangible specifications that can be applied to the development of real instruments, as was done with the new Noisebox-inspired instruments presented in Chapter 4.

6.2.3 Ongoing collaboration for long-term use

The augmented harp projects presented in Chapter 5 have been productive and provide a clear example of long-term designer/performer collaboration. While the purpose-built designs don't speak to previously voiced concerns identified around the slow uptake of DMIs into more widespread use, overall the work reflects a refined method of collaboration that has led to the incorporation of novel designs into a professional performance practice. As such, the methods are presented as a validated model for long-term artistic collaboration.

While the model of collaboration presented here is one to one, prospects for combining approaches with the design workshops is bright. Scenarios can be envisioned where initial workshops lead to continued collaborations, not only with individuals but small groups with similar interests and needs. Ultimately, this combined approach may provide the best opportunity for developing instruments that will be robust and appealing for more long-term and widespread professional use.

6.2.4 Tools for design, tools for prototyping

A final contribution of knowledge is offered in the form of empirically gathered practical insights and suggestions for efficient technical design and prototyping of hardware-based DMIs (including embedded instruments as well as hardware controllers that connect to computers):

- **Use multiple approaches to prototyping at different levels of fidelity.** The design of the Noisebox-inspired instruments and augmented harp controllers entailed the development of a variety of simultaneous physical and digital models to examine different parts of the design: simple non-functional prototypes to experiment with shapes, sizes, placements and materials; touchscreen apps like touchOSC for immediate working interactive prototypes that can be used as functional stand-ins for future hardware; 3D CAD models to quickly visualize and inspect ideas when physical prototypes aren't feasible.

- **Design as much as you can digitally, then build.** Depending on the scope of design and materials used, a majority of all technical design work - including software development, circuit design and especially 3D modeling of physical enclosure and other structural components, can be accomplished before manufacturing a single part. While it may still require multiple iterations to finalize an instrument (which may vary greatly depending on scope), robust digital prototyping will facilitate easy transfer to production and minimize unexpected obstacles. There is also a caveat, as discovered in the speaker design of the Tapbox instrument in Chapter 4 (Section 4.3.2), that unforeseen issues may present themselves when moving from digital to hardware prototypes. Nonetheless, time and care spent in the digital design phase will always pay off in the long run.

- **Incorporate rapid physical prototyping techniques including CAD design, 3D printing and laser cutting as part of a core instrument design toolbox.** These methods allow for fast and accurate design and fabrication of high fidelity prototypes and even finished products, making for a streamlined and efficient design workflow.

- **Design software (and hardware, where appropriate) to be extendable and reusable.** More often than not, the continued design of instruments, whether continuing to refine existing designs or creating new instruments, involves the same processes, tools and raw materials. Thus, designing software and other assets to be reused is an important step. This echoes past design recommendations from Hattwick (2017) ("Keep an eye towards future applications") that resonated strongly in the work presented here. In addition to streamlining future development, this can also be an important way to address environmental sustainability and conservation in DMI design research. These issues have not been widely raised in literature previously, however there is more emphasis and awareness being fostered now (Masu et al., 2021).

- **Create detailed design documentation throughout the process.** This can be invaluable if things go wrong, and be a useful roadmap for the planning of new projects.

6.3 Limitations and future work

One of the aspects that the Electronic Musical Instrument Survey intended to investigate was diversity across different performance communities. While the survey did identify different types of performance practices, many of the respondents shared many of the same characteristics which could be attributed to “NIME-style” practice: ample formal musical training and experience, musical styles predominantly weighted towards experimental and electroacoustic, and only occasional performances. Thus, while the results provided a wealth of information, it was difficult to make conclusive statements differentiating one group from another. It could be highly informative to carry out a follow-up survey with more targeted distribution across different performance demographics. This could also extend the third section of analysis that was introduced for the survey data, in which responses were crosstabulated between different performance attributes.

The list of design considerations compiled from the survey also present areas for deeper investigation, especially in in the topic of user engagement. Our analysis and synthesis of existing models of long- and short- term engagement associated several instrumental qualities; it would be highly informative to expand this further into a unified framework of DMI engagement.

The Design for Performance workshops and subsequent DMI designs will benefit from additional workshops, as well as continued long-term study to evaluate the effectiveness of the design process. The initial workshop design intended for follow-up sessions to present the finished instrument prototypes to the participants for initial feedback and continued input on the development. Due to suspension of in-person research activities due to COVID-19, the additional sessions were ultimately called off. Additionally, between the first pilot workshop that was run with music technology students knowledgeable in DMI design and the official workshop sessions that were run with expert performers, the question was raised of comparing design outputs of the two groups. This indicates potential for a dedicated workshop-based study to be conducted in the future.

A full and long-term design cycle is envisioned for the Design for Performance project that includes longitudinal evaluation of the instruments through applied artistic use. Longitudinal studies have been shown to be highly useful in understanding changes over time such as frequency of use and development of technique (Gelineck & Serafin, 2012), as well as measuring long-term engagement. Positive results were shown from a similar long-term approach in the Digital Orchestration Project (Ferguson & Wanderley, 2010) in which designers, composer and performers collaborated over three years to bring new new instruments into applied artistic use, which continued even past the official conclusion of the project.

6.4 Closing Remarks

Through this dissertation I have investigated several aspects of digital musical instrument design with a continued focus on their development and integration into real-world musical practice. Through the investigation of people that use digital instruments and through practice-based research designing new instruments with and for performers, knowledge has been collected about the particular needs, requirements and preferences performers have for their instruments, and formulated into methods to address those aspects throughout the design process. It is my hope, therefore, that the insights shared here can be of value to other instrument designers, and that collectively we can create better, more playable, more enjoyable instruments that performers will be excited to use.

Appendices

Appendix A

EMI Survey: Questionnaire

Electronic Musical Instrument Survey

A questionnaire on the use of technology in live performance

Hello! If you are an active musician, we would like to hear from you about the use of electronic instruments in performance. You are invited to take this survey whether or not your personally use electronic instruments, and no matter what style of music you play.

By participating in this survey, your can enter to win a $100 CAD gift certificate to an online music retailer like Moog Audio or Sweetwater.

This work is part of ongoing research on the design of new instruments, tools and techniques for music performance being conducted at McGill University. The principal investigator for this study is John Sullivan, supervised by Dr. Marcelo Wanderley. This work has been certified by the review ethics board. No risks are associated with this research and your confidentiality for participating in this study will be protected.

You must be 18 years of age or older to participate. The survey may take between 10 and 30 minutes to complete. While it is accessible across all devices, you may find it most convenient to complete on a computer or tablet equipped with a keyboard.

I. Performance Practice

A. Background info

1. What is your age?

○ 18 to 24
○ 25 to 34
○ 35 to 44
○ 45 to 54
○ 55 to 64
○ 65 or older

2. What gender do you identify with?

○ Female
○ Male
○ Non-Binary
○ I prefer not to say
○ Other

3. What country do you live in?
{dropdown list of countries}

B. Musical training and experience

4. How long have you been playing music?

○ Less than 1 year
○ 1 to 5 years
○ 6 to 10 years
○ 11 to 20 years
○ More than 20 years

5. Have you had any formal training? *Check all that apply.*

□ University - Undergraduate
□ University - Graduate
□ Conservatory
□ Private instruction
□ Other
□ None

5a. *{if 'Other'}* Please specify.

____

5b. *{if 'Private instruction' or 'Other'}* For how long?

____

5c. *{if 'Private instruction' or 'Other'}* What area(s) of focus?

____

6. Do you have any experience with computer programming or electronics?

○ Yes ○ No

C. Performance practice

7. What is/are the primary genre(s) of music that you perform? *Choose up to 2.*

- ☐ Avant-garde/Experimental
- ☐ Blues
- ☐ Classical
- ☐ Country
- ☐ Dance/EDM
- ☐ Electro-acoustic
- ☐ Folk
- ☐ International
- ☐ Jazz
- ☐ Latin
- ☐ Pop/Rock
- ☐ R&B
- ☐ Rap
- ☐ Stage/Theater

8. If there are specific sub-genres or styles of music that you play, what are they?

____

9. How many times per year do you perform in public?

- ○ 0 to 10 times
- ○ 11 - 20 times
- ○ 21 - 50 times
- ○ 51 - 100 times
- ○ More than 100 times

10. What size and type of venues do you typically play in?

____

____

11. Do you play solo or in a group or ensemble?

○ Solo ○ Group/ensemble ○ Both

12. Which instruments are used? Can you describe your setups?

____

____

II. Electronic Musical Instruments and Controllers

A. Use of electronic musical instruments and controllers

13. Do you use electronic musical instruments in performance? ○ Yes ○ No
{if 'No' skip to Sec. D to conclude survey.}

14. What type(s) of instruments do you use?

- ☐ Keyboard synthesizers
- ☐ Drum machines
- ☐ Computer software
- ☐ Modular synthesizers
- ☐ FX processors
- ☐ MIDI controllers
- ☐ Samplers
- ☐ FX pedals
- ☐ Other

14a. *{if 'Other'}* Please specify.

____

15. Do you prefer computers or dedicated hardware? Why?

____

____

B. Description and functionality

16. What is the name of your instrument or controller?

____

17. During a typical performance, what percentage of time do you use it?

____

18. Is it commercially available? ○ Yes ○ No

18a. Who built/designed it?

____

18b. Can you describe it?

____

____

18c. How old is it?

____

19. What kinds of sounds or sound manipulations do you produce with it?

____

____

20. How do you use the configuration options that your instrument provides?

____

____

21. What do you like about this instrument?

____

____

22. Is your instrument or controller in its preent form satisfactory or would you like it to have different functionalities? Please explain.

____

____

23. How reliable is your instrument or controller? Are there any random or recurrent hardware or software issues?

____

____

24. Would you like to answer the previous questions abour another instrument or controller you use? ○ Yes ○ No
{Participant can repeat this section up to 3 times.}

C. Acquisition and continued use

25. What factors influence you to take up a new electronic instrument?

____

____

26. Is the look and feel of an instrument an important factor in choosing it? If yes, how so?

____

____

27. Is the flexibility of an instrument an important factor in choosing it? If yes, how so?

____

____

28. On average, how long do you typically use an electronic musical instrument before retiring it? What factors influence you to stop using certain electronic instruments?

____

____

29. Are you familiar with the history, traditions and repertoire (if applicable) of your instrument(s), and do they play a role in your performance?

____

____

30. Do you have any other comments or information that would be helpful to understand your use of electronic instruments and controllers that have not been addressed in this survey?

____

____

D. Conclusion

31. Would you be interested in participating in a follow-up interview? ○ Yes ○ No

32. Would you like to be entered to win a $100 CAD gift certificate to either Moog Audio or Sweetware Sound? ○ Yes ○ No

32a. *{if 'Yes'}* Please enter your email address.

____

Appendix B

EMI Survey:

Codebook and additional analysis

B.1 Codebooks

1. Instrument descriptions and functionality:
    (a) Recurrent Quality Attributes
    (b) Requested Features
    (c) Instrument Issues
2. User engagement
    (a) Uptake, Longevity and Abandonment (Exploratory coding)
    (b) Short-term engagement (O'Brien and Toms)
    (c) Long-term engagement (Wallis, *et al.*)

Codebook: I. Instrument Descriptions and Functionality

Name	Description	Quote
Instrument issues	**Issues or problems identified with current instrument**	
broken bits, knobs, keys, etc	minor instrument breakage, wear and tear, etc.; instrument can still be played	"Broken buttons used for switching between patches/sounds, and a broken pitch-bend/expression knob."
software issues	any problems with software, could be bugs, incompatibility, improper configuration, etc.	"Sometimes crashes, sensitive to the order of the hook up of assorted components (sound card, controller, etc.)"
hardware limitations	encountering issues or limitations of hardware,sometimes mentioned as a positive attribute	"Tuning / intonation is always a problem with the buchla, and getting it warmed up is absolutely mandatory before a performance. there are always adjustments that need to be made to the intonation of the keyboard"
poor quality	issues with overall build quality and instrument performance	"Replace the pads in the sl that are really h-o-r-r-i-b-l-e."
cables and connections	issues involving faulty wires and cables, electronic connections, may be intermittent	"Sometimes the cables are a bit finicky and need to be massaged to make proper connections."
general computing devices	issues relating to the use of general purpose computers and input devices (computer keyboard, mouse) instead of purpose-built devices	"Somretimes manipulating with a mouse is hard, might try other controllers in the future but have not yet."
hard to control	issues that make an instrument difficult to control	"At the same time, the eigenharp has yet to really help me in the way it should. for instance, it's been difficult for me to use it to play harmonically."
hardware issues	problems with physical hardware, electronics, etc.	"Sometimes the rc505 will permanently edit my samples without my permission. most of the time i am in agreement with its creative choices."
latency	unwanted delay between input signal and resulting output, usually between user input (control) and sound output	"The low frequency to midi conversion is slow in the low frequencies. perhaps it is due to needing a longer buffer size so higher frequency resolution can be achieved with the frequency transform."
noisy audio	poor quality audio signal, may be either digital or electronic (poor wiring or low quality components)	"The only problem is the connection current noise, but for that i use a gate on ableton live"
Recurrent quality attribute themes	**Aggregation of quality attribute codes from instrument description and functionality coding. What are the positive features and aspects of an instrument?**	
accommodation	***Supplying a need, want, convenience. Related to affordance.***	
size and portability	physical property of the instrument (usually smaller preferred), and the capacity to be easily transported.	"I like that it's small easily portable and light weight."
playability	general attributes that contribute to an instrument's capacity for being played effectively, such as ergonomics or well-designed UI	"Physicality and ease of control."
compatibility and interoperability	capacity for instrument to integrate with other instruments, setups, players and systems, adherence with industry standards (communication protocols, cables, jacks, etc.)	"Using hardware, i have the option to either simplify my setup by using less gear which is more versatile or augmenting a more complex setup and maintaining its balance more carefully."
ease of use	attributes that support an instrument's uncomplicated use, smooth operation, and minimal setup and configuration	"The ease of use and convenience make effects pedals a great choice for guitarists."
appropriation	***Suitable or fitting for a particular purpose, person, occasion, etc.; belonging to or peculiar to a person***	
embodied connection	connection between performer and instrument, especially as mediated through the body and physical interaction	"I also like the ability to use physicality for playing music."

Name	Description	Quote
personalization	customization and modification of an instrument, making it unique to the owner; establishment of personal bond to instrument	"By making it more personalized, responding and doing action that are relevant to my music."
handling complexity	***Flexibility and variability, vs. simplicity and constraints***	
flexibility	able to carry out a variety of tasks, versatile	"It's also a really flexible device, when you get down to it. it can work like a melodic/harmonic grid, which is really useful for me. but it can also be a 3d controller, a control surface, a drum machine, a vj controller, etc."
simplicity and constraints	ease of operation coming from limited possibilities or dedicated functionality.	"Comparatively simple to use, immediate results, low cognitive effort to control the setup"
other qualities	***Other frequently mentioned codes that don't fit with the other categories***	
sound quality	quality of an instrument's sound, generally an evaluation of the instrument quality itself (good components or algorithms)	"It sounds amazing."
cost and affordability	the accessible price of an instrument, which would make it obtainable	"It's relatively in-expensive, and i have gotten a lot of miles out of it."
aesthetics	positive attributes of an instrument coming from sensory appreciation (esp. value arising from aspects not directly related to sound production, such as the look or feel of an instrument)	"I also think that it is a very nice piece of furniture to keep in my living room, it has wood and everything!"
Requested features	**Things that one would add to their current instruments if they could**	
more or improved controls	specifically relating to the user interface, either more controls (ability to control more parameters) or improved controls (greater resolution or accuracy)	"I am considering getting a new controller with larger faders and more trigger buttons."
added features and functionality	additional elements that could augment an existing instrument without changing existing capabilities	"Being somehow able to modulate the note whilst it it on, using pressure or similar, would be a great additional feature."
connectivity	ways that an instrument can connect with other instruments and systems, interfacing with standard cables, jacks, connectors, or protocols	"The hardware lacks of booth outputs and xlr outs"
high level programming	ability to programatically modify the behaviour of an instrument at a high level, eg., without having to write computer code	"High level lang like pd instead of doing code."
standalone	ability for an instrument to operate without connecting to other systems (computer, speakers, etc.), can be different degrees of 'standalone-ness'	"Internal high quality sounds or synthesis capabilities"
better feel and ergonomics	improving physical elements of an instrument to improve handling and performance with it	"It would be nice if it could simulate the mechanical sensation present in an acoustic grand piano (not just weighted keys, but also hammer knuckle feeling)"
feedback	ways that an instrument can provide information back to the user	"A visual feedback for bpm"
improved quality	better overall build quality and function. may be better components, better overall design, better software	"Specifically, i would like for all of the buttons to work including the pitch bend/expression knob. i would love for it to have a decent piano sound."

Codebook: II. User Engagement

Name	Description	Quote
Uptake, longevity and abandonment	**Open exploratory coding from survey**	
Uptake	***Attributes around beginning to use new instruments***	
constraints	*limiting the set of possible actions that can be performed on a system*	
simplicity		"Simplicity, fuctionality, sound quality and size"
limitations of hardware		"I might go for some hardware instrument in a near future. I sometime start to think that having constraint is way to develop more "virtuosity" with the instrument, because you are force to be creative with specific parameters that can't be change."
influence	*compiled or influenced by actions of others*	
heard the instrument played		"Often influenced by listening to music with that instrument."
recommendation		"Suggested by another musician."
novelty and variety	*seeking new experiences or qualities, more options to choose from*	
expand or diversify performance practice		"Different function or sound from something I already have. If I have a project/idea that the instrument fits with."
exploration		"Is it "interesting" does it do something that nothing else does?"
new or improved sounds		"I want to be able to have different sounds at my disposal."
other factors	*includes learning curve, ease of use, stage presence, flexibility and versatility*	
learning curve, ease of use		"My desire to learn and a small amount of envy of people who can play certain instruments."
movement around stage		"How well it integrates with my setup and the playing of my instruments and moving onstage"
never new instruments		"I built my own instrument almost 20 years ago. I do not intend to take up any new one."
options, versatility, flexibility		"Flexibility of usage between studio and performance work"
same computer, new patches		"In a sense, I can say that I haven't taken a new instrument in years because I've been performing with a computer for more than a decade. In another sense, I may say that I often change instruments, as every time I develop a new patch my instrument is fundamentally transformed."
practical concerns	*likely to succeed or be effective in real circumstances*	
being a percussionist		"As a percussionist, I am always taking up new instruments."
cost and availability		"Price/value is a big one, to be honest. Especially for a "mere" controller. It really needs to provide huge added value for me to want to invest any money."
integration with current instruments and setup		"The chance to integrate it to my setup, in terms of sync and modularity"
reliability and quality		"The engineering of it"
replace general computing solution		"Wish to investigate control possibilities for the sound manipulation processes that I was already using and controlling with the laptop."
size and portability		"Performance possibility and compactness"
upgrades	*improving upon existing instruments*	

Name	Description	Quote
acquire specific functionality		"Different function or sound from something I already have. If I have a project/idea that the instrument fits with."
improved interaction or control		"Before taking up a new instrument I have to feel that what is capable in terms of performance on that instrument occupies a new or advanced realm of creative expression not possible with other gear."
new features		"If a device has a tool I want and I can't do that with my current devices I'll look into getting a new device"
Longevity and abandonment	***Attributes around long-term use of instruments, and retirement/abandonnent of instruments***	
broken or unreliable	loss of functionality, requiring repair or replacement	"Until I can no longer use it, due to it being broken/totally unreliable"
constant change	avoiding stagnation, seeking novelty, new things, sources of creativity	"The mind changed and you need to change sources of sound, the feeling change, the fashion change the vibe change and the budget for good music festival, all changes and move etc..."
imbalance	individual components not fitting with entire setup	"Sometimes I'll retire a piece of gear because it doesn't inspire balance within my setup"
loss of interest or usefullness	boredom with an instrument, loss of creativity or inspiration	"Until I either get tired of the sound or (if it is a controller) start finding it uninspiring."
never retire instruments	keep for an instrument's lifetime	"I wouldn't say I retire any electronic instruments - I think there's a lot of potential in old or "outdated" electronics and I would never consider anything truly retired."
newer prototype	replace with newer, self-built DMI	"Usually one year per prototype."
obsolescence and incompatibility	loss of functionality due to out of date software or hardware, loss of compatibility with other instruments, systems, softwares etc.	"Bummers, incompatibilities with new operating systems, new cabling standards, and so on."
replace with better, more suitable	replacement or upgrade	"Sometimes they are superseded by an instrument that is more performance-friendly, has a better feature set or has a sound that is more closely in harmony with the music I want to perform."
streamline setup	eliminate redundancy, reduce unnecessary or non-essential parts	"A machine that does one thing very well is half as good as something that does 10 things reasonably well"
vibe, flow, balance	interconnectedness between audience, other musicians, setup, set, etc.	"I'll stop using an intrument that doesn't connects with me; or stops my playing flow."
Short-term engagement	**Event-level engagement attributes (by O'Brien and Toms)**	
aesthetic and sensory appeal	rich physical and graphical interfaces, multimodal feedback	"Has a sound that is more closely in harmony with the music I want to perform"
affect (negative)	negative emotions, uncertainty, doubt, frustration towards technology, anxiety about how much time spent on a task, boredom, guilt about putting other things off	"Then I just get bored"
affect (positive)	positive emotions, enjoyment, satisfaction, fun	"If i like it, i'll use it until it breaks."
attention	The concentration of mental activity; can be divided (attending to multiple stimuli simultaneously, i.e., multitasking), or selective (concentrating on one stimulus only and ignoring all others	"I usually do an investigation about the sound and the possibilities of the instrument"
awareness (external)	concentration on particular external stimuli, awareness of other people in both real and virtual environments	n/a
awareness (self)	cognizance of one's environment, losing consciousness of physical surroundings, flow state	"How well it integrates with my setup and the playing of my instruments and moving onstage"
challenge	The level of cognitive effort experienced by the participant in performing a task	"In recent years I have also performed with hardware synthesizers, because due to the technical limitations in terms of connecting sound they are challenging me in different ways."

Name	Description	Quote
control	How "in charge" users feel over their experience with the technology	"Flexibility of preset timbres and options for editing"
feedback	Response or reaction from the task environment or system that communicates the appropriateness of the users' past actions or demonstrates progress toward a specific goal; serves as a basis for future action	"The user interface"
interactivity	customization, being part of a story, being able to select information	"Its versatility, that is to say different modes and functions, the possibility of using it in different places of instrument chains"
interest	"Feeling that accompanies or causes special attention to an object or class of objects" (Merriam-Webster Online)	"If I really connect with an instrument then I use it for a long time."
motivation	success coming from getting what one wants	"I will invest myself in a new piece of gear/instrument if I feel it will help me to achieve an existing artistic goal"
novelty	Inquisitiveness; tendency to seek the new, unusual, or interesting in one's environment	"Trying to expand my horizons in performance."
perception of time	impression that it takes a lot of time, surprised by time passing	n/a
Long-term engagement	**Long-term engagement with musical instruments (by Wallis, et al.)**	
Mastery (competence)	***being good at, or capable of becoming good at, something difficult***	
complexity	Potential complexity of interaction; ceiling of expertise	"I have to feel that what is capable in terms of performance on that instrument occupies a new or advanced realm of creative expression not possible with other gear."
immediacy	Whether obstacles to participating in the activity are low	"If the controller increases ease of use, better responsiveness or control intimacy, or, to put it another way, if it allows simple control over complex sound structures, I'm all in."
incrementality	Whether progression in difficulty from beginner to expert is gradual (learning curve)	"An instrument which requires a lot of time to learn can be very valuable for the learning itself (if the learning experience is pleasant and/or if the knowledge gained can lead to something really new). At the same time, the need to spend time learning a new instrument can feel very overwhelming."
Autonomy	***an individual's free choice to engage in an activity, and do it in their own way***	
ownership	Whether users have options, configurability, or ways to express or invest themselves	"I built my own instrument almost 20 years ago. I do not intend to take up any new one."
operational freedom	Whether interaction seems driven by user or interface	"My inability to overpass its user interface deficiencies, a better designed easier-to-use one has been released."
Purpose (relatedness)	***activities containing a social element or an element of relatedness with other people***	
demonstratability	Whether user can demo expertise to another	"The awe of seeing another player engage with it."
cooperation	Whether users can work together	"If the concept of performing the instrument myself is more favorable than collaborating with someone who is already proficient in that instrument."

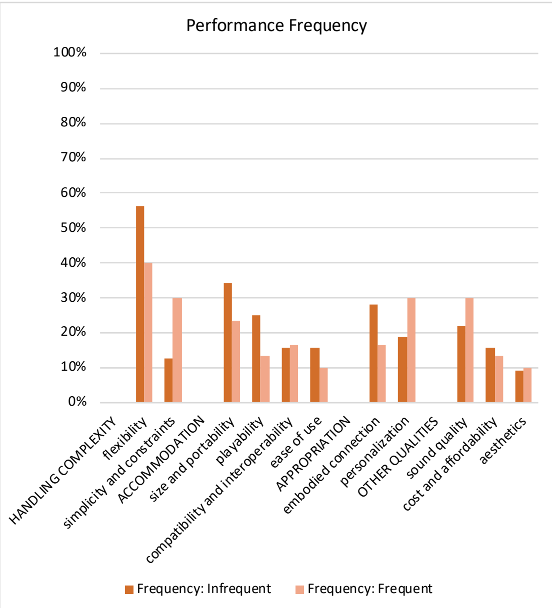
B.2 Qualitative Crosstabulation Analysis Sheets

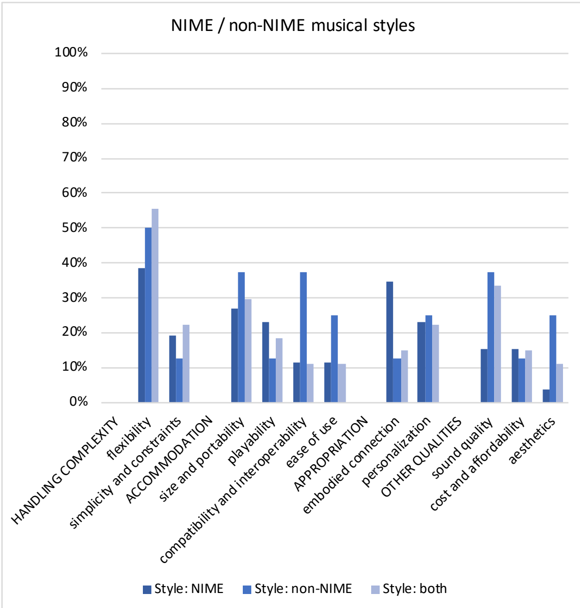
1. Recurrent Quality Attributes of EMIs, tabulated by a) performance frequency (fewer or more than 10 performances per year), b) musical style (NIME, non-NIME or both), and c) both attributes combined.

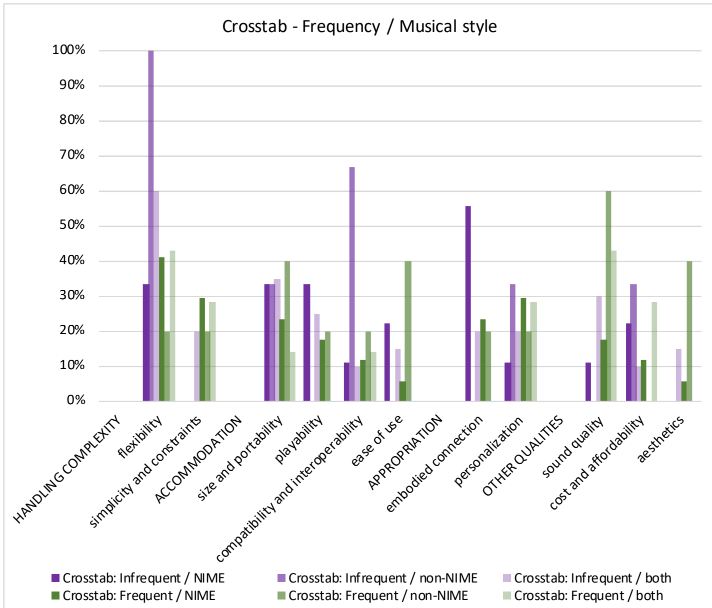
2. Combined attributes for uptake and long-term engagement with EMIs tabulated by a) performance frequency, b) musical style, and c) both attributes combined.

Crosstabulation Analysis: Recurrent Quality Attributes of EMIs by Frequency of Performance (</> 10x per year) and Musical Style (NIME/non-NIME/both)

Nodes	Frequency: Infrequent	32	Frequency: Frequent	29	Style: NIME	26	Style: non-NIME	8	Style: both	27	Crosstab: Infrequent / NIME	9	Crosstab: Infrequent / non-NIME	3	Crosstab: Infrequent / both	20	Crosstab: Frequent / NIME	17	Crosstab: Frequent / non-NIME	5	Crosstab: Frequent / both	7	Total	61
HANDLING COMPLEXITY																							**62.30%**	**38**
flexibility	56.25%	18	40%	12	38.46%	10	50%	4	55.56%	15	33.33%	3	100%	3	60%	12	41.18%	7	20%	1	42.86%	3	47.54%	29
simplicity and constraints	12.50%	4	30%	9	19.23%	5	12.50%	1	22.22%	6	0%	0	0%	0	20%	4	29.41%	5	20%	1	28.57%	2	19.67%	12
ACCOMMODATION																							**52.46%**	**32**
size and portability	34.38%	11	23.33%	7	26.92%	7	37.50%	3	29.63%	8	33.33%	3	33.33%	1	35%	7	23.53%	4	40%	2	14.29%	1	29.51%	18
playability	25%	8	13.33%	4	23.08%	6	12.50%	1	18.52%	5	33.33%	3	0%	0	25%	5	17.65%	3	20%	1	0%	0	19.67%	12
compatibility and interoperability	15.62%	5	16.67%	5	11.54%	3	37.50%	3	11.11%	3	11.11%	1	66.67%	2	10%	2	11.76%	2	20%	1	14.29%	1	14.75%	9
ease of use	15.62%	5	10%	3	11.54%	3	25%	2	11.11%	3	22.22%	2	0%	0	15%	3	5.88%	1	40%	2	0%	0	13.11%	8
APPROPRIATION																							**39.34%**	**24**
embodied connection	28.12%	9	16.67%	5	34.62%	9	12.50%	1	14.81%	4	55.56%	5	0%	0	20%	4	23.53%	4	20%	1	0%	0	22.95%	14
personalization	18.75%	6	30%	9	23.08%	6	25%	2	22.22%	6	11.11%	1	33.33%	1	20%	4	29.41%	5	20%	1	28.57%	2	22.95%	14
OTHER QUALITIES																							**39.34%**	**24**
sound quality	21.88%	7	30%	9	15.38%	4	37.50%	3	33.33%	9	11.11%	1	0%	0	30%	6	17.65%	3	60%	3	42.86%	3	26.23%	16
cost and affordability	15.62%	5	13.33%	4	15.38%	4	12.50%	1	14.81%	4	22.22%	2	33.33%	1	10%	2	11.76%	2	0%	0	28.57%	2	14.75%	9
aesthetics	9.38%	3	10%	3	3.85%	1	25%	2	11.11%	3	0%	0	0%	0	15%	3	5.88%	1	40%	2	0%	0	9.84%	6
Total (Unique)	**90.62%**	**29**	**90%**	**26**	**96.15%**	**25**	**100%**	**8**	**81.48%**	**22**	**100%**	**9**	**100%**	**3**	**85%**	**17**	**94.12%**	**16**	**100%**	**5**	**71.43%**	**5**	**90.16%**	**55**

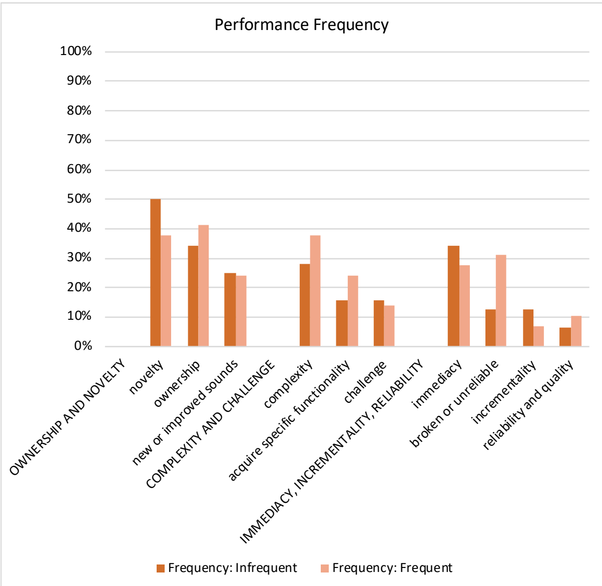


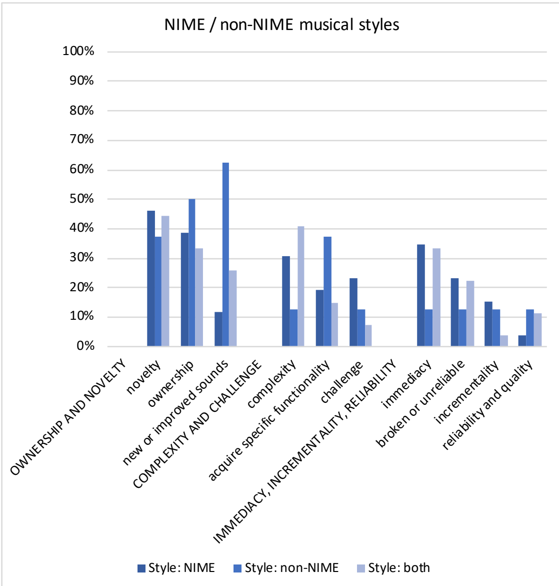


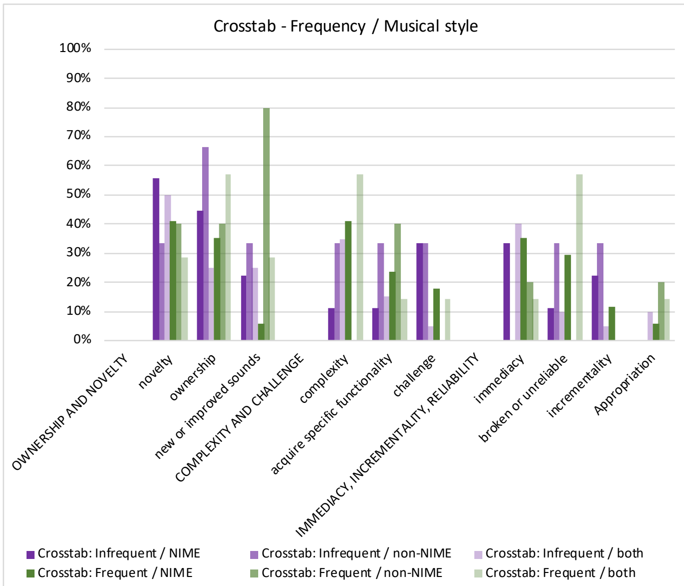


Crosstabulation Analysis: Combined Engagment Attributes of EMIs by Frequency of Performance (</> 10x per year) and Musical Style (NIME/non-NIME/both)

Nodes	Frequency: Infrequent	32	Frequency: Frequent	29	Style: NIME	26	Style: non-NIME	8	Style: both	27	Crosstab: Infrequent / NIME	9	Crosstab: Infrequent / non-NIME	3	Crosstab: Infrequent / both	20	Crosstab: Frequent / NIME	17	Crosstab: Frequent / non-NIME	5	Crosstab: Frequent / both	7	Total	61
OWNERSHIP AND NOVELTY																							**70.49%**	**43**
novelty	50%	16	37.93%	11	46.15%	12	37.50%	3	44.44%	12	55.56%	5	33.33%	1	50%	10	41.18%	7	40%	2	28.57%	2	44.26%	27
ownership	34.38%	11	41.38%	12	38.46%	10	50%	4	33.33%	9	44.44%	4	66.67%	2	25%	5	35.29%	6	40%	2	57.14%	4	37.70%	23
new or improved sounds	25%	8	24.14%	7	11.54%	3	62.50%	5	25.93%	7	22.22%	2	33.33%	1	25%	5	5.88%	1	80%	4	28.57%	2	24.59%	15
COMPLEXITY AND CHALLENGE																							**54.10%**	**33**
complexity	28.12%	9	37.93%	11	30.77%	8	12.50%	1	40.74%	11	11.11%	1	33.33%	1	35%	7	41.18%	7	0%	0	57.14%	4	32.79%	20
acquire specific functionality	15.62%	5	24.14%	7	19.23%	5	37.50%	3	14.81%	4	11.11%	1	33.33%	1	15%	3	23.53%	4	40%	2	14.29%	1	19.67%	12
challenge	15.62%	5	13.79%	4	23.08%	6	12.50%	1	7.41%	2	33.33%	3	33.33%	1	5%	1	17.65%	3	0%	0	14.29%	1	14.75%	9
IMMEDIACY, INCREMENTALITY, RELIABILITY																							**54.10%**	**33**
immediacy	34.38%	11	27.59%	8	34.62%	9	12.50%	1	33.33%	9	33.33%	3	0%	0	40%	8	35.29%	6	20%	1	14.29%	1	31.15%	19
broken or unreliable	12.50%	4	31.03%	9	23.08%	6	12.50%	1	22.22%	6	11.11%	1	33.33%	1	10%	2	29.41%	5	0%	0	57.14%	4	21.31%	13
incrementality	12.50%	4	6.90%	2	15.38%	4	12.50%	1	3.70%	1	22.22%	2	33.33%	1	5%	1	11.76%	2	0%	0	0%	0	9.84%	6
reliability and quality	6.25%	2	10.34%	3	3.85%	1	12.50%	1	11.11%	3	0%	0	0%	0	10%	2	5.88%	1	20%	1	14.29%	1	8.20%	5
Total (Unique)	**93.75%**	**30**	**93.10%**	**27**	**92.31%**	**24**	**100%**	**8**	**92.59%**	**25**	**100%**	**9**	**100%**	**3**	**90%**	**18**	**88.24%**	**15**	**100%**	**5**	**100%**	**7**	**93.44%**	**57**







Appendix C

Design for Performance Workshop: Supplementary Materials

C.1 Schedule and script

Location: CIRMMT A-832 (conference room)
Workshop A: Friday, 14:00 - 15:30.
Workshop B: Saturday, 11:00 - 12:30.

Schedule

- Welcome and introduction (5 min)
  - Short and practical. Aims to mark the beginning of the experience.
- Prompt: "Draw the music" (5 min)
- Prototype building
  - Reveal materials and introduce activity (5 min)
  - Prototyping activity (25 min, can extend to 30)
- Presentations and 1st discussion (5 min apiece, 30 min total)
- Dot voting and feature selection (5 min)
- Final discussion (10 min)

The workshop will run 80 - 90 minutes.

Room setup

- Whiteboards erased. Have dry erase markers and eraser on hand.
- In the middle of the table, prototyping materials arranged and easily accessible to all the participants who will sit around the table. Cover with something so they are not seen. (Iron Chef style. . .)
- For each participant: white mat, index card blank side up, black marker.
- Facilitator: have spreadsheet open (or pen/paper) for notes, can assign P1 to Px for quick IDs of participants
- Have timer available (can be on computer, watch, phone. . .)

Activities for assistant

During the workshop, an assistant can facilitate the participants by ensuring they have the materials they need (unwrapping for packaging, etc.) and some photo documentation if the participants consent.

For Saturday workshop, assistant may need to wait at front door to Elizabeth Wirth building if it is locked for the weekend.

Script

As participants arrive, they can sit down, help themselves to food/drink, and read and sign the consent form.

I. Introduction: (5 min)

Welcome to this workshop. Today each of you are going to design a musical instrument to perform with. In a moment I am going to give you a short activity to get the workshop started and to get everyone thinking creatively. I'll then lay out the criteria and guidelines for the main activity.

First, each of you need to read and sign the information and consent form in front of you. Please take a moment and do that now, if you haven't already. As long as you don't object, we would like to take some pictures and video record some part of the workshop, for documentation purposes. Is this okay with everybody?

(take note of everyone's reply - if it is a unanimous YES, assistant will photo document, if not unanimous, then skip)

I'll introduce myself briefly: John Sullivan, instrument designer, researcher working on design methodologies and evaluation of new musical instruments for performance. Also introduce Collin, Master's student at the School of Information Studies, where is is studying HCI.

Group introduce themselves to me? First name, and a sentence or two about your musical performance practice. *(quickly, and write down to associate post-it colors, participant IDs)*

Here are a few guidelines to follow throughout this workshop:

1. There is no right or wrong.
2. The activities are short, so move quickly.
3. Be honest, respectful, and supportive to yourself and the other participants.
4. Make sure everybody can be heard.
5. Be creative, enjoy the process and have fun with it!

II. Prompt (5 min)

(each participant has a black marker and blank index card in front of them.)

Let's begin with the first activity. Take a moment to think about the music you make (or want to make). What kind of music is it?

How do you play it?

What does the music sound like? *(pause)*

What does the music look like?

Pick up the marker. You will have 2 minutes for this exercise. Now, draw the sound of the music you have in your mind on the card.

And... GO.

(2 minutes pass)

And... STOP. Markers down.

III. Non-functional prototype building (25 min)

Now we come to the main activity of the design workshop. In a moment I'm going to ask you to build a new instrument to create the music that you drew.

In the center of the table are a variety of materials available to use in your designs.

(crafting materials are revealed)

Bear in mind you are building non-functional prototypes. You do not need to select and build with materials for their acoustic properties, nor do you need to be overly concerned with technical feasibility.

To assist you, here are some things to think about:

Think about the following *qualities* of your instrument and how you will perform with it:

- Functionality (how does it function?)
- Playability (how do you play it?)
- Musicality (what does it sound like, and how does it facilitate musicality)
- Context (where and how will this be used?)

Considerations:

- Physical form and ergonomics
- Interaction methods: available sensor technologies: movement, knobs/buttons/sliders... what else?
- Sound production? Synthesized? Sampled? Live input?

- Feedback - what kind of feedback will the performer have?
- What is it called?

You will have 25 minutes to create your instrument starting... NOW.

(25 minutes pass - While they work, I will write the above lists on the board. Also periodically keep them informed of the time remaining.)

(as 25 minutes approaches, see if they are nearing completion. Can add more time as needed in 5 minute increments, but shouldn't go much beyond 30 minutes or so.)

And... STOP.

IV. Discussion (5 min each == 30 min)

Ok, now I'm going to ask each of you to present your instrument. For your presentation, I'll ask each of you to come to the front with your instrument and your index card. Think about the music that you drew. Can you play it on your instrument?

First show your index card and explain your drawing and the music. Then give a brief description of your instrument, followed by a short "performance" or demonstration. Afterwards, if you consent, we'll take a photo of you presenting your instrument and index card.

While presenting, remember the categories on the board. I will write down characteristics of your instrument while you talk and post them next to their associated categories.

After each presentation we will have a quick discussion where everyone can ask questions, comment, and highlight key features, interesting characteristics, elements, concepts, that can be added to the board.

V. Voting (5 min)

Now, think about an instrument we can collectively design and build. Consider the features, characteristics, keywords and phrases posted on the board, use the stickers in front of you to vote on the elements that you would include in our collaborative design.

(participants dot vote, votes are tallied and top elements are highlighted.)

VI. Final discussion (10 min)

Are there areas of general consensus or disagreement? Are some features complimentary to others? What groups of features could we combine into one or more prototypes?

For a future workshop, I will present some functional instrument prototypes based on the ideas generated at this and the other session.

Thank you for participating!

C.2 Key elements and dot voting results

Sessions A and B

These sheets show all of the key elements identified by the facilitator, presenter and other participants during the individual instrument presentations. Parenthesized numbers indicate the number of votes received during dot voting, and the highlighted items indicate elements receiving more than one vote.

SESSION A	P1	P2	P3
Operational qualities and usage			
Functionality	playful unreliability (3)	individual string control (1)	layers
Playability			move while you play (2)
			range of motion
Musicality	organic (1)		
	liveliness		
Context	blending (2)	singing w/ guitar	
		shifting sands	
Design features and fundamental components			
Physical Form	wireless (1)	guitar body	
	modular/modules (3)	strap	
	flexible		
Interaction Methods	gesture	strings	X/Y pad
	multifunction control	knob	sponge/pressure pad (1)
	matrix	buttons	touching (2)
	ribbon controller (1)	scroll wheel	bow (1)
	foot control	vocal mic (1)	
Sound Production	radio (2)	vocoder	resonate (1)
		onboard FX	oscilators
		pad	
Feedback			textures (tactile) (3)

SESSION B	P4	P5	P6	P7	P8	P9	P10
Operational qualities and usage							
Functionality	audiovisual experience (4)	control generator	configurability (1)		MIDI device	*audiovisual experience*	
	multiple sounds on one device				continuous control of a keyboard	interface for acoustic instrument	
	spatialization (1)				string sounds/slide		
Playability	MIDI output (3)	Eurorack	workstation (multifunction) (2)	simple (2)			
				user friendly			
Musicality	bring music of different cultures together	control sensitivity (1)			accompany voice with sounds		have fun
Context			audio-visual integration		ondes-martinot like	improvisation (2)	explore relationships
							walking around
Design features and fundamental components							
Physical Form	acoustic/digital hybrid (2)	resonant physical materials	MPC-inspired	tiny	tabletop	augmented instrument (2)	
	resonators (1)			foot and hand control	*bi-manual*	portability/embedded (1)	
	handheld (1)					sitting	
						bi-manual (1)	
Interaction Methods	strings	strike (2)	pads (1)	tactile/body control (2)	sliding ring	*contact mics*	button
	drums	pressure sensor (4)	keyboard (2)	bow	knob	motion (1)	*bow*
	multi-parametric keyboard (1)		X/Y pad	strings - tension adjust (2)	pedal	sliders (1)	*motion*
	contact mics (1)		*sliders*				
Sound Production		physical excitation (1)	sampler	*physical excitation*		live processing (2)	synthesis (5)
				plucking (4)			
Feedback			display	(passive) force feedback			light (1)
			dual display				
			fog machine				

C.3 Workshop presentations thematic analysis full results

The following table shows the codes generated from our thematic analysis of the instrument presentations. They are grouped into themes and are sorted by the number of unique cases (participants) each occurs in. The rightmost column indicates the total number of times (references) that code appeared, though it may have been mentioned several time by a single participant. Thus we find the "Cases" column to be more accurate.

Themes and Codes	Cases	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Refs
interaction	***10***	***X***	***X***	***X***	***X***	***X***	***X***	***X***	***X***	***X***	***X***	***71***
standard input controls	8	X	X	X		X	X		X	X	X	20
strings	5		X		X			X	X		X	8
tactile interaction	4	X		X		X		X				9
movement and position sensing	4		X		X					X	X	5
physical interaction	3			X		X		X				13
materiality	3	X		X		X						4
bowing	3			X	X			X				3
continuous control	2				X				X			6
microphone input	2				X			X				2
bi-manual control	1									X		1
signals, connections and mapping	***9***	***X***	***X***	***X***	***X***	***X***	***X***		***X***	***X***	***X***	***20***
mapping	8	X	X	X	X	X	X			X	X	15
control signals (MIDI, CV, wireless)	4	X				X			X		X	5
computer	2								X		X	2
sound production and processing	***9***	***X***	***X***	***X***	***X***	***X***	***X***	***X***	***X***	***X***		***42***
external input	6	X	X	X	X		X			X		8
mixing sounds	4		X	X	X				X			8
effects	3		X					X		X		7
acoustic sound production	3			X	X	X						6
resonance	3			X	X	X						5
sampling	2			X			X					5
designing own sounds	1								X			1

Themes and Codes	Cases	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Refs
spatialization	1				X							1
synthesized sounds	1				X							1
referencing existing instruments	***7***		***X***	***X***	***X***		***X***	***X***	***X***	***X***		***23***
keyboards and pianos	4			X	X		X		X			6
guitar	2		X					X				4
vocals	2		X						X			4
Ondes-Martinot	2						X		X			2
DAW production	1						X					2
augmented instrument	1									X		1
drums	1				X							1
harp	1									X		1
instrument-inspired	1		X									1
sampler	1						X					1
versatility	***6***	***X***	***X***		***X***	***X***	***X***				***X***	***29***
combining functions	4	X	X		X		X					8
multipurpose/function	4	X			X	X	X					7
flexible routing	3	X			X		X					4
fungibility	3	X				X					X	3
modularity	2	X				X						5
independent elements	1		X									2
performance environment	***5***		***X***		***X***		***X***			***X***	***X***	***12***
audiovisual	4				X		X			X	X	7
physical space and movement	2		X								X	3
audience	1										X	1
immersive environment	1				X							1
size and form factor	***4***	***X***	***X***		***X***			***X***				***10***
stand-alone embedded	4	X	X		X			X				5
portable	1							X				2
radio	1	X										2
large immersive space	1				X							1
desirable or undesirable qualities	***4***						***X***	***X***	***X***		***X***	***5***
limitation of current instrument	2						X		X			2
DIY	1							X				1
simple	1							X				1
stability	1										X	1

Themes and Codes	Cases	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Refs
posture	***3***		***X***							***X***	***X***	***3***
sitting	1									X		1
strap	1		X									1
walking	1										X	1
feedback	***2***						***X***	***X***				***4***
visual display	1						X					3
passive haptic feedback	1							X				1
cultural context	***1***				***X***							***3***
geographical and cultural relevance	1				X							3

Appendix D

Research Ethics Board Approval Certificates

The studies presented in this dissertation were carried out in accordance with the recommendations of the McGill University Policy on the Ethical Conduct of Research Involving Human Participants and the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans, McGill University Research Ethics Board II (REB II). All participants gave written informed consent in accordance with the Declaration of Helsinki. Protocols for activities involving human participants were approved by the McGill University Research Ethics Board II, a unit within the Office of the Vice Principal (Research & Innovation). Ethics certificates for the following experiments are included here:

- Chapter 2: The Electronic Musical Instrument Survey. REB File number: 254-117.
- Chapter 3: Design for Performance workshop: REB File number: 188-0918.
- Chapter 5: Gestural Control of Augmented Instrumental Performance (motion capture study). REB File number: 361-0117.

Research Ethics Board Office
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Montreal, QC H3A 0G4

Tel: (514) 398-6831

Website: www.mcgill.ca/research/researchers/compliance/human/

Research Ethics Board II
Certificate of Ethical Acceptability of Research Involving Humans

REB File #: 254-1117

Project Title: A questionnaire on digital musical instrument use in live performance

Principal Investigator: John Sullivan

Status: Ph.D. Student

Department: Music Research

Supervisor: Prof. Marcelo Wanderley

Approval Period: **December 18, 2017 to December 17, 2018**

The REB-II reviewed and approved this project by delegated review in accordance with the requirements of the McGill University Policy on the Ethical Conduct of Research Involving Human Participants and the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans.

Deanna Collin
Ethics Review Administrator, REB I & II

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* Approval is granted only for the research and purposes described.
* Modifications to the approved research must be reviewed and approved by the REB before they can be implemented.
* A Request for Renewal form must be submitted before the above expiry date. Research cannot be conducted without a current ethics approval. Submit 2-3 weeks ahead of the expiry date.
* When a project has been completed or terminated, a Study Closure form must be submitted.
* Unanticipated issues that may increase the risk level to participants or that may have other ethical implications must be promptly reported to the REB. Serious adverse events experienced by a participant in conjunction with the research must be reported to the REB without delay.
* The REB must be promptly notified of any new information that may affect the welfare or consent of participants.
* The REB must be notified of any suspension or cancellation imposed by a funding agency or regulatory body that is related to this study.
* The REB must be notified of any findings that may have ethical implications or may affect the decision of the REB.

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Website: www.mcgill.ca/research/researchers/compliance/human/

Research Ethics Board II
Certificate of Ethical Acceptability of Research Involving Humans

REB File #: 188-0918

Project Title: Building performance practice around new instruments: A longitudinal study of the Noisebox

Principal Investigator: John Sullivan

Department: Music Research, Music Technology Area

Status: Ph.D Student

Supervisor: Professor Marcelo Wanderley

Co-Supervisor: Professor Catherine Guastavino (McGill)

Approval Period: <u>November 5, 2018 to November 4, 2019</u>

The REB-II reviewed and approved this project by delegated review in accordance with the requirements of the McGill University Policy on the Ethical Conduct of Research Involving Human Participants and the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans.

Georgia Kalavritinos
Ethics Review Administrator

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* Approval is granted only for the research and purposes described.
* Modifications to the approved research must be reviewed and approved by the REB before they can be implemented.
* A Request for Renewal form must be submitted before the above expiry date. Research cannot be conducted without a current ethics approval. Submit 2-3 weeks ahead of the expiry date.
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* The REB must be notified of any findings that may have ethical implications or may affect the decision of the REB.

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Website: www.mcgill.ca/research/researchers/compliance/human/

Research Ethics Board II
Certificate of Ethical Acceptability of Research Involving Humans

REB File #: 361-0117

Project Title: A Kinematic Analysis of Gesture in Harp Performance

Principal Investigator: John Sullivan

Status: Ph.D. Student

Department: Music Research

Supervisor: Prof. Marcelo Wanderley

Co-Investigator (s): Alexandra Tibbitts, Université de Montreal; Olafur Bogason, McGill University

Approval Period: <u>February 21, 2017 to February 20, 2018</u>

The REB-II reviewed and approved this project by delegated review in accordance with the requirements of the McGill University Policy on the Ethical Conduct of Research Involving Human Participants and the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans.

Deanna Collin
Ethics Review Administrator, REB I & II

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* Approval is granted only for the research and purposes described.
* Modifications to the approved research must be reviewed and approved by the REB before they can be implemented.
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* The REB must be notified of any findings that may have ethical implications or may affect the decision of the REB.

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