JACK ARMITAGE

SUBTLETY AND DETAIL IN DIGITAL MUSICAL INSTRUMENT DESIGN

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Submitted in partial fulfilment of the requirements of the
University of London Degree of Doctor of Philosophy
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Media and Arts Technology
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Jack Armitage: *Subtlety and Detail in Digital Musical Instrument Design,*
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Dedicated to Sophie Xeon.

ABSTRACT

Subtlety and detail are fundamental to what makes musical instruments special, and worth dedicating a life's practice to, for designer, maker, player and listener alike. While instruments are recognised and classified by form, it is the nuances of individual instruments that constitute their power to say what could not be said any other way.

Digital musical instruments (DMI) have long been criticised as lacking expressive depth, but technology of sufficient fidelity now exists, which raises compelling questions. What can contemporary DMI designers learn from heritage practices about mastering subtlety and detail? What forms does this mastery take, and how can it be elucidated, compared and shared? Using DMI design tools, kits and activities as probes, this thesis addresses these questions from the perspectives of design, embodiment and craft.

In a preliminary study, violin luthiers were asked about subtlety and detail in their practice and culture. The outcomes suggested that subtle details originate in the tacit and embodied realms, which are facilitated to develop by specific contexts, environments and materials.

In the first study, attendees of a DMI research conference participated in a workshop reflecting on subtlety and detail. Attendees were divided into groups and explored the physical details of a DMI design kit, in an activity book ended by discussion. Responses focused on re-interpretations of instrumental identity, suggesting that the provided context motivated in the opposite direction to the original brief.

In the second study, the same kit was deployed with single rather than co-located groups of digital luthiers, modifying instead the sound of the instrument via a Pure Data patch, and responses focused less on instrumental identity and more on gesture-sound mapping strategies. Provocatively, neither studies resulted in sustained focus on details, motivating a novel DMI probe and activity for individuals.

In the third study, digital and traditional instrument makers, musicians and other creatives, were invited to handcraft the resonance models of a digital tuned percussion instrument using sculpting clay, responding to constrained briefs. Participants' backgrounds deeply influenced their responses, and distinctive themes emerged related to aesthetics, tacit and embodied knowledge, and algorithmic pattern.

This thesis introduces a scale-based ontology of DMI design, dividing detail into macro, meso and micro levels. Focusing on the micro scale, a series of reflections and suggestions are provided based on the investigations, for how DMI design practitioners, technologists and researchers can illuminate this domain, for the benefit of subtle and detailed digital musical expression.

ACKNOWLEDGMENTS

This work was made possible by the support of a great number of people to whom I would like to express my sincere gratitude.

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During this work I was part of the Augmented Instruments Lab (AIL) within in the Centre for Digital Music (C4DM), at the School of Electronic Engineering and Computer Science (EECS) at Queen Mary University of London (QMUL). AIL has been a wonderful group to do research with, and it has been a real pleasure to be inspired on a daily basis by the group's members and their work. Thanks in particular to Fabio Morreale for your guidance over coffee at various stages of this work, to Laurel Pardue for the improvisatory musical collaborations, and to Lia Mice for organising the lab's concerts. Thanks to AIL Ltd. and the entire Bela team for creating a platform that made my research questions viable in the first place, in particular thanks to Giulio Moro for your generous technical support. Thanks also to Fabio, Jacob Harrison, Robbie Jack and Astrid Bin for help with the NIME 2017 workshop. I was also part of the Media and Arts Technologies (MAT) PhD programme at QMUL, and owe my thanks to all the friendly, kind and intelligent MAT students, and to Jonathan Winfield, Geetha Bommireddy, Karen Shoop and Nick Bryan-Kinns for coordinating and supporting this programme. Thanks in particular to Sophie Skach for sketching digital luthiers for me and taking me to Austria. Finally, thanks to Kok Ho Huen for support with the EECS labs and facilities.

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DECLARATION

I, Jack Armitage, confirm that the research included within this thesis is my own work or that where it has been carried out in collaboration with, or supported by others, that this is duly acknowledged below and my contribution indicated. Previously published material is also acknowledged below.

I attest that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge break any UK law, infringe any third party's copyright or other Intellectual Property Right, or contain any confidential material.

I accept that the College has the right to use plagiarism detection software to check the electronic version of the thesis.

I confirm that this thesis has not been previously submitted for the award of a degree by this or any other university.

Reykjavík, Iceland, April 2022

Jack Armitage

PUBLICATIONS

Some ideas and figures have appeared previously in the following publications:

1. Jack Armitage. "An Experimental Audio-Tactile Interface for Sculpting Digital Resonance Models Using Modelling Clay." In: *Conference Companion of the 4th International Conference on Art, Science, and Engineering of Programming*. 2020.
2. Jack Armitage and Andrew McPherson. "Bricolage in a Hybrid Digital Lutherie Context: A Workshop Study." In: *Proceedings of the 14th International Audio Mostly Conference: A Journey in Sound*. 2019.
3. Jack Armitage and Andrew McPherson. "Crafting Digital Musical Instruments: An Exploratory Workshop Study." In: *Proceedings of the International Conference on New Interfaces for Musical Expression*. 2018.
4. Jack Armitage, Fabio Morreale, and Andrew McPherson. "The Finer the Musician, the Smaller the Details: NIMEcraft under the Microscope." In: *Proceedings of the International Conference on New Interfaces for Musical Expression*. 2017.

CONTENTS

COMPANION MATERIALS

Companion materials for this thesis can be found at
https://jackarmitage.com/phd

1 INTRODUCTION

> *Transistors which had been rejected as 'out of specification' were purchased by Roland and used as part of the TR-808's sound generating capability. Although they weren't faulty, they did exhibit some very particular qualities that helped give the 808 its distinctive sizzling sound. In fact, this tiny component, also known as an 2SC828-R, was so important to the final sound, that once supplies were used up, the TR-808 was discontinued. It's also partly why most modern analog takes on the TR-808 don't really stand up to scrutiny.*
>
> — Roland Corporation, *The TR-808 Story* [262]

This thesis is about subtlety and detail in digital musical instrument design, and presents a series of studies attempting to elicit the usually invisible processes behind them. When we look at a musical instrument, its identity primarily strikes us through its size, shape, material, and colour. When we observe groups of instruments together, perhaps in a band, orchestra or museum, visual relations between their identities suggest common ancestries and shared ideas. What we do not see are the thousands of hours instrument makers have dedicated to perfecting their craft and delighting musicians and audiences. Considering two violins, their differences in quality will be stark if one is the work of a master luthier, and the other a student. The epigraph above attests to similar issues persisting with analog electronic instruments; it was not just that the *2SC828-R* was detailed, as any precision manufactured component would be, it was also subtly different and uniquely suited to its task. Fine levels of quality have so far been the Achilles heel of digital musical instruments (DMIs), with great efforts in recent decades going towards defining, increasing and evaluating their expressivity. However, DMI design practitioners, technologists and researchers still face complicated issues when it comes to addressing subtlety and detail. These differences, and the processes they result from, are too subtle to fully articulate in words, yet largely define an instrument's value, and are therefore important to understand.

Unlike their antecedents, DMI design practitioners are faced with designing instruments from scratch, rather than replicating and perfecting existing designs. Before they can fully address subtle details, they must engage with everything else about an instrument's form and function, which necessitates vast amounts of creative and technical decision-making, as well as time and perseverance [290]. Even then, without strong cultural memory associated with them, new subtle details still lack shared meaning, which must be slowly accreted through their integration into communities of composers, performers, audiences and so on [260]. Technologists seeking to meet the needs of daily practice (which often includes their own), are subsequently more likely to develop tools which are optimised for earlier stages of design, that either enable users to abstract away subtle details, or simply hides them altogether [38]. Rather than studying DMI design processes, researchers involved in DMI design are quite often also designers and technologists themselves, and are often seeking feedback on instruments and tools they have created, or using them as probes to research other people such as musicians [124] and audiences [26]. Furthermore, while mainstream research venues accept both artistic and scientific works based on DMI usage, and scientific works based on DMI creation, they are less likely to accept more subjective works about DMI creation [9]. Every incremental improvement in quality that a DMI designer achieves – every significant progression in depth – makes their work less technically valuable to the research community, as currently construed. Overall, the current ecosystem disincentivises designing subtle and detailed DMIs, developing tools which directly support subtle and detailed DMI design processes, and researching what these processes might be and how they function.

This thesis is motivated primarily by the latter issue, of understanding subtle and detailed DMI design processes at a basic level. What happens when DMI designers first encounter novel subtle details? What motivates them to consider some details important and others not? How do they use their bodies and the spaces surrounding them to become aware of, start to manipulate, and ultimately make sense of subtle details? How do materials and tools become adapted to the highly specialised needs of subtle, detailed design? What do designers know about these details, what forms does their knowing take, and how can it be communicated? What happens when these processes are repeated over and over again, potentially over many years? How do designers' and performers' knowledge of the subtle details of the same DMI differ? How do these issues propagate through and interact with broader musical ecologies? We believe that addressing these questions would incentivise DMI design technologists and practitioners to engage more deliberately with subtlety and detail in their work. And were that to be the case, we hope this would in turn contribute to the flourishing of the art and craft of DMI design, as well as the science, for all music lovers to enjoy.

That being said, these questions are too multifaceted to be addressed by any singular effort, and this thesis concerns only a small aspect of a greater whole. I nevertheless hope that this work can provide useful leverage and intellectual nourishment to others with similar interests. The aim of this research has been to investigate subtle and detailed DMI design processes in the context of one hour activities with purposefully constrained DMI design toolkits. The leverage sought through this effort is to make these processes easier to observe, describe, compare and share. We also offer our own interpretations and reflections on how these processes work and what they are about, as appetizers for wider discourse. As researchers, both myself and my supervisor, we found it incredibly difficult to elicit subtle and detailed DMI design processes, in one hour, in a way that we felt did some level of justice to the art that luthiers do every day. At the very least, readers of this thesis can anticipate being greatly informed about how not to do so. One way or another, if readers come away with better and clearer ideas about subtlety and detail than those presented herein, then we will count our aim as met.

1.1 PRELUDE

There are two contextualising narratives that I believe are prudent to first describe. The first narrative situates this research regarding the development of my personal interest in the topic. The second explains the difficulties alluded to above, the somewhat haphazard path taken during the course of these investigations, and the way this is reflected in the structure of this document.

1.1.1 *Thesis pre-history*

In the two and a half years prior to commencing my PhD studies, I was employed as a Research Engineer at music technology startup company ROLI[1]. Initially, I was responsible for the quality assurance of the company's debut product, the Seaboard GRAND[2] [157]. At the time I arrived, the abundantly talented team of around 20-25 had so far produced an exciting late-stage prototype, which nonetheless required an additional year of intense cross-disciplinary integration and validation before it would be ready to deliver to customers. Working across the various internal design and engineering teams, I became intimately familiar with the instrument's handcrafted production processes, and its materials, hardware, firmware, and software. I was also involved in designing usability studies for validating design changes and production processes, working closely with a small group of burgeoning Searboardists to maximise the instrument's playability.

Through this experience, I gained an unforgettable appreciation for the staggering amount of care and attention to detail that is required for producing a high-end, commercial DMI. Microns of adhesive, microlitres of silicone, microseconds of time, and millidegrees Celsius, all mattered in distinguishing pass or fail. As a team we were also con-

1 https://roli.com
2 https://en.wikipedia.org/wiki/ROLI_Seaboard

tinually humbled by the mercurial and mystical nature of accurately and precisely measuring instrumental quality. Automations lagged miles behind players in adjudicating musical touch, and even blind tests with musicians could produce contradictory results. I would later draw on these experiences during my research in quite unanticipated ways, which made me ever more grateful for them.

Once the Seaboard GRAND was launched, I was fortunate enough to take the Project Lead role for an Innovate UK funded research project exploring multimodal sensors which targeted increased dynamic ranges for sensing touch. Andrew McPherson, the supervisor of this thesis, was an expert academic consultant on this project, who needless to say made brilliant contributions both conceptual and technical. It was during this time that I started to reflect more on DMI design as a process, and started to formulate early ideas for PhD research. I noticed in myself a sense of shame, that designing high quality DMIs took so long, was so prohibitively expensive, and required so much diverse talent (enjoyable though it was to be around!). Even with access to these resources, I felt that the available design tools and methods could not facilitate exploration of a satisfying number of ideas, and that DMI design spaces were being abandoned early and left underexplored. I wondered what a world would look like where this was not the case, and started to think that this could be a starting point for a PhD. With Andrew's group about to launch the first KickStarter campaign for Bela[3] (which this thesis would not be possible without), and PhD scholarships available through Queen Mary University of London's Media and Technology Arts doctoral training programme, the timing felt ideal for me to start taking the idea of a PhD more seriously.

At this time, I was (and still am) heavily inspired by the work of Bret Victor[4], and what would later become known as the Explorable Explanations[5], Tools for Thought[6] and Future of Coding[7] communities. I had a hunch that relatively simple but deep changes in technological perspective implied rich results for the kinds of problems I was drawn towards. Looking back, I now recognise the naïveté of what I would describe as a more overtly technocentric position than the one I hold now. Suffice it to say that although this thesis has concerned itself with technological matters, my initial ideas were broadened beyond the technological early on in the research process.

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3 https://bela.io
4 See https://worrydream.com and https://dynamicland.org.
5 https://explorabl.es
6 https://numinous.productions/ttft/
7 https://futureofcoding.org

1.1.2 *Thesis history*

In the initial period of my studies, while I was attempting to formalise my thesis topic, I began assisting with a study which was already in-progress, conducted by my supervisor and Fabio Morreale, who was a postdoctoral researcher at the time. It was a captivating study investigating how changing properties of violins, such as size or quality, disrupts the sensorimotor expertise of professional violinists [213]. It featured motion capture of violinists playing the same pieces on various violins, including their own, along with interviews about their experiences. At the time, we discussed how the players certainly knew that their playing experience was being manipulated profoundly, yet the language to articulate exactly how simply did not exist. It occurred to me that violin luthiers might have something to say about this issue of sensorimotor disruption, and the idea was put forward that I would recruit and conduct interviews with a few luthiers.

However, when it came to drafting questions for violin luthiers, I found that with my background in *digital* musical instruments, and in an industrial product design context, I simply had no idea what their instrument making experience was like. The interviews I eventually conducted were much more broad and open-ended (Chapter 4), and as a result, I became completely fascinated with the apparent miracle that such incredibly subtle and detailed objects could be realised by the hands of an individual person. This forced me to completely recontextualise my experiences in industry, and to question the technocentric approach I had been developing thus far.

At this point in time, I was digesting Harry Collins' models of tacit and explicit knowledge [48], which turned my epistemic world view upside down. My sense at that moment was that digital creation tools predominantly deal with explicit knowledge, the sum of which was negligible compared to the sum of tacit knowledge. And consequently, it was this tacit knowledge that must explain on some level how the technical existence of a violin was possible. I was also fortunate to be introduced to the work of Sarah Kettley at around the same time, by my then colleague Astrid Bin. In a recent publication, Kettley had formulated seven foundational principles for understanding craft practice which synthesised values, materiality and embodiment [153]. These principles seemed to model quite perfectly the aspects of violin lutherie practice that I had been trying to grasp. These works by Kettley and Collins caused two paradigm shifts in my perspective, the consequences of which I am still unraveling.

Inspired by Jordà's definition of instrumental *micro-diversity* — the ability for performances of the same piece to differ [136] — my supervisor and I arrived at a working definition for subtlety and detail in DMI design, which we described as *the micro scale details between otherwise identical instruments* (Chapter 2). From here, the challenge became to create contexts in which we could observe the manipulation of micro scale details, so that we could then try to make sense of what emerged.

In our first two attempts at this, described in Chapters 5 and 6, we essentially failed to elicit micro scale activity. On the one hand, this was not surprising: the first attempt was during a NIME workshop hosted by members of our research group [197], which was deliberately open-ended and full of fun crafting materials to encourage discourse. People mostly engaged with *macro* instead of micro scale details, and while we had not planned to interpret the workshop outcomes (or treat them as a "study"), we were unable to dismiss the idea that something about our probes and brief had also contributed. Since the data we had was so unclear, we repeated the activity, exchanging the crafting materials for a Pure Data patch. This time, the outcomes appeared to be less macro than before, but still not micro, suggesting a possible *meso* scale in between.

During this process of elimination, our early publications about these outcomes could not discuss subtlety and detail. Despite discussions about changing the research topic to focus on the macro and meso outcomes we had so far produced, we determined to continue with the original aim. Learning as best we could from our initial results, we completely rethought our approach, and I invested over a year developing a new set of probes (Chapter 7) and briefs (Chapter 8). This final study had to be able to address subtlety and detail directly, or at least produce interesting enough results that some kind of PhD thesis could be written about it.

Fortunately, the final study outcomes meant that we could return to subtlety and detail, through the lens of our definition of micro scale details. This meant that the preceding studies were now finally useful failures, sign posts that future researchers could use to steer clear of the more fateful paths we had taken. The primary reason for recounting this tale is to explain the distribution of content in this thesis, which is heavily weighted towards the later chapters. In addition, the earlier research questions and sub-questions bare some surgical scars, as they encompass the duality of standalone publications which did not address subtly and detail, and thesis chapters which now do. The next section lists these questions, and provides additional context for how they should be regarded in terms of overall importance.

1.2 RESEARCH QUESTIONS

The preceeding section (Section 1.1.2) described the twisting and turning chronology of this thesis, and the impact this had on the exacting research focus at any given point. Surveying the research questions in this section absent of this context could give the misleading impression that they have equal importance, and confuse as to how they are connected. In fact, as Section 1.1.2 described, the questions we really wanted to ask to begin with, and thus the most important overall, were not possible to address until the end (Question 5).

The main research question was first introduced at the beginning of this chapter. By main question, we mean the overall question we aim to address, in its most general form:

QM How can the design of subtle details of digital musical instruments be observed, described, compared and shared?

Chapter 2 unpacks the main question from numerous angles; as a set of definitions, through a literature review, and via the introduction of our scale-based ontology of DMI design. This chapter is framed by Question 1:

Q1 What environments and contexts can facilitate DMI design research on subtlety and detail? (Chapter 2)

Question 2 arose from the opportunity to discuss instrument making practice with violin luthiers (see Section 1.1.2 for more context), which shaped the questions and studies that followed:

Q2 What can the DMI design community learn from violin luthiers about the design of subtle details? (Chapter 4)

a. How do violin luthiers discuss subtlety and detail in violin making?
b. How do they learn to achieve subtlety and detail?
c. What impact do scientific and engineering tools have on their practice?

Questions 3 & 4 frame our first two attempts at encouraging subtle and detailed DMI design activity, which as Section 1.1.2 describes, were not successful in the way that was initially hoped for. As such, their subquestions deviate from the main question (QM), reflecting our attempts to draw as much as possible from the outcomes, despite their divergence:

Q3 How does a community of DMI design researchers respond when encouraged towards subtle and detailed design of a gestural DMI via a physical design kit and crafting materials? (Chapter 5)

a. How do participants explore in an environment featuring both a kit-based instrument and crafting materials?

b. How do they balance material constraints against their own ideas?

c. What scale of detail do participants spend most of their attention on?

Q4 How do groups of DMI designers respond when encouraged towards subtle and detailed design of a gestural DMI via Pure Data patching? (Chapter 6)

a. How much does workflow liveness affect the creative process?

b. What impact does working as a group with a Pure Data patch have on the process and outcomes?

c. What scale of detail do participants spend most of their attention on?

Question 5 focuses more directly on subtle and detailed DMI design activity, which was enabled by the creation of the apparatus described in Chapter 7. Being closest to the main question (QM) in terms of scope and outcomes, we view it as the most important in terms of contributions to the overall aim of this thesis:

Q5 What methods and processes emerge when instrument makers encounter a subtle and detailed design space? (Chapter 8)

a. What motivates instrument makers and creatives to focus on subtle and detailed design or not in a one hour activity?

b. How do instrument makers and creatives from different domains approach subtle and detailed design?

c. What kinds of comparative activity are present when subtle and detailed design is taking place?

1.3 STATEMENT OF CONTRIBUTION

The main contribution of this research is the elaboration of a perspective on DMI design research which foregrounds subtlety and detail. This research also proposes approaches and reflections that aim to support others to benefit from and build upon this work. The contributions are summarised here in order of appearance:

(A) Chapter 2 defines a scale-based ontology of DMI design that identifies micro scale details as the differences between otherwise identical instruments, and provides a literature review from this perspective.

(B) Chapter 3 describes a methodology for how DMI design toolkits and activities can be used as probes for investigating subtlety and detail. The design of such probes is described in Chapters 5, 6 and 7.

(C) Chapter 4 provides five key insights into subtlety and detail from violin lutherie, to serve as comparative inspiration for digital lutherie, and to problematise common DMI design tools and methods.

(D) Chapter 5 presents reflections from the NIME community on subtle and detailed design, and demonstrates how the scale-based ontology can be used to interpret workshop outcomes, in this case identifying predominantly macro scale responses.

(E) Chapter 6 presents novel methods for analysing DMI design behaviour using visual programming languages by way of visual analysis and source history analysis of Pure Data patches.

(F) Chapter 6 suggests that visual programming languages in DMI design contexts are predisposed towards constraining macro and micro scale activity, and encouraging meso scale activity.

(G) Chapter 7 describes the design of an apparatus for investigation of subtle and detailed DMI design, inspired by handcraft in violin lutherie, and featuring interfaces for audio-tactile sculpting of digital resonance models using modelling clay.

(H) Chapters 7 and 8 demonstrate how a DMI design research apparatus and activity can be constrained at the macro and meso scales, and rich and open-ended at the micro scale, in order to motivate micro scale design responses.

(I) Chapter 8 shows that motivation towards micro scale details in an experimental setting is inextricably linked to the role of micro scale details in participants' creative practices.

(J) Chapter 8 compares the advantages and disadvantages of different skills and knowledge between digital luthier and acoustic luthier archetypes, when encountering a hybrid lutherie apparatus and activity focused on micro scale details.

(K) Chapter 9 presents three emergent themes based on micro scale design activity, encompassing micro scale cartography, metrology and algorithmic pattern, and explores their implications for DMI design practitioners, technologists and researchers.

1.4 THESIS STRUCTURE

PART I lays the foundations of this research by describing the central issues of subtlety and detail in relation to DMI design and associated research fields, and presenting perspectives on these issues based on interviews with violin luthiers.

Chapter 2 addresses Q1 by outlining the area of DMI design and introduces a scale-based ontology for describing it based on three broad levels of detail — macro, meso and micro. Focusing on the micro scale, the chapter then comments on incentives towards doing research at this scale, and introduces further external literature which I have found useful for building the subsequent investigations upon.

Chapter 3 operationalises the definitions and ontology of Chapter 2 into a methodology. The framing and context are first described, followed by detailed descriptions of the methodology, focusing on probe and activity design, and thematic analysis.

Chapter 4 addresses Q2 by presenting a short, preliminary study based on interviews with violin luthiers about their embodied craft practice. The interview outcomes are thematised, and from these themes provocations for digital lutherie are suggested, which influenced the main investigations to come.

PART II presents practical investigations undertaken across three studies, addressing Q3-Q5. Each study involved a one hour DMI design activity with an apparatus and briefs that encouraged subtle and detailed design and craft in different ways. The goal in each case was to elicit micro scale DMI design activity such that it could be decomposed, analysed and reflected on. However, as described in Section 1.1.2, the first two investigations were unsuccessful in eliciting the hoped for activity, and were instead interpreted as predominantly focusing on macro and meso scale design activity respectively. As a result, the design process for the final investigation's apparatus was substantial enough that it warranted a separate chapter, which is followed by the study activity design and outcomes.

Chapter 5 addresses Q3 by describing the outcomes of a workshop hosted at the *New Interfaces for Musical Expression* (NIME) conference, in which a room full of groups of attendees participated in discussion and a practical activity centred around reflecting on subtle details. In the activity, the groups were given a DMI design toolkit called the *Unfinished Instrument*, and were given a wide range of crafting materials with which to manipulate it. Thematic analysis brings together photographic and video documentation of the workshop, along with post-activity interviews with some participants.

Chapter 6 addresses Q4 by describing the outcomes of a study involving a similar activity and apparatus to Chapter 5, where crafting materials were substituted for Pure Data patching. Visual analyses of the Pure Data patches in their final states are presented, along with temporal records of design activity, which are supplemented with thematically analysed quotes from the participants.

Chapter 7 describes the apparatus designed to address Q5, which can roughly be described as a set of audio-tactile interfaces for sculpting digital resonance models with clay. An overview of the various interfaces and the system architecture are first described, followed by four sections each covering the digital tuned percussion instrument, sculpting tool, mapping algorithm and session navigation interfaces.

Chapter 8 addresses Q5 by describing an activity design paired with the apparatus described in Chapter 7, along with the outcomes from a study involving individual participants with backgrounds varying across digital and acoustic luthiers, musicians, craftspeople and other creatives.

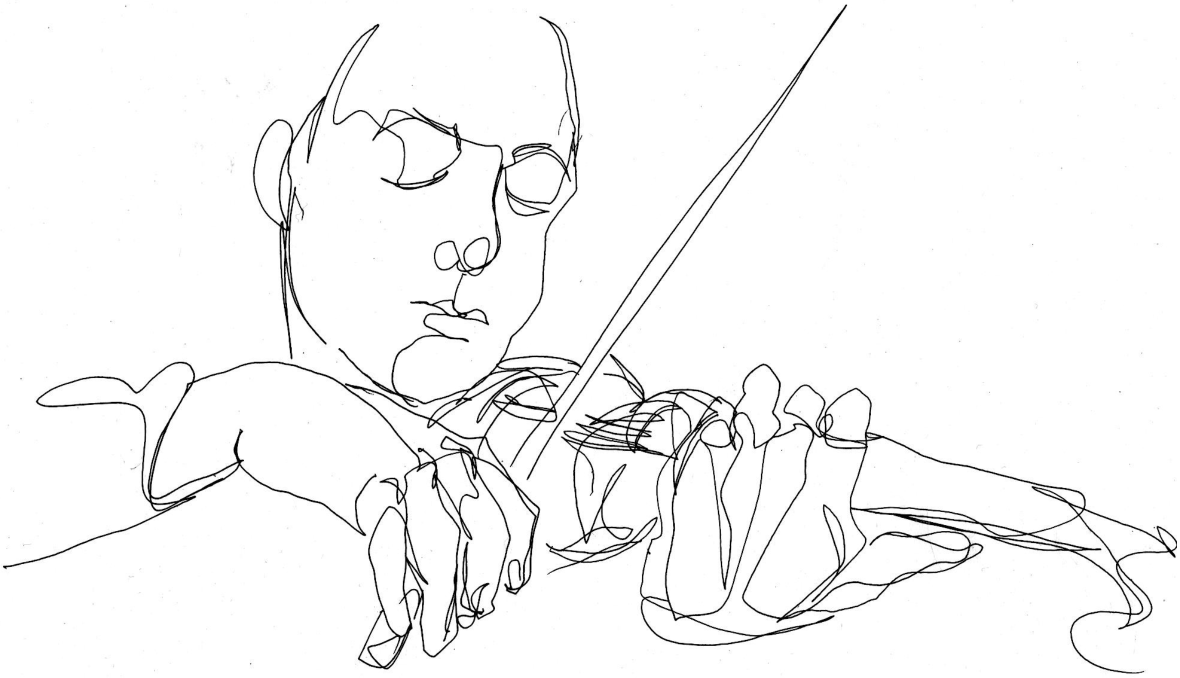
PART III reflects on the outcomes of the investigations in light of the original motivations and research questions.

Chapter 9 presents three emergent themes about micro scale DMI design activity, based on the outcomes of the final investigation described in Chapter 8.

Chapter 10 concludes this thesis by reviewing the main contributions, providing final reflections including upon the limitations of this work, and ends with suggestions for future research in DMI design and related fields.

Part I

FOUNDATIONS



2 BACKGROUND

> *La différence (dimensionnelle) entre 2 objets faits en série [sortis du même moule] est un infra mince quand le maximum (?) de précision est obtenu.*
>
> *The (dimensional) difference between 2 objects made in series [coming from the same mold] is an infra thin when the maximum (?) of precision is obtained.*
>
> — Marcel Duchamp, *Notes* [69]

This chapter is built on material from "The finer the musician, the finer the details: NIMEcraft under the microscope", by Armitage, Morreale, and McPherson, originally published in the proceedings of the International Conference on New Interfaces for Musical Expression, NIME 2017, Copenhagen, Denmark [9].

This chapter is framed by Research Question 1:

What environments and contexts can facilitate DMI design research on subtlety and detail?

To address this question, I aim to enrich the problem of subtlety and detail in DMI design, through close readings of literature from a variety of disciplines, and critical readings of the field itself. Divided into three sections, this chapter first explores the meanings and possible definitions for subtlety and detail in DMI design, proposing an operational definition that guided the research. The second section sets these definitions in a broader context, through an interdisciplinary narrative spanning from epistemological concerns through to practical matters of handcraft. The key areas discussed are tacit and explicit knowledge, embodied expertise and the hands, and craft practice. This review also serves as a general conceptual preface to the thesis, front-loading ideas which will be commonly referenced in later chapters. The third section then presents a scale-based ontology of DMI design, which reflects on the definitions and context provided to survey and scrutinise DMI design. Each of the three suggested levels of detail is described in turn, followed by a discussion of the relationships between them, and the benefits of such a framing of the field. Finally, I briefly return to the framing question above to summarise the positioning of the research carried out in this thesis.

2.1 DEFINING THIS RESEARCH

This section first of all breaks down the title of this thesis in order to define the key areas and ideas of interest, starting with a consideration of subtlety and detail. I then introduce the term DMI and provide context about how the probes in this thesis relate to it. An operational definition of subtle and detailed DMI design is then proposed, based on a gap identified in the DMI analysis and evaluation literature. This definition is further clarified by distinguishing it from other types of DMI design, which I argue do not focus on subtlety and detail. These definitions are elaborated further in Section 2.3. Finally, the design processes underlying subtle and detailed DMIs are considered, in relation to another perceived gap in the literature, this time regarding DMI design frameworks.

2.1.1 *On subtlety and detail*

With an operational definition to come in Section 2.1.3, here we take the liberty of considering our main theme at a higher level. When paired, the words subtlety and detail provide an alluring entry point into discussing the manifestation of fine instrumental quality. According to its definition, *subtlety* can imply delicate precision, understated complexity, and meticulous cunning, and generally conveys an admiration for sophistication[1]. In terms of the qualities of musical instruments, this aptly encapsulates their sometimes dualistic nature of being unmistakably present yet irreducible into words or formulas. *Detail* can refer neutrally to an individual fact or item, as well as pejoratively to an insignificant, minor or decorative feature[2]. By contrast, its usage in a phrase like "down to the last detail" implies a sense of care for every possible feature, and "go into detail" suggests a full account of something. Musical instrument makers embody a sense of care, attending to detail in the form of elusive instrumental phenomena which are very fine in nature, and otherwise underappreciated.

Together, these two words form various contradictions — vague and specific, major and miniscule — befitting of the tacit and subjective aspects of instrumental quality. Pirsig, in the all the more philosophical sequel to his novel *Zen And The Art of Motorcycle Maintenance: An Inquiry into Values*, embraces this contradiction in his Metaphysics of Quality (MOQ):

> *Quality doesn't have to be defined. You understand it without definition, ahead of definition. Quality is a direct experience independent of and prior to intellectual abstractions. Quality is indivisible, undefinable and unknowable in the sense that there is a knower and a known, but a metaphysics can be none of these things. A metaphysics must be divisible, definable and knowable,*

1 https://www.oed.com/view/Entry/193191
2 https://www.oed.com/view/Entry/51168

> *or there isn't any metaphysics. Since a metaphysics is essentially a kind of dialectical definition and since Quality is essentially outside definition, this means that a 'Metaphysics of Quality' is essentially a contradiction in terms, a logical absurdity.* [243]

Quality ultimately lying outside of definition appeared not to phase Duchamp, who found a provocative way to discuss it 'from the outside'. The epigraph of this chapter is an example of what he termed *infrathin*, a concept which he insisted cannot be defined as a noun, only used as an adjective to describe subtle phenomena [69]. In its most abstract form, infrathin refers to possibility, and spaces between spaces:

> *The possible is an infrathin.*
>
> *The possible, implying the becoming - the passage from one to the other takes place in the infra-thin.* [69]

Duchamp offered scant examples, among them "the warmth of a seat, which has just been left", and "when the tobacco smoke smells also of the mouth which exhales it" [69]. To expand on this minimal repertoire, poet Kenneth Goldsmith commissioned his students to write *1000 Infrathins* (including such pearls as "cryptocurrencies", "semicolon vs em-dash" and "gradually turning into your mother") [97]. A few happen to reference musical matters, among them the following:

> *The time between the vibration of a string and the audible sound of a note.*
>
> *The lingering of a musical note long after it is played.*
>
> *How two copies of the same LP sound different because of the way they're scratched.* [97]

These examples, when read in succession, conjure a mode of perception that reveals every day subtleties. When it comes to craft practice, Kettley argues that when perception of the subtle meets with the technical ability to shape fine details, authenticity of process results for the practitioner [154]. In this sense, we frame subtlety and detail in this thesis as reciprocal parts of a perception-in-action cycle that allow instrument makers, given enough time and perseverance, to recurse towards ever finer instrumental quality.

2.1.2 *Defining and applying the term DMI*

It is important to acknowledge that the term DMI has many meanings and is used in diverse contexts. If taken literally, the term DMI is all too easy to deconstruct, not least due to the word *digital* referring to currently fashionable technology, rather than having any fundamental relationship with discrete mathematics, or conversely with ancient digital technologies [193]. The primary academic venue for discourse around DMIs is the *New Interfaces for Musical Expression* (NIME) conference[3]. My experience of the term DMI based on my involvement in NIME and related communities, is that DMIs are musical instruments that involve contemporary computer technology, and various forms of interaction with human performers. With that footing as a starting point, I will briefly outline the wider DMI landscape (a project worthy of multiple theses), and then situate the DMI-related probes used in this work against it. A recent and non-exhaustive review of practices involving DMIs identifies a variety of sub-genres [26]. Those categories are reproduced here, with those that are most applicable to the probes in this thesis highlighted in bold:

1. **Augmented instruments**.
2. **DMIs inspired by traditional instruments**.
3. DMI as networked object.
4. **Performance-focused DMIs**.
5. Commercial DMIs.
6. Electronics-led DMI performance.
7. **DMI as performance object**.
8. Software instruments and computer languages.
9. **Body-focused approaches**.
10. Synthesis as instrument.
11. "Other experiments".

This list was offered only three years ago, and to demonstrate how rapidly the DMI landscape is evolving, one could easily extend it by adding for example DMIs which hybridise digital and acoustic processes [30], DMIs that explore robotics and machine learning techniques [104, 187], and those based on adaptive methodologies for musicians with disabilities [106]. To address this sprawling complexity, Magnusson proposes a digital organology based on rhizomatic, on-demand taxonomies which can be queried across materiality, functionality and genealogy [171]. We will return to this issue of taxonomy promptly in the next section.

Returning to the list itself, the bolded selections above are clearly influenced by my personal background (Section 1.1.2), and not least my

3 *"The International Conference on New Interfaces for Musical Expression gathers researchers and musicians from all over the world to share their knowledge and late-breaking work on new musical interface design. The conference started out as a workshop at the Conference on Human Factors in Computing Systems (CHI) in 2001. Since then, an annual series of international conferences have been held around the world, hosted by research groups dedicated to interface design, human-computer interaction, and computer music."* - http://nime.org

supervisor, whose research group takes category 1 as its namesake[4]. This group also influenced by the research questions (Section 1.2) and external literature (Section 2.2) which formed the backbone of this thesis, focusing as it does on the relationship between embodied craft practices and subtle and detailed design activity. In this respect, the probes in this thesis can be said to focus on subtle and detailed timbres and tactile interaction, since it was hoped that these features would naturally encourage hands-on attention to detail on the part of the study participants.

Those highlighted categories can also be grouped together in terms of their relative conservatism towards the idea of what musical instruments are. This is much less of an artistic statement, and more of what felt like practical necessities for designing DMI probes that would be suitable for investigating subtlety and detail. The probes in this thesis needed to present some level of familiarity to study participants, in terms of musicality and gestural interaction, to quickly establish rapport within the one-hour time constraints of the activities. We saw this familiarity as being equally important for the type of conversation that was intended with the reader regarding the issues at hand. The DMIs in this thesis were not conceptually or categorically innovative; the methods of refining them were instead, to focus the discourse on subtle and detailed design processes. Since the insights in this thesis have been drawn from fairly simple and obvious DMIs, it is hoped that the reader will see potential in them to be tested across DMI design more broadly.

A final comment needs to be given regarding how the term luthier will be used in this thesis. Etymologically, a luthier is literally a lute-maker, but at some point this term became generalised to include all makers of string instruments. In the DMI design community, Jordà introduced the term digital luthier [136], taking the term further still from its origins. Carrying on this tradition, in this thesis, the term luthier will refer to anyone who designs or makes musical instruments. Although this does in some sense make the term interchangable with DMI designer, the term luthier implies a certain reverence for craft, through its association with heritage craft practices such as violin lutherie. Similarly, we wish to impress upon the reader the transformative potential of revering the DMI designer and their practice, particulary when regarding the topic at hand - subtlety and detail.

2.1.3 *Defining subtlety and detail in DMI design*

The previous section briefly highlighted the organological and taxonomical issues related to defining and surveying DMIs, which are discussed in detail by Magnusson [171]. Many DMI taxonomies have been proposed over the years, considering modes of interaction [167],

4 https://instrumentslab.org

number and types of inputs and outputs, mappings from action to sound [113], and relation to traditional instruments [308]. An overview is provided by O'Modhrain [231], who states that they "serve to systematize thinking and promote reflection". Like classical orchestration textbooks, these taxonomies can provide structured comparison between the form, function and usage of different instruments. However, they often fail to encompass subtle, important details regarding the fine aspects of craftsmanship that distinguish great instruments from mediocre ones. Returning to our earlier example of two violins, consider as an example a *Stradivarius* and a factory-made violin intended for a beginner or student. According to most taxonomies (and indeed, most orchestration textbooks), these instruments are nearly identical in size, interaction mode, controls, mapping, and pitch range. Nonetheless, nuances in sound and tactile response will result in vastly different experiences for professional violinists. Just as master violin luthiers possess years of accumulated knowledge in crafting fine violins, many experienced DMI designers in NIME and in industry have developed detailed personal practices to produce refined DMIs. Some have shared personal reflections on their design practices in papers [51] and in interviews [70]. However, as in the example of the two violins above, these highly valuable aspects of DMIs and DMI design practice are invisible when observed through traditional taxonomical lenses.

In a thesis chapter titled *Towards a framework for new instruments design*, Jordà in 2005 attempted to provide means of comparing between *performances* with DMIs at three levels of abstraction, describing what he termed the *musical diversity* of an instrument [136]. These three levels were termed macro, mid and micro-diversity, where:

- **Macro-diversity** describes an instrument's ability to support playing in different styles;
- **Mid-diversity** describes an instrument's ability to support playing different pieces, and;
- **Micro-diversity** describes the potential an instrument has for performances of the same piece to differ.

The latter definition of micro-diversity is relevant to this thesis, as it directly addresses the issue of nuance. Re-purposing this definition in terms of instruments rather than performances, the following operational definition (meaning we can base practical investigations on it) of subtlety and detail in DMI design can be proposed[5]:

The subtle and detailed nuances between otherwise identical instruments, and their underlying design processes.

5 In our original paper on this topic we labelled this definition using the neologism *NIMEcraft* [9].

If one were to build two of the same DMI, aiming to make them as similar as possible, there would always be some difference between them. The more similar these two DMIs are, the more subtle and detailed their differences would be. Our definition assumes that underlying these differences are design processes that somehow produce them. In contrast, the taxonomical frameworks described earlier compare across high-level features like interactive paradigms, and features which are neither high nor low-level, such as mapping configurations, or numbers of inputs and outputs. Continuing the analogy to Jordà's levels of musical diversity, these frameworks could be said to address *macro* and *meso* scale differences between DMIs, and their underlying design processes. While there are plenty of frameworks which address these macro and meso scales, far less has been written about the micro scale. We will return to defining and comparing these scales of detail more thoroughly in Section 2.3, but first we must address these so-called underlying design processes that have now been mentioned numerous times.

2.1.4 *Analysing DMI design processes*

In the previous section, DMI design at the micro scale was defined by observing a gap in taxonomical frameworks for describing, analysing and evaluating DMI subtlety and detail. These frameworks analyse the *outcomes* of DMI design processes, rather than analysing the design processes themselves. As this thesis aims to address these underlying processes, this section builds off the description of research methods in Chapter 3 to discuss analysis of DMI design processes in relation to subtle detail.

When it comes to design processes, there is significantly more NIME literature prescribing them than analysing them, and we address these in Section 2.3.3. Where analysis of design process is concerned, this is usually focused on evaluating a design method [19] or tool [38], rather than the process. Some examples of the latter are starting to emerge at NIME [313], however the methods required for this type of research at an advanced level are not enculturated in the NIME community. An example of this can be found outside NIME, in the work of Delle Monache and Rocchesso [57]. Their work has focused on researching sound design cognition, and employs methods from design studies, such as linkographic analysis [95], and ontology-based protocol analysis [143]. The probes and briefs act to constrain design sessions, and make them discretisable, the latter being a prerequisite for analysis. The goal of analysis is to isolate *design moves* — discretised steps of design decision-making — and cross-reference them to form a linkograph, revealing the design state space and its non-linear progressions [95]. Additional ontologies can then be applied to address concerns such as design cognition, and the impact of probes and briefs [142].

As in this research, their motivation is to understand design processes, and to explore the implications of increased understanding for practitioners and technologists [57]. Still, there are two important differences between the studies in this thesis and Delle Monache and Rocchesso's described above. The first difference is that the studies in this thesis are not DMI design cognition studies, because we do not have reason to believe that micro scale DMI design processes are primarily cognitive, as shall be discussed in Section 2.3.2. Second, although the methods of design studies have influenced our approach (for example, Chapters 6 and 8 both feature study probes that discretised design moves), we did not pursue formal protocol or linkographic analysis, partly due to their logistics and labour overheads. But more fundamentally, we did not possess a model of micro scale DMI design to base any such protocol analysis on. Although we propose a scale-based ontology of DMI design (Section 2.3), this served to isolate micro scale design from the macro and meso scales, and made few rigid assumptions about micro scale processes themselves. Instead, we chose to start with observations of the micro scale, from which models could potentially later be hypothesised.

2.1.5 *Summary*

In this section, we have introduced the theme of subtlety and detail in DMI design, and started to define it in terms of existing DMI design literature. The next section brings outside influences into the fold to enrich the topic further, before we ultimately use this setting to define a scale-based ontology of DMI design.

2.2 KNOWLEDGE, EMBODIMENT AND CRAFT PRACTICE

In Section 2.3, we introduce a scale-based ontology of DMI design, which has three scales *macro*, *meso* and *micro*. In advance of this, this section defines and describes ideas from a variety of fields which will be then referred to across the descriptions of the three scales, and in the subsequent discussion. As this is inherently interdisciplinary research, the surveys provided will always be brief and incomplete compared to those produced by domain experts, and where this is especially the case indicative references are provided. Nevertheless, my aim has been for the integration of outside influences to enrich the issues at hand for the benefit of the reader, and to construct a more insightful perspective upon which to base my research.

In the first section, the distinction between tacit and explicit knowledge is described and considered. Next, we dive into embodied expertise as a subset of specialist tacit knowledge, and deeper still into the central role of the hands in embodiment. Finally, these two subjects are contextualised against the broader and more ambiguous perspective of craft practice.

2.2.1 *Tacit knowledge*

The phrase tacit knowledge is now fairly common, but as I briefly recounted in Section 1.1.2, recognising its meaning and consequences in full can turn common sense upside down. To perform this examination requires first turning to Michael Polanyi, a polymath who made contributions to physical chemistry, and later the social sciences when he became occupied with trying to understand what science actually was. Writing in 1966, he recounted:

> *Upon examining the grounds on which science is pursued, I saw that its progress is determined at every stage by indefinable powers of thought. No rules can account for the way a good idea is found for starting an inquiry; and there are no firm rules either for the verification or the refutation of the proposed solution of a problem.* [246]

It was through this work that he arrived at the basic insight that "we can know more than we can tell", in light of which "the fact that it is impossible to account for the nature and justification of knowledge by a series of strictly explicit operations appears obvious" [247]. Following this conclusion through brings about some dramatic implications for our understanding of science, and knowing in general:

> *It appears then that scientific discovery cannot be achieved by explicit inference, nor can its true claims be explicitly stated. Discovery must be arrived at by the tacit powers of the mind and its content, so far as it is indeterminate, can be only tacitly known.*
>
> *While tacit knowledge can be possessed by itself, explicit knowledge must rely on being tacitly understood and applied. Hence all knowledge is either tacit or rooted in tacit knowledge. A wholly explicit knowledge is unthinkable.* [246]

Illuminated in this way, the mirage of science as a process of manipulating pure forms, with scientists conveying them absolutely among each other, vanishes. These realisations also have consequences for how we view powers of intuition, and how intuition relates to the explicating of the tacit through language, science and technology:

> *The speed and complexity of tacit integration far exceeds in its own domain the operations of explicit inference. This is how intuitive insight may arrive at unaccountable conclusions in a flash.*
>
> *Formalisation of tacit knowing immensely expands the powers of the mind, by creating a machinery of precise thought, but it also opens up new paths to intuition.* [246]

Polanyi's ideas were influential during the early days of what would become known variously as sociology of science, science and technology studies (STS), social construction of technology (SCoT) and other related disciplines. However, the idea of tacit and explicit knowledge in its original form was only significantly elaborated 44 years later, by Harry Collins in 2010 [48] (Figure 2.1). Since we are more interested in tacit knowledge, suffice it for the reader to know that he begins by defining explicit knowledge via six conditions for communicability, four types of explicability, and eight types of "cannot be explicated". He thereafter divides tacit knowledge into three unique kinds (paraphrased for clarity, with examples by myself):

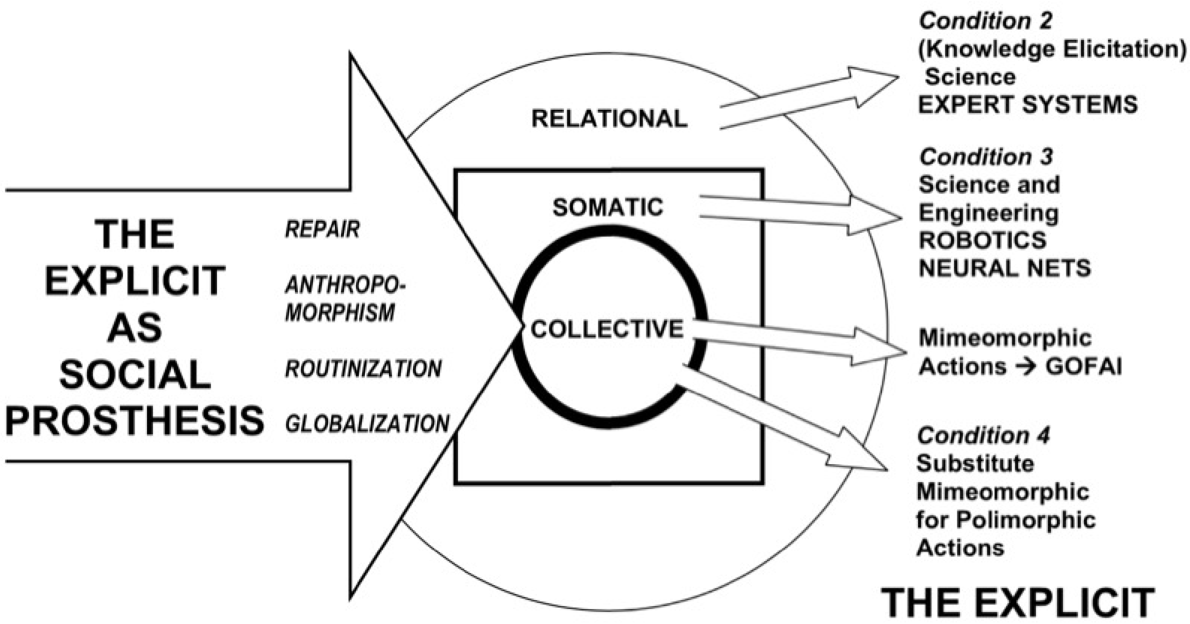


Figure 2.1: Collins' maps of tacit knowledge [48], which I have adapted into one figure. In the centre are three concentric levels of tacit knowledge, with the strongest form in the centre. The three forms are relational (RTK - weak), somatic (STK - medium) and collective (CTK - strong). On the right are four examples of technological interventions which render the tacit explicit, for example STK is made explicit by robotics. On the left are four forms of 'explicit as social prosthesis', whereby society externalises tacit knowledge in a homogenising way, to achieve certain sociopolitical aims.

Relational tacit knowledge (RTK, weak):

Knowledge that could be made explicit but is not due to social contingencies. It is a matter of how particular people relate to each other, either because of their individual propensities or those they acquire from the local social groups to which they belong.

Example: A master withholding knowledge from an apprentice for pedagogical reasons.

Somatic tacit knowledge (STK, medium):

Properties of individuals' bodies and brains as physical things [...] this kind of tacit knowledge is continuous with that possessed by animals and other living things. In principle it is possible for it to be explicated, not by the animals and trees themselves (or the particular humans who embody it), but as the outcome of research done by human scientists.

Example: How to tie shoelaces, ride a bike, or pole vault.

Collective tacit knowledge (CTK, strong):
A kind of knowledge that we do not know how to make explicit and that we cannot foresee how to explicate in any of the senses of explicable. Strong tacit knowledge, as intimated, is the domain of knowledge that is located in society - it has to do with the way society is constituted.

Example: How to navigate through road traffic, or order at a restaurant.

Subsequently, Collins investigates explication processes specific to these three kinds of tacit knowledge. He also considers how society imposes explicitness on otherwise tacit knowledge to make certain communications more efficient (he terms this process *explicit as social prosthesis*). His "map" aims to bring these ideas together, depicted in Figure 2.1. Although all forms of tacit knowledge are at play in DMI design practice, in this thesis we are particularly interested in the somatic tacit knowledge of the practitioner, discussed next.

2.2.2 *Embodied expertise*

> *One's ability to articulate an idea always lags behind the understanding of the idea, and the understanding of an idea often lags behind the embodiment in which it is first given life.* — Bret Victor [304]

Using Collins' terms described in Section 2.2.1, inventor Bret Victor could be said here to be referring to the process of explicating *somatic* (or embodied) tacit knowledge. Collins' classification of embodied knowledge as a subset of tacit knowledge might suggest that it is somehow a smaller subject. However, embodiment as a concept lies at the heart of many disciplines including embodied cognition, and embodied interaction[6]. Since the literature connected to this topic is so vast, we assume the reader has some familiarity with it (for indicative texts, see [44, 46, 67, 118, 159, 224, 300]). This section discusses embodiment in the context of tacit expertise and embodied cognition.

Collins and Evans define specialist tacit knowledge as the apex of a hierarchy of expertises, which can only be acquired by immersion or enculturation within a community of practice [49]. However, they propose distinguishing between *interactional* and *contributory* specialist tacit knowledge:

> *Two categories of higher level expertise are found [...] The highest level is contributory expertise, which is what you need to do an activity with*

6 *The ACM International Conference on Tangible, Embedded and Embodied Interaction (TEI) addresses issues of human-computer interaction, novel tools and technologies, interactive art, and user experience. The work presented at TEI has a strong focus on how computing can bridge atoms and bits into cohesive interactive systems.* — https://tei.acm.org

> *competence. Just below this, however, is interactional expertise, which is the ability to master the language of a specialist domain in the absence of practical competence.* [49]

They define contributory expertise as the "traditional category of ability to perform a skilled practice". They explain its acquisition using the example of Dreyfus and Dreyfus' five stage model of expertise, where a practitioner progresses through *novice*, *advanced beginner*, *competence*, *proficiency* and *expertise* stages [68]. Their expertise hierarchy is transitive; those with contributory expertise will possess interactional expertise, but not vice versa. To illustrate this, they consider the problem of how a coach can direct athletes' actions through words:

> *The human coach can teach some things through the medium of spoken language because the coach shares some of the nonexplicit skills of the student: the shared linguistic skills can transfer mutually understood tacit meanings that would not be available to those with levels of expertise below interactional.* [49]

In contrast, Marchand describes transmission of contributory expertise through purely embodied means as language-like:

> *Physical practice communicates, and therefore, like language, its component elements can be parsed by an observing party and acquired as mental representations by his or her motor domains of cognition. Motor representations yield embodied simulations of actions, or they can be systematically re-combined, with the effect of producing physical imitation or novel articulations of knowledge-in-practice.* [182]

But nevertheless, according to Collins and Evans this type of knowledge would not transfer to those with only interactional expertise, since they do not possess the "simulations" that the embodied expert uses to internalise and re-synthesise their observations. This distinction between specialist tacit knowledge based in language versus fully embodied practice will become important again when we return to tacit knowledge in DMI design in Section 2.3.

Focusing on contributory, embodied expertise, the five stage model allows us to imagine gradations of skill [68]. Klemmer argues that parallel gradations exist in the affordances of tools and media, where some offer rich opportunities for specialist tacit knowledge acquisition, and others do not:

> *We draw attention to the importance of tacit knowledge because computerization can, often accidentally, inhibit it. For example, Zuboff's studies of paper plants found operators distrustful of recent computer mediation that interpreted plant conditions for them. Prior to this mediated experience, one plant operator could judge paper condition by his arm hair sensitivity to electricity in the atmosphere around a dry roller machine; another could judge pulp roll moisture content through a slap of the hand on the roll.* [156]

Not only do the extraordinary physical skills mentioned above enable incredibly subtle perceptive evaluations of environments, they also enable unique types of thinking with the body. Kirsh describes thinking with the body as a coupling between epistemic and enactive states, with simulation occurring in a commingled fashion across mind and reality:

> *When people think with things they rely on the world to simulate itself and in so doing they stimulate themselves. They indirectly control their epistemic state. The world executes part of the reasoning process, therefore, by carrying them to a new state that is reasoning relevant. Thus, as the thing they manipulate undergoes change, people revise their continuation system.* [155]

Kirsh illustrates this idea using an example of someone twisting off a beer bottle cap:

> *If we were to ask our cap twister whether he thinks that if he continues twisting he will remove the cap, his answer (yes) looks like it is the product of thought. And it is. But it is not propositional thought in a classical sense [...]*
>
> *On those occasions where he cannot simulate the future well internally, or if there is too much uncertainty in how he thinks things will unfold, he can reach out and begin twisting the cap, that is, perform an outer simulation.* [155]

Returning to Victor, his current research project Dynamicland[7] (Figure 2.2) aims to build an architectural scale, communal computer operating system, where performing outer simulations is a first-class property. Dynamicland aims to raise the "low ceiling" [312] on embodied expertise with computing systems, by modelling the spatial and embodied cognition processes Kirsh describes:

> *Regardless of the quality of the programming environment, it's always much easier [with current systems] to program a simulated falling object "inside the computer" than it is to record and analyze a real one "outside the computer" [...]*
>
> *My group is building a non-boxed computing system that is grounded in and participant in the physical world, observing and responding, with close commingling of physical and computational processes. If you want the position of a falling object over time, you might just pick up some object and drop it [...]*
>
> *One goal is to put "experimentation" on equal footing with "simulation", to encourage "getting the actual models from nature".* [33]

2.2.3 *The hands*

In this section we have so far explored what embodied knowledge and cognition are, their relationship with reality, and the roles they play in

7 https://dynamicland.org

Figure 2.2: "Thinking like a whole human" in Victor's Dynamicland.

expertise. There is one part of the body which is central to all of this taking place, and that is the hand. Hands are extraordinarily capable instruments of feeling and manipulating (Figure 2.4). Their function and structure is described in [135] and their evolution is described in [219]. For detailed reviews of the physiology of touch in particular, see [88, 252].

The hands and fingertips (Figure 2.3) perform incredible feats such as using subtle thermal cues in material discrimination [320], and are deeply intertwined with the brain to the extent that hand use predicts the structure of representations in the sensorimotor cortex [71]. In design studies, hand gestures have been identified as a resource for "virtually prototyping ideas" on the fly [43], but a study of the development of problem-solving abilities in children concluded that "mouse and graphical user interface [...] may limit skills development [and] inhibit the development of a successful mental strategy" [5]. Victor describes this inhibition resulting from use of current computer interfaces "finger-blindness":

> *The density of nerve endings in our fingertips is enormous. Their discrimination is almost as good as that of our eyes. If we don't use our fingers, if*

Figure 2.3: Coloured scanning electron micrograph (SEM) of part of a human fingerprint, showing details of skin ridges in the outer epidermis. The small circular apertures on the ridges are the openings of sweat glands. Epidermal ridges occur on the soles and palms, and they form a distinct pattern. The patterns are classified into four main types: loops, whorls, arches, and combinations of these three.

Papillary ridges are found on the palm of the hand and occur on those areas involved in grasping, where it is assumed that they act as friction pads [...] It is interesting to note that during contact, droplets of sweat form evenly along the fingerprint ridges. This has led to the intriguing speculation that during contact, the fingertip skin is softened, rendering it more compliant. The sweat also increases friction between skin and surface. In both ways, then, the production of sweat may help to stabilize an object when it is grasped. [135]

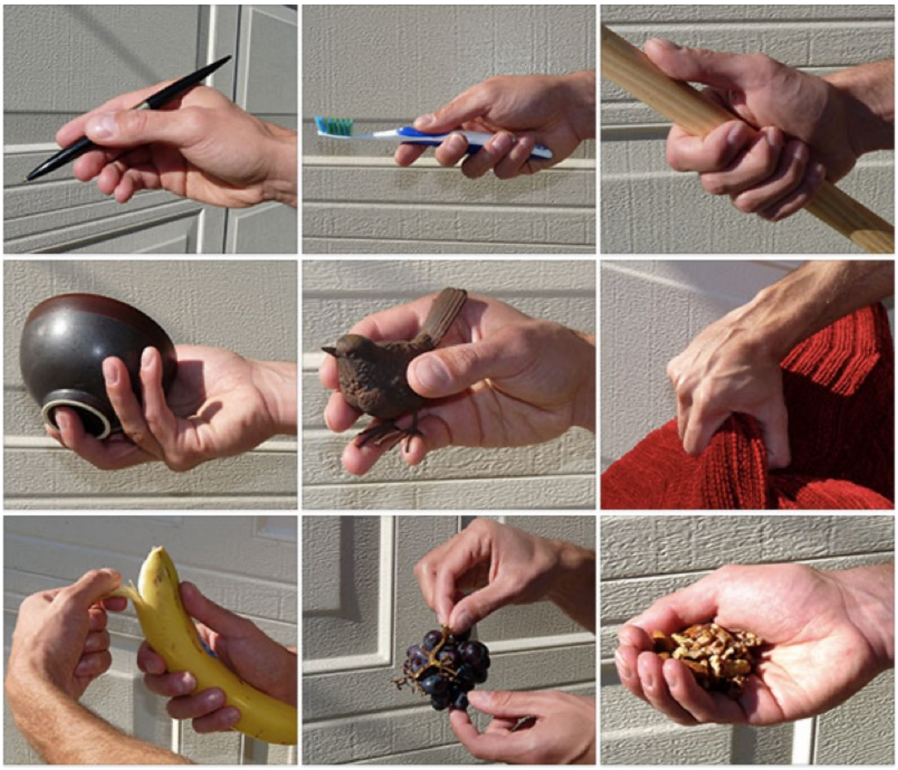


Figure 2.4: Victor demonstrating various types of grip:
Our fingers have an incredibly rich and expressive repertoire, and we improvise from it constantly without the slightest thought. In each of these pictures, pay attention to the positions of all the fingers, what's applying pressure against what, and how the weight of the object is balanced. [302]

> *in childhood and youth we become 'finger-blind', this rich network of nerves is impoverished - which represents a huge loss to the brain and thwarts the individual's all-around development. Such damage may be likened to blindness itself. Perhaps worse, while a blind person may simply not be able to find this or that object, the finger-blind cannot understand its inner meaning and value.* [302]

To explore the hands' critical role in the interpretation and negotiation of meaning and value, there is no better context than craft practice. Craft researchers identify the mind-hand connection as resulting in something much greater than their sum:

> *Craft is understood not only as a way of making things by hand, but also as a way of thinking through the hand manipulating a material. Craft is thus a means for logically thinking through senses.* [222]

Next on our literary tour we consider tacit knowledge, embodied expertise and the hands from a craft practice perspective.

2.2.4 *Craft practice*

In recent decades, craft-inspired approaches have become increasingly present in the field of HCI [85]. The culture and scholarship around craft practice complicates matters of materiality, meaning and ethics in ways which are usefully provocative to new fields with technological dispositions. Attempting to help ground other disciplines who are not traditionally associated with craft culture, Kettley provides seven principles as foundations for integrating craft values and methods into new domains [153]:

1. **Risk and visual language.** Risky non-predetermined process results in original visual language, seen to embody particular political and metaphorical values.
2. **Extending material.** 'Material' may include traditional materials, technologies, processes and methods, each having their own affordances and constraints.
3. **Internalization of material:** Internalization of both source material and the material being worked is essential for the development of original language.
4. **Processes of internalization:** Internalization of materials is achieved through action - techniques include drawing, direct manipulation of material and repeated exposure to the material.
5. **Embodied process:** Control over formal expressive elements at diverse effective ranges is dependent on an embodied understanding of the processes of production.
6. **Signifiers and authenticity.** Signifiers of craft are not to be confused with the original visual language that emerges only from the internalization of material.
7. **Undecideability.** Craft practice, objects and consumption are characterized by an undecideability of purpose and cultural placement: as such, they are unfixed and occupy a unique space between art and life.

Reviewing these principles in the context of the preceding sections, we can clearly see how tacit knowledge and embodied expertise play fundamental roles. Connecting principles 3-5 for instance, the embodied process of internalising material neatly aligns with the five stage model described in Section 2.2.2. And Kettley's own accounts of craft practitioners suggests similar frustrations with indirect manipulation of material, to that which Klemmer and Victor criticised about computer interfaces:

> *[...] makers who had tried explicitly to develop drawings as a discrete design step found that they sacrificed spontaneity, introducing distance between themselves and the source material, and between themselves and the material being manipulated. Most found in this instance that they fell back on existing [visual] language, instead of growing personal expression [...]*

> *For many craftspeople, 'the design is operated within the matter itself'.* [153]

Even the default mental image one has when reading the phrase 'craft practitioner' will probably involve an environment like a craft workshop, within which a practitioner works material with their hands, with little reference to any explicit knowledge. But, Kettley's principles also seem to hint at something beyond the conceptual definitions that we have covered so far. For example, Baber refers to handcraft as having a transformative effect which is not encapsulated merely by the term expertise:

> *It is not simply that the craft worker has "superior" manipulative skills than other people, nor that they are just "better" at using their hands than other people, but rather that the craft worker has a different view of the world and the artefacts it contains.* [13]

The idea of expert handcraft as a gateway to an entirely altered perspective is reminiscent of the depiction of *infrathin* in Section 2.1.1 as a mode of perception of the subtle. Further, handcraft cannot be contemplated in a vacuum. *Handmade* is often a synonym in craft culture for authenticity [226], which embroils makers' embodied expertise in a broader ecological setting, where meaning is negotiated with interactional experts (Section 2.2.2) and even with more casual aficionados. As we shall see in the next section, this 'undecideability' of craft is useful for problematising contemporary DMI design practice, technology and research.

2.2.5 *Summary*

In summary, the preceding sections have identified somatic, embodied, contributory expertise as the superlative form of specialist tacit knowledge, which is the foundation of master craftsmanship. We have seen that linguistic tacit expertise exists, but is inferior to practice-based expertise, with the latter being both enabled by, and dependent on, the development of fine manual skill. The culmination of these ideas will be present across the next section, where we introduce a scale-based ontology of DMI design.

2.3 A SCALE-BASED ONTOLOGY OF DMI DESIGN

At the beginning of Chapter 1, we claimed that DMI design faces complex issues regarding subtlety and detail, which the ecosystem is disincentivised to address, at the expense of valuable knowledge about the field. Having defined the general research terms in Section 2.1, and contextualised the topic area in Section 2.2, we now turn to elaborating on this central argument. The main device which we are going to use to frame this discussion is an ontology. Since ontologies are models, and all models are wrong, it is important for us to first define that this ontology's primary goal is to be a vehicle for our perspectives on the main issue of this research, namely:

1. A great deal of DMI design research and practice addresses primarily high-level concerns, leaving subtlety and detail underexplored, and undervalued.
2. DMI design tools, frameworks and methods tend to mediate design processes in obfuscated and unacknowledged ways, through rigid high-level choices and low-level abstractions, rarely considering the needs of subtle and detailed design processes.
3. Addressing and understanding the subtleties and details of DMIs, and their underlying design processes, is both an important and tractable goal for the field.
4. Clearly defining the first two issues is a helpful first step towards addressing the third, but observation-inspired models of subtle and detailed DMI design processes, at first in isolation from other concerns, will ultimately be a greater incentive for future research.

In this section, we address each of the ontology's three proposed scales of DMI design in turn, and a discussion follows thereafter. Before we begin, however, we define and offer an overview of the ontology, including simple examples of its application, to ensure that the discussion to follow is unhindered by semantic uncertainty.

2.3.1 *Overview*

We propose a scale-based ontology of DMI design, based on the operational definition of subtle and detailed DMI design given in Section 2.1.3. By ontology, we mean a schema, model or framework that aims to capture or highlight salient features of a domain [91, 143]. Regarding scale, we mean level of abstraction, spanning from the most abstract (macro) to the most specific (micro), without providing units of measure, or implying either end is finite. And with DMI, DMI design and DMI design processes, we refer to the definitions provided in Section 2.1. A visual illustration is given in Figure 2.5, and the ontology is summarised as follows:

Where each scale considers digital musical instruments,

and their underlying design processes:

the macro scale	defines	*roles, forms and functions of instruments across ecologies*,
the meso scale	defines	*configuration and mappings across taxonomically similar instruments*, and
the micro scale	defines	*subtle and detailed nuances between otherwise identical instruments*.

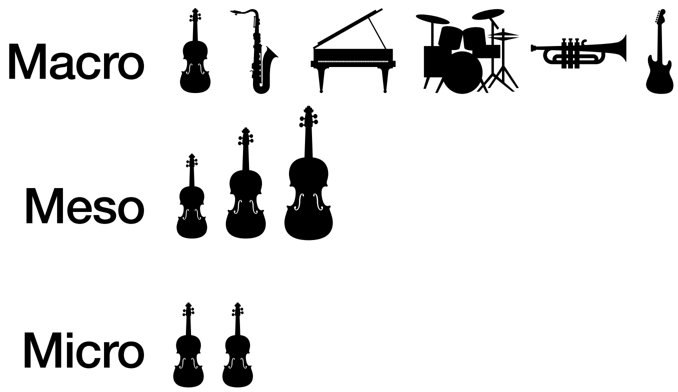


Figure 2.5: Illustrated examples of the scale-based ontology of DMI design:
The macro scale considers completely different kinds of instruments;
The meso scale considers similar instruments, and;
The micro scale considers instruments which are the same at macro and meso scales.

Each scale is defined in terms of a set of attributes, and a context. A notable distinction between the macro and meso scales, and the micro scale, is that the former have noun attributes, whereas the latter has adjective attributes. This follows from the discussion of subtlety and detail in Section 2.1.1, where quality, and Duchamps' concept of the infrathin, were approached as being describable but not definable. It also captures the partially subjective and "undecidable" aspects of micro scale details (Section 2.2.4). An apparent contradiction arises out of this linguistic choice, where the adjectives that define the micro scale validly apply to the nouns of the other scales. For example, the form and mappings of DMIs can clearly be subtle and detailed. This is why each scales' attributes are paired with a context. That is, we do not describe the micro scale just as *subtle and detailed nuances*, we describe it as *subtle and detailed nuances of otherwise identical instruments*. The meso scale is set within the context of taxonomically similar instruments, alluding to the similarities observed between instruments in a string quartet, or between vintage analog electronic drum machines. The macro scale addresses instrumental ecologies, encompassing music cultures in the large and all the complexity that entails.

Per mutating each definitions' attributes and contexts can perhaps help to reinforce their intended meaning:

- Roles, forms and functions differ across instrumental ecologies *(macro)*, but are the same in taxonomically similar instruments *(meso)* and otherwise identical ones *(micro)*.
- Configuration and mappings are closely related across taxonomically similar instruments *(meso)*, vary widely across instrumental ecologies *(macro)*, and are subtly different in otherwise identical ones *(micro)*.
- Otherwise identical instruments have the same role, form and function *(macro)*, and the same configuration and mappings *(meso)*, and are distinguished via their subtle and detailed nuances *(micro)*.

In other words, there is a hierarchical or dendritic aspect to these definitions. Any two DMIs will possess micro scale details, but unless they are identical at the macro and meso scales, comparing their micro scale details will not reveal subtle details at the fine level we are trying to engage with. This is not to say that DMI design always begins at the macro scale and proceeds in a linear and hierarchical manner towards the micro; in fact, we argue closer to the opposite in Appendix A.1.

To give a brief example of applying these definitions, consider the grand piano. Already, I do not need to elaborate further what is meant by grand piano, since its macro, meso and micro scales have been stabilised over centuries. From the perspective of this ontology, the prepared piano represents a macro scale change in the role and function of the instrument, involving a reconstitution of its meso scale configuration, which in turn introduces a novel field of micro scale details, which are not germane to the instrument's previous idioms. In contrast, the *Magnetic Resonator Piano* (MRP), an electromagnetic, non-destructive augmentation of the grand piano, makes meso scale interventions, but does so subtly to preserve the existing macro, meso and micro scale identity of the original instrument [196, 198]. Both scenarios might involve underlying design processes which are themselves subtle and detailed, but the context of the MRP would lead one to assume that it would out of necessity have to exhibit a great deal of subtlety in order to be successful, whereas with prepared pianos the design solution space is deliberately large to facilitate high-level artistic exploration.

An obvious but important caveat with this ontology, as with any other, is that in reality, one would expect the boundaries between scales to be fuzzy rather than distinct, and even slightly contradictory (or perhaps infrathin, Section 2.1.1). It might therefore be more useful to think of fuzzy macro-meso and meso-micro borders, depending on the context. As the saying goes, *the map is not the territory*, but we believe this map has allowed us to achieve some clarity on the issues of subtlety and detail in DMI design, which we later were able to turn into practical enquiries that provided further insight still. It is in this spirit of pragmatic curiosity that we offer this ontology, rather than being motivated by a theory of everything.

While this thesis focuses primarily on the micro scale, the other scales have turned out to be useful for elucidating what the micro scale *is not*. They emerged in a specific order during the research process based on the study outcomes; first we defined the micro scale, then the macro scale as its opposite, and finally meso as what lay between (Section 1.1.2). However, we present them here in order, starting with the micro scale, in order to consolidate what this chapter has discussed so far, and to provide a through-narrative.

2.3.2 *The micro scale*

In effect, we have spent up to this point in the chapter defining and describing what we propose to refer to as the micro scale in DMI design. Namely, Section 2.1 defined the micro scale as encompassing subtlety and detail in the context of comparing otherwise identical instruments, in doing so highlighting a gap in coverage by existing DMI taxonomies and design frameworks. Based on this foundation, Section 2.2 went on to describe the epistemological and practical bases for acquiring expertise about micro scale issues. Here we supplement these earlier depictions with more examples from the DMI design literature.

As has already been mentioned, longitudinal ethnographies [291] and reflections on practice [51] are a primary source for accounts of micro scale details [290]. Michel Waisvisz notably developed three distinct versions of his DMI *The Hands*, over a time span of more than twenty years [70, 307]. Torre and Andersen describe how these versions became increasingly micro scale in their differences:

> *The customisation phase began in 1990 with the development of Version 2 of The Hands and ended in 2000 with the release of Version 3. The differences between these two versions are minimal compared to Version 1 [...] After the finalisation of version 3 of The Hands, Waisvisz made the decision to stop developing and accept the physical layout as is. From this point onwards, he concentrated on refining the software settings and musical content of the performances [...] By freezing the design modifications and extensions when The Hands were physically stable and durable, it became possible to focus on the musical intent beyond the novelty of the devices.* [290]

Waisvisz' motivation to refine rather than continue to explore was motivated in large part by his own musical needs, a theme which is common among digital luthiers who are often designing for themselves, and need time to nurture their musical practice. *The Hands* were such a new idea at the time that Waiswisz, and other practitioners working with glove-based instruments such as Sonami [80, 274], out of necessity spent the early years of their process exploring macro and meso scale DMI design spaces, before eventually focusing solely on the micro scale. Not all DMI design processes traverse from macro to micro however, and a prominent counterexample already mentioned is McPherson's *Magnetic Resonator Piano* (MRP) [196]. He was at first casually exploring electromagnetic actuation of piano strings, inspired by the guitarists' EBow[8] rather than similar piano augmentations of which he was at that time unaware. Similar to Waiswisz, McPherson became driven by a musical necessity, but as a composer rather than a performer. He found a need for a "creative inlet" into composition for solo piano as part of his PhD studies, yet where "the piece could exist without the technology":

> *I wasn't really thinking of the piano being transformed into a fundamentally different instrument. I think what I had in mind was the idea that you would have something that was still recognizable as a piano but had a sort of extraordinary range of tone color, especially the idea that you can kind of separate the timbre from the the dynamics.*[9]

Where the macro and meso scales of *The Hands* and similar instruments required inventing by practitioners, the MRP aimed to preserve the existing macro and meso scale details of the grand piano, and extend its micro scale domains while minimising their perturbation.

Research concerning DMI design methods and practices that register subtlety and detail among their concerns has increased in volume in recent years. Jack et al. highlight the benefits for in-the-wild research [261] of framing DMI research artefacts as finished products rather than functional prototypes, noting the inherent subtleties involved in realising them:

> *We see research products as a natural counterpart to the technology probe approach. The differences in physical properties of what is considered a probe or product might be subtle, or even non-existent [...] Importantly, research products place an equal emphasis on non-technical design choices such as materiality, 'feel', and visual aesthetics, alongside the more technical questions of sensor technology, mappings, and sound-design.* [125]

These subtleties become foregrounded further still when considering the issue of DMI replicability [39, 40]. Zayas et al. investigated this through the intimate lens of apprenticeship, where an apprentice aimed for exact replication of a DMI, under the supervision of the original designers [322]. They provide first-hand reflections from the DMI apprentice in their paper:

> *One of the most salient points of shared tacit knowledge was when the designer disassembled one of the strings and demonstrated how to achieve the optimal tension in the string. Achieving this requires that one plucks the string repeatedly while tightening it in order to get both a feel of the string and to make sure it is not producing an audible tone.*

Practice-based accounts such as these provoke enticing questions regarding how expertise about subtle details develops, and how it

8 https://en.wikipedia.org/wiki/EBow
9 Personal correspondence, April 2021.

manifests through design processes and tool use. At the moment, however, the resolution of these accounts is severely limited. The first stage of revealing micro scale details is to isolate them from other aspects of DMIs and their underlying design processes. The next section begins this process by distinguishing meso from micro scale DMI design.

2.3.3 *The meso scale*

In our discussion of micro scale details in the preceding section, we highlighted methods and practices that support the development of the embodied expertise that is required for working with subtle details. However, this short review did not reference the majority of the commonest DMI design tools. Practitioners clearly do use common tools such as Arduino and Max/MSP for subtle and detailed DMI design, however despite claims by toolmakers about their limitlessness, we believe that such tools are primarily predisposed towards supporting meso scale configuration and mapping of DMIs. At the micro scale, details are either abstracted away entirely, or affordances for working with them are severely underdeveloped. Further, we point to existing literature identifying these tools as embedding macro scale assumptions which their users accept, blindly or not. These two distinctions justify the inclusion of three scales in the ontology, instead of just micro and its macro opposite. The meso scale lies between form and detail, a space defined by negating both macro and micro, occupied by DMI design philosophy and know-how made explicit.

2.3.3.1 *Meso versus micro*

DMI design toolkits are useful design aids that abstract implementation details into modular parts whose combination can be rapidly explored. Toolkits reflect specific musical cultures and knowledges [167] such as instrument classification systems [38] and synthesis approaches, which through abstraction gain extra flexibility allowing for novel recombinations. However, as Perner-Wilson et al. note:

> *Construction kits make building technology easier. As systems of modular parts they lower the entry bar to science, engineering and technology disciplines. Their modularity allows for them to be assembled and almost as easily disassembled in order to iterate through a series of designs. But this modularity comes at the cost of constraint. The parts of a construction kit function inside modular systems and the designs realized with these kits are limited. They constrain what we build and how we think.* [239]

This approach to designing toolkits often literally reduces the DMI design space to a pre-defined, combinatorial set of possible instruments, where the designer's role is limited to picking from a curated list of ingredients and letting someone else cook. This is a simulacrum

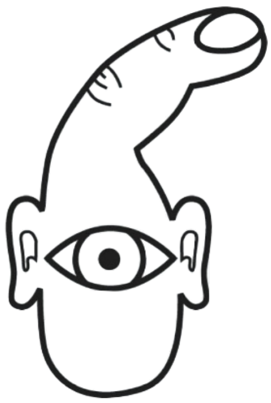


Figure 2.6: Computer's model of a user [227].

of DMI design, as *GuitarHero* is to playing guitar [10], or the design equivalent of the slogan "everyone can play music" that commercial DMIs like to repeat [200]. While it has pedagogical and entertainment value, it is insufficient for working with micro scale details. Whether their designers intend to do so or not, modular toolkits often end up with standardised micro scale details for the sake of compatibility between parts and modules, which eradicates material subtlety. The same tangible media markers perform the same functions regardless of materiality [249], which is filtered out and abstracted away by recognition systems [111]. While evidence suggests that expert toolkit users overcome the toolkit's influence [25], for beginners it is easy to mistake a toolkit's perspective for the art and craft itself [211].

Not all DMI design tools abstract away micro scale details; platforms like Bela and Elk[10] market themselves as catering towards the realisation of subtle and detailed musical and auditory interactions [202, 212, 294]. Though these platforms have enabled closer investigation of issues such as latency and tangibility for DMI performers [124], the same can't be said for DMI designers, whose haptic, tactile, and spatial abilities are in comparison neglected [35]. From the perspective of embodied craft process (Section 2.2.2) and handcraft (Section 2.2.3), DMI designers using these platforms are impoverished in how they can display/read and manipulate/author micro scale details. The embodied expertise that DMI design platforms do recognise, the majority of which can be reduced to touch typing and visual symbol manipulation (Figure 2.6), is more often than not a few levels of indirection [117] away from the behaviour DMI designers are actually trying to create. As a result, DMI designers acquire little physical experience of the phenomena they care about, instead watching text console logs slowly printing non-dimensional numbers, which stunts and limits the growth of their specialist tacit expertise. An analogy would be learning to play the violin whilst wearing baggy rubber gloves and

10 https://elk.audio

earmuffs, or trying to build a mechanical watch through a letterbox with the lights out.

To disrupt this status quo, we advocate for making digital lutherie more deeply embodied, and enabling luthiers to employ their full bodily capabilities in making and feeling micro scale details. A healthy assumption in this regard, would be that a decent micro scale DMI design tool requires its own dedicated Bela or equivalent device. Using DMI design tools should be at least as finely embodied as playing DMIs, though the machine that makes the machine is usually the more subtle or sophisticated one; violin luthiers for example spend considerable time and effort sharpening their tools for this very reason.

2.3.3.2 *Meso versus macro*

The most cited DMI design topic, and a mainstay of NIME publications over the years, is mapping [77]. Mapping was established early in NIME's history as an important topic [113, 114, 299], continuing a theme that can also be traced back through the literature of the *International Computer Music Conference* (ICMC) [31]. Since then many mapping frameworks, strategies and tools have been published, too many to review here. Much of the discourse around mapping and mapping toolkits is fundamentally meso in scale because it already assumes a particular architecture of data flow. Regardless of topology or configuration, there is a rigid intellectual model behind the idea of mapping, which presumes (not always, but often) temporally static relationships amongst features, with numerical weights and transforms between them. DMI designers using these tools benefit from access to the enormously complex space of possible mappings, but it is not possible for them to escape from thinking in terms of mapping. Unless, however, they have mastered the tool to the level of transcendence or re-appropriation [60], at which point they would be better off implementing a new tool from scratch. Not all DMIs need to be conceived through the mapping way of thinking, and considering alternative paradigms in relief creates a landscape of truly macro scale differences.

Magnusson describes these conceptual features as epistemic dimensions that designers encode into tools, deliberately or not [167]. A hypothetical pianist who has never seen or heard any other instrument would be stunted in their ability to imagine non-pianistic musics [100]. Similarly, DMI design tools encode worldviews which are invisible to their designers and users, unless they happen to have experienced others and are paradigmatically well travelled. This type of blindness is captured by general idioms like "can't see the wood for the trees", and "if all you have is a hammer, everything looks like a nail", and also even within technology discourse through phrases like "we shape our tools, and then our tools shape us" and "we have become the tool of our tools". Abstracting the overall sentiment, characterises the meso scale as giving the illusion of being macro scale; if all you know is a specific meso scale framework or tool, the space you are in will appear to be macro in character.

Similarly to mapping tools and frameworks, sound and music computing (SMC) languages (such as [191, 250, 309]) also fall into a meso scale hall of mirrors illusion, by professing to be universal by design [199, 201, 273]. Two psychological sources for this claim are the *technical* computational universality of Turing-complete SMC languages, and the proximity between programming and natural language, relative to most other tools [59]. The trap lurking beneath Turing-completeness is the *Turing tar-pit*, "in which everything is possible, but nothing of interest is easy" [238]. That monkeys randomly typing will reproduce Shakespeare given infinite time, is not good marketing spiel to audiences who would preferably be alive at the time of publication. This is nevertheless the aura around tools such as Max/MSP, which as Snape and Born point out is problematic in myriad ways, that go beyond the mere comment on affordances presented here:

> *The discourse that surrounds Max, then, constructs the software as aesthetically neutral, transparent and infinitely reconfigurable – a mirror reflecting back pure authorial intention. In short, as not a mediator [...] It envisages for Max a universal, purely technical functionality that denies its embeddedness in social and cultural formations, as well as its technical specificities and their musical consequences.* [273]

2.3.4 *The macro scale*

In Section 2.3.3, we characterised the mediation of meso scale tools in terms of their impact on the micro and macro scale. The meso scale, we have argued, covers a huge swathe of DMI design research. What does that leave for the macro scale? We define the macro scale in DMI design as the roles, forms and functions of instruments across ecologies, and their underlying design processes. In this section, we first explore what meaning is implied by the three attributes in this definition. Thereafter, we survey how these terms have served as high-level themes in DMI design research over recent decades. Then, we review how these early issues are being subjected to a variety of critical perspectives in recent years, which has occurred simultaneously with a proliferation of critical practices and practice-based or inspired research and pedagogical methods.

Taken at face value, DMIs like all instruments describe themselves through their names, what they look like, and what they do. Even a DMI's name by itself, gives away far more information than merely how to refer to it. For instance, surveying some DMI names at random from the past four years of NIME, will reveal a variety of technological, musicological, organological, typographic and cultural references, all attempting to communicate deeper meanings via association. Some names are more ambiguous, hiding behind acronyms, backcronyms and puns, or referring to an unfamiliar aspect of its own form or function, in an attempt to highlight its novelty:

Alto.Glove [285] *bEADS* [316] *Bendit_I/O* [180] *Excello* [267] *FabricKeyboard* [314] *GeKiPe* [78]

gibberwocky [258] *HandSolo* [128] *Hitmachine* [127] *HypeSax* [83] *Magpick* [215] *MicroJam* [188]

MOM [210] *Parthenope* [271] *SlowQin* [109] *SpectraScore* [42] *SQUISHBOI* [56] *Strummi* [107]

Svampolin [237] *Tremolo-harp* [151] *Tromba Moderna* [16] *Vodhrán* [236] *WELLE* [301]

While a DMI can attempt to assert its identity through an iconic name, or indeed an iconic silhouette, its role can be understood from a design perspective as the sense in which it is useful in someone's life [112]. This could include a DMI's musical purpose or *teleology* [92], for example within an orchestra or ensemble, or towards a pedagogical or accessibility goal [110]. Its role could also be driven by the motivation to explore a new technology, as is apparently frequently the case for DMI designers [73]. Taken in a broader sense however, a DMI's role could be considered as contextually equivocal, an argument Bates makes through the metaphor of musical instruments having social lives:

> *Instruments are entangled in webs of complex relationships — between humans and objects, between humans and humans, and between objects and other objects. Even the same instrument, in different sociohistorical contexts, may be implicated in categorically different kinds of relations.* [22]

Another high-level concern in DMI design research has been novelty, and what *new instruments* should be or do. As McLean *et al.* point out, the *digital* in all digital arts stands not for discreteness but for contemporary technology, and in practice analog and digital media are always nested within each other recursively [193]. Interpreting the digital in DMI design this way, there is a clear emphasis on exploring the novelty of contemporary technologies in DMI design research, to the extent that it is eponymous with the community's leading venue, *New Interfaces for Musical Expression*[11]. There is a fairly common abstract notion of the idealised new instrument in the DMI design field, which is often tied to select keywords. From the perspective of Andersen and Gibson:

> *A new instrument provides an intuitive interface between gesture and sound; it allows for the development of virtuosity [...] can provide long-lasting and fulfilling interactions that exceed the novelty of its modifications and extensions [...] capable of surprising the performer and allowing the continual*

11 https://nime.org

renewal of musical possibilities [...] requires a certain level of stability and durability, providing the longevity suitable for traveling and performing. [3]

In Section 2.1.3, we briefly surveyed DMI frameworks for taxonomical analysis and evaluation, which was a common theme especially in the first decade of NIME literature [131, 132], and many of which were based on the keywords above. Noteworthy high-level discourses subsequently fell directly out of differing interpretations and critiques of *expressivity* [61] and *evaluation* [18, 133, 256] in DMI design. And over in the artistic side of the community, numerous surveys of DMI performers have strongly and repeatedly indicated the dominance of experimental aesthetics [50, 208, 216, 220, 311], which are often high-level in nature. To say the trend of high-level concerns has continued in recent years would be correct, however such a statement would belie the sheer magnitude with which critical perspectives and practices are presently reshaping DMI design research at all levels, including macro. Although from an inside perspective this is perhaps a consequence of a maturing field [77], critical research practices have also spread throughout HCI and related fields over the past decide.

A critically-based practice implies dissecting technological and scientific paradigms and philosophies, sociopolitical power structures and hierarchies, and entrenched systematic beliefs and behaviours, turning academic writing and making into activism [58, 228, 254, 263]. In attempting to define criticality for itself [41], various perspectives are emerging in the DMI design community, such as those proposing practice-based [99, 134, 287], ecological [75, 87, 278] and anti-solutionist [164, 214] stances, with similar patterns to be found in tangential fields like organology [62, 63, 171]. As addressed later in Section 3.5, the community is also more directly addressing issues of equity and justice around politics, diversity, racism, environmentalism, ableism, and more. A goal of these perspectives is to transform DMI design practice through critical making [160], in particular with craft-inspired approaches [85] proving valuable for holding space for marginalised voices [279]. Artificial intelligence researchers are also subverting the hegemonic monoculturalism of Western and European DMI design, through the exploration of transcultural representations of sound and music, that reject seemingly fundamental constructs like frequency and notes [103].

2.3.5 *Summary*

Section 2.3 has introduced a scale-based ontology of DMI design, which serves to highlight and probe the nature of subtle and detailed DMI design. Three scales have been proposed, the micro scale which encapsulates subtle details, and meso and macro scales which do not. Separating the micro from the meso and macro allowed us to narrow our focus on the micro, and to begin to understand how to practically investigate it. Though the model vastly over-simplifies DMI design research and practice, and it most readily applies to the types of DMI design probes that are exhibited in this thesis, it serves its main aim better than any existing perspective that we are aware of. Nevertheless, we presented the three scales in relative isolation, and although we have provided some examples, these have mostly been convenient in some way, and not at all representative of the diversity of DMI design practices. There are of course further clarifications to make and edge cases to consider, and the reader can find a discussion of at least some of these in Appendix A.

2.4 CONCLUSION

This chapter sought to address Research Question 1:

What environments and contexts can facilitate DMI design research on subtlety and detail?

We started in Section 2.1 by attempting to define subtlety and detail at a high-level, and then in a more specific way by situating it within the context of DMI design research. This was followed up in Section 2.2 by expanding the initial context through a discussion of tacit and explicit knowledge, embodied expertise, handcraft and craft practice. This all came to a head in Section 2.3, where we formally introduced a scale-based ontology of DMI design, which features macro, meso and micro scale levels, and seeks to make it easier to isolate and investigate subtlety and detail.

3 METHODOLOGY

> *One of the ways of escaping the present, is to have a glimmer of an idea, take it so far out that you don't have to worry about how you're going to get there, and then you bring it back. So instead of innovating out from the present, what you want to do is invent the future from the future: go out and live in the future and bring the future back.*
>
> — Alan Kay, *How To Invent The Future* [1]

The investigations in this thesis used numerous methods following prior research in DMI design, which in turn were often inspired by human-computer interaction (HCI) research. The research in this thesis was founded on designing research probes and activity briefs, observing participants' responses to them, subsequently interviewing participants, processing and coding the resulting data, developing thematic interpretations into insights, reflecting on the process, and sharing the outcomes. As the quote above suggests, the probes in this thesis explored possible futures for handcraft in lutherie, as inspired by the discussion in Section 2.2. Each investigation had its own specific needs and challenges, which are addressed in each respective chapter. In this chapter however, I attempt to contextualise the methodological perspective underpinning this work, and to describe the specific methods in as much detail as possible. I also partially address the limitations of the approaches I used, while further post-hoc reflections can be found in Chapter 10.

This chapter is structured in five sections. The first section describes where this research took place, how it was funded and how that impacted the methodology, and how I perceive it empirically and practically. Before diving into our approach to probe design, I first provide some additional methodological context regarding the prior methodological art around DMI design research. In the third section, I describe how I have regarded the artefacts in this thesis as probes, and how these probes fit into a higher-level perspective on the direction of research. This section also addresses why this work has focused on one hour, closed activities. Following this, I describe the process of collecting, processing, coding and thematically interpreting data. I describe how themes were pursed from both top-down and bottom-up angles, how vignettes were chosen, and the constraints around how themes are presented. Finally, I offer a reflexive account of the potential biases, harms and ethical issues arising from this research.

3.1 FRAMING THIS RESEARCH

This work was conducted in the Augmented Instruments Lab (AIL)[1], part of the Centre for Digital Music[2], in the School of Electronic Engineering & Computer Science, at Queen Mary University of London, between 2016 and 2020. I was funded by a PhD scholarship through the Media Arts and Technologies (MAT)[3] Centre for Doctoral Training (CDT)[4], itself funded by the Engineering and Physical Sciences Research Council (EPSRC)[5].

The AIL doesn't prescribe what augmentation means to each individual PhD researcher, but the most straightforward interpretation refers to augmenting existing musical practices while preserving musical skill instead of rendering it obsolete, as the lab's founder did with the Magnetic Resonator Piano [196]. In this work I most strongly identified with augmentation in Engelbart's sense of expanding human capabilities to collaboratively address ever more complex scenarios [74]. MAT research is applied research, seeking applications of technologies with a high Technology Readiness Level (TRL) to what the UK Government refers to as the Digital and Creative Economies.

This PhD was funded by EPSRC and thus examined from a STEM perspective, and although part of the EPSRC remit overlaps with humanities research, this was often a source of tension for me, and probably for other MAT students too. In my experience, many MAT PhDs find themselves pushing against the limits of what counts as EPSRC-fundable research. This is one of the main reasons why my work uses heritage craft practices as a base, since they are so historically intertwined with democratic socialism and other socially progressive humanist movements before that [176]. Hopefully, my contributions in this thesis lay foundations of the sort that will help other researchers in similar situations, seeking a well-grounded humanistic perspective for technical research.

Practice-based PhD students from other institutions have joked about our PhD programme that we do two PhDs: one practice-based and one written or theoretical. The practice in question in my case, which will be explored in this chapter, encompassed designing and building probes, designing activities, working with participants, and thematically analysing outcomes. However, it was not a requirement for the artifacts of the practice to serve a function outside of enabling the "empirical" work to take place. This issue is well remarked upon in design research corners of HCI [130] with research through design (RtD) arguing that intellectual outputs are not limited to written words,

1 https://instrumentslab.org
2 https://c4dm.eecs.qmul.ac.uk/
3 https://mat.qmul.ac.uk/
4 https://en.wikipedia.org/wiki/Doctoral_Training_Centre
5 https://epsrc.ukri.org/about/

but in some cases other forms of contribution ought to be considered as equally important.

Given a binary choice, this work is quite clearly qualitative humanities research and not quantitative human factors research. Nevertheless, the goal was to create a foundation for quantitative research to take place in the future. This has included prototyping possible quantitative approaches, and evaluating them qualitatively. I could have conducted quantitative research on much narrower questions, but in many ways that would have been less interesting work. It will be up to future researchers to see if this work can inspire more quantitative approaches.

Finally, referring back to the epigraph of this chapter, rather than incrementing from the present, in this thesis I tried to do inventive applied research, in the spirit of Alan Kay and Bret Victor, based on a perspective about the future similar to theirs. That is, being "radically pessimistic" about humanity's present reality and trajectory, while being "desperately optimistic" about our course-correcting potential [15]. Our current computing and digital technologies are destroying the environment, culture and democratic society, but technologists can still do something about this, if they focus on humane and ethical principles, and long-time perspectives. One of the best ways to do this, they argue, is to become aware of and then escape from the present and incrementalism as contexts for humanist invention.

3.2 methodological context

At the outset of this research, I felt like there was little in the way of precedent within DMI design research that pointed towards specific tools, methods or approaches. Because of this, there was a lot that seemed to need inventing before the research could properly begin. As discussed at the beginning of Chapter 1, a large percentage of DMI design researchers are music technologists who study musical behaviour, and not design technologists who study design behaviour, and the methods commonly used in the field reflect this. There were no frameworks that focused on or adequately acknowledged subtle and detailed DMI design, and there were no domain-specific ontologies or protocols for analysing DMI design processes (of any scale). For example, while there are many studies involving Pure Data and Max/MSP, and a great number of DMI design researchers have been using and teaching these platforms for decades, there are no common qualitative or quantitative methods in the field for analysing their use. This means that every study involving interpretation of the use of these tools needs to invent its own research methods and tools to support them, but at the same time other researchers do not benefit from any such tools.

While there were a lot of examples of technology probes in DMI design research, these were mostly applied to musical rather than design scenarios (for example see [124, 125]). The reportage in such research papers was centred more around the probe design and build process and less on the activity or context design (we touched on this in Section 2.1.4), which turned out to be equally important in our investigations. In the end this translated into a skills gap on my part for context and activity design with probes, which took significant time to address, and could perhaps have been more integrated with the study design process from the beginning.

We were also unable to find existing 'digital materials' that were open-ended enough to become satisfyingly hand-craftable, which meant we had to implement our own. Finally, there was no integration between scientific (i.e. JupyterLab[6]) and embedded (i.e. Bela[7]) computing environments for DMI design research, which was a significant source of frustration. Even transferring simple pieces of stored data between them in an 'offline' scenario was cumbersome to begin with. Taking a bootstrapping approach [14, 74] resulted in the same hybridised scientific-embedded environment being used for the apparatus and the analysis of its usage, which was economically crucial for this research. In fact, the same arguments I will later make about the needs of DMI designers in Section 10.2.1 applied equally to my own research practice.

3.3 DMI DESIGN PROBES AND ACTIVITIES

The artefacts in this thesis' practical investigations — DMIs, DMI design tools and toolkits, and supplementary design materials — we identify collectively as *probes*. The specifics of each probe are described and reflected on in each chapter, and here I attempt to describe the common approach. Gaver et al. describe *cultural probes*, objects which are deployed within communities to "provoke inspirational responses" that can give insight into complex lived experiences [89]. Hutchinson describes *technology probes* as enabling researchers to understand people's needs, field-test designs, and stimulate new ideas [119]. Probes in DMI design research have enabled the investigation of creative constraints [101, 168, 195], the role of instruments in disability and access [106], tangibility and richness of DMIs [124], and much else. I will first describe the methodological framing and role of probes in this thesis, then subsequently return to the literature cited above to provide further contextualisation.

Taking the research framing given in Section 3.1 into account, the probes in this thesis are to some degree responding to the following

6 https://jupyter.org
7 https://bela.io

brief: in a world where projects like Dynamicland[8] have succeeded, what could lutherie look like? I tried to invent things that could exist in this future landscape, and to me the optimistic part is that it could look very similar to traditional handcraft (Section 2.2.3). Contextually, this is an important lens through which to view this research, not least because it is also one of the lenses through which I approached and evaluated it.

A second high-level methodological lens through which to view this research is represented by Figure 3.1. This illustration breaks down the main research question (Section 1.2) into stages - observation, description, comparison and sharing - and pairs these with stages of the probe-based methodological process, which can be elaborated further thus:

1. Probes constrain practice and facilitate observation;
2. Observations reveal design processes enabling their description;
3. These descriptions are comparable because of their shared constraints (where in-the-wild data is *not*);
4. Models of subtle and detailed DMI design can then be proposed, and finally;
5. These models can be tested through the design of new probes, taking us back to the first step.

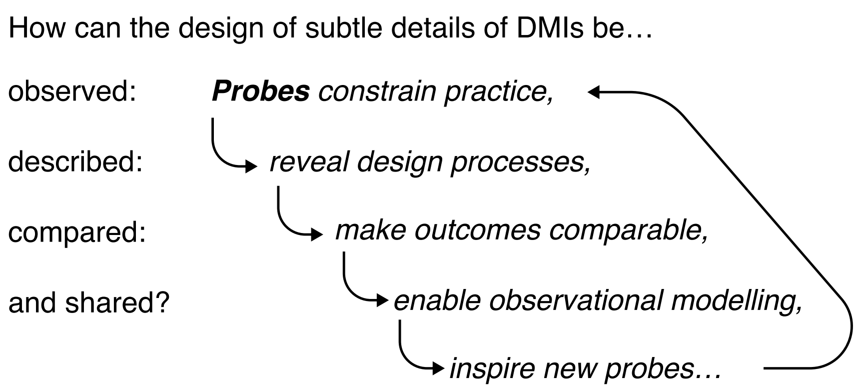


Figure 3.1: The methodological feedback loop (Section 3.3) underpinning the investigation of the main research question (QM, see Section 1.2).

Unlike in Gaver and Hutchinson's definition of cultural and technological probes, in this thesis the probes were not used in open, in-the-wild [261] or longitudinal contexts. Instead, in this research the activities took place in closed laboratory contexts over short time periods of one hour. First of all, we do not see open, in-the-wild, longitudinal contexts as either superior or inferior to closed ones. They

8 https://dynamicland.org

both have pros and cons and are as such complimentary. Yet, closed methods for studying subtle and detailed DMI design do not exist, to the detriment of open methods and to the field in general. It has been our objective to develop and share such closed methods and show how they can work, so that future researchers can choose to mix open and closed methods.

Here we elaborate further on the reasons underpinning our decision to work in closed contexts. In Section 2.3.2, we noted that research about micro scale DMI design exists, but only in the form of ethnographic accounts of subjective practices regarding isolated instruments and design processes. This methodology means detailed comparisons are not possible, and therefore no progress can be made with properly defining and studying micro scale DMI design processes, which is the aim of this thesis. Referring back to Figure 3.1, we identify making outcomes of DMI design processes comparable as essential to this work. This is achieved by designing probes that produce design process data, preferably discretised into design moves (Section 2.1.4), which is amenable to thematic interpretation and analysis (Section 3.4).

The second reason for preferring refers to the framing given in Section 3.1. Probes 'in-the-wild' necessarily imply probes existing in the *present*, and as discussed in Section 3.1, we were deliberately aiming to escape the present in this work. A closed context is nevertheless a context, and so the probes in this thesis are about creating contexts where subtle and detailed design are the focus, and future lutherie practice can take place in the present. The probes in this thesis are almost completely useless in the present, and deliberately so, unless viewed from this perspective. I argue they are still probes though, because they are physically manifested slices of possible future practices, and that imagined practice itself constitutes a 'wild'. They are also literally probes; physical investigatory objects.

A key distinction related to this issue, is that in this work we are not interested in our probes as technical tools created as "solutions" to any particular problem, and we are not investigating their efficacy or lack thereof. Rather, the reader might consider them as inspirations or provocations. Conceptually this resonates with a probe-based methodology, even if Gaver or Hutchinson might not strictly consider our work an implementation of their specific probe methods. In short: even if the method isn't the same, the methodology is similar in that they inherit from similar values.

Why did we not only choose to avoid longitudinal studies, but go to the extreme of constraining our activities to one hour duration? In the end, we envisage for DMI design research a spectrum of methods appropriate to specific timescales from longitudinal to brief episodes, and we have planted our flag at the one hour mark to contrast with existing research which tends to span weeks and months, if not years. Shorter closed research activities are much more scalable than longer ones, which is significant when not all researchers have the funding and facilities to pursue longer activities broken up over longer time periods. Methods that enable shorter activities therefore enable more researchers from more diverse backgrounds to work on certain questions. This scalability means that activities are easier to reproduce, and larger numbers of participants can take part in research, which increases reproducibility and the significance of comparing across the outcomes.

One hour felt like a good challenge for this research, because in the end we wanted to be able to say that if this type of research can be done in one hour, that means it can be done in more than one hour if beneficial, and it can also possibly be done in less than one hour. We do not imply that one hour is better or worse than 30 minutes or two hours - that choice would depend on the question being asked. In design studies which we referred to in Section 2.1.4, it is sometimes common to hold one hour activities but then only study 5-10 minutes of that activity in detail, or even shorter episodes or chains of design moves. To truly understand subtle and detailed DMI design, this level of granularity will also be necessary.

Equally, there are aspects of researching subtle and detailed DMI design processes, that could only be approached through longitudinal investigation. Unfortunately however, the longer a study goes on, the less comparable the outcomes are across participants, as practitioners goals and techniques naturally diverge. This is especially the case when considering the "future lutherie practice" brief that inspired this research (Section 3.1). Again, we propose that our methods could in future address this scenario, where a longitudinal study could be punctuated with specially designed shorter, closed activities.

In all of the investigations of this thesis, I was present with the participant(s) throughout. Firstly, this enabled me to ensure the correct functioning and smooth operation of the DMI design probes throughout. This was especially necessary in Chapter 8, where the probes were fairly complicated to operate, and quickly onboarding participants required a hands-on guided demonstration. Being present also allowed me to ask questions during the sessions which would not be possible to ask afterwards, and to observe the proceedings first hand which would later feed into thematic interpretation. I believe the proximity I had to the DMI design process as a result of this approach was necessary for thorough qualitative evaluation to occur. There are downsides to this approach, as my presence certainly will have influenced the proceedings. Once the themes of this research have been more thoroughly studied, it will probably no longer be necessary for in-person researcher observation to take place.

In some of the chapters in this thesis we refer to pilot studies taking place to aid in the final stages of probe and activity design. What we mean when we say pilot studies, is that a casual or informal version of the activity has taken place, usually with a colleague standing in as a participant. The main goals of this type of pilot study are to identify technical issues with the probes, briefs, scripts and environment. In addition, the goal is to train myself as a researcher to gain practical fluidity with all aspects of the study, in order to execute the activity as consistently as possible. Where pilot study outcomes were influential on fine tuning decisions, this is described in the specific chapter.

Finally, we do not suggest that we are DMI design probe design experts. As described in Section 3.2, the majority of the methods and tools used in this work to do the research, were being invented and/or used for the first time. As such, we will not attempt to provide a generalised notion of probe design here, instead we point the reader to each individual investigation chapter to see how the particular issues at hand fed into the probe designs. Naturally, there is plenty of room for reflection and improvement, which can also be found within each chapter, as well as in Section 3.5 and also in Chapter 10.

3.4 INTERPRETING AND THEMATISING OUTCOMES

While quantitative data from study probes was captured in some of the investigations that follow, thematic interpretation of session videos and structured interviews with study participants, account for the majority of the data analysis in this thesis. Thematic analysis is a process where researchers immerse themselves in data, developing and applying coding protocols, some of which are deductive or top-down, and some of which are inductive or bottom-up readings [32, 55]. Labelling and then iteratively re-labelling data based on spending considerable time reviewing it, eventually leads to convergence between expected and emergent themes. Throughout this process, the researcher is journaling their decisions and in-situ reflections, which subsequently enable reflection at a higher level. Where relevant, thematic codings are reproduced and reflected on. In this section I attempt to describe how this process was for me, addressing data collection and processing, thematic coding, top-down versus bottom-up themes, and validation and presentation of themes.

In this thesis, the entirety of the coding and thematic analysis was carried out by myself alone. The data I coded included data from pre-activity surveys, activity audio and video, data logged from probes (which included software logs and hardware sensor logs), and post-activity surveys and interviews. Generally, audio transcription was performed via automated means and then manually corrected, and it has to be said that the accuracy of the automated part changed considerably in the years between 2016 and 2020. Initially I was using the YouTube algorithm, which in 2016 was sometimes wildly inaccurate depending on the speaker's accent and the audio quality. By

2020 I was using commercial services like Otter[9], which were far more affordable, and generally more powerful and accurate than they were in 2016, but still required manual correction, especially for domain specific terms like "lutherie".

Practically speaking, the exact techniques of coding evolved across the studies, but the general approach stayed the same. Initially I trialled commercial textual data analysis software like MaxQDA[10], and by the end I was still experimenting with software, trialling Roam Research[11]. No matter what I tried, I didn't find the technical part of this process to be satisfying at any point, and I'm sure there will be better tools for this job created in future. The general approach I took was to tag or annotate the data based on top-down and bottom-up schemas, and then re-organise and review the data based on the different tags, to experience these tags as perspectives and see if they really made sense to both myself and my supervisor. In contrast to the coding tools, I did find that the evolution of probe data did positively impact the coding and thematic analysis process. The sophistication of probe data and what I was able to do with it increased as the investigations went on, and this influenced not only the top-down thematic analysis, but the bottom-up and emergent themes as well, since it became easier to ask more questions about the data. In the final study (Chapter 8), I was able to accurately synchronise probe data with audiovisual material, and play back both at the same time using custom designed web interfaces (Section 3.2). This also made it possible to query video based on probe data, automatically segment session datasets based on design moves (Section 2.1.4), and query across participants to establish detailed comparisons.

For each investigation, the process of coding would begin before any sessions with participants had been carried out. First, I would devise a top-down or deductive coding schema based on a number of factors: the study research questions, the backgrounds of the participants, the DMI design data produced by the probes and activity environment, the post-activity structured interview questions, and the expected outcomes. I would then discuss this top-down schema with my supervisor to determine whether these elements all aligned together, and whether we could be reasonably confident about producing intellectually viable interpretations. There would always be an element of uncertainty before carrying out an activity, and if this was deemed to be too high, the viability of the themes could be factored into pilot studies (Section 3.3). The top-down themes were not completely rigid and could be iterated on; they did not change dramatically but were sometimes refined and articulated more precisely.

Since this research was so qualitative and exploratory, it was never expected that top-down themes would capture all of the interesting

9 https://otter.ai
10 https://www.maxqda.com/
11 https://roamresearch.com/

aspects of what transpired. Capturing the interestingness of everything else felt like a more creative and engaged endevour to me, which the literature on thematic analysis also identifies [32]. In that sense, it is almost a much harder process to describe. Practically, I would begin this process by tagging and annotating low-level data in a freehand way, without thinking too hard, based on whatever I found to be interesting that wasn't already being captured by the top-down themes. Later, when these miscellaneous tags had accumulated, I would survey them to see if there were commonalities among them, and then I would try to describe these in writing and verbally, giving specific examples as evidence, and presenting these during supervision sessions. To my mind there is no exact way to describe why certain themes happen to emerge - that is why I describe them as emergent. In general, the most valuable emergement themes somehow capture the most interesting aspects of the data, in the most clearly evidenced, convincing and concisely articulated way.

In terms of validation, as I have mentioned, weekly supervisor meetings were the main structure around which repeated examinings and reflections on the codes and themes took place. In most cases the most valuable ingredient for improving a thematic analysis appeared to be time, especially if time permitted another complete pass of the data, which it often did not. Cross-validating themes with other researchers would of course have been interesting though complex to try, but it was not possible or feasible within the context of my research programme (Section 3.1). Apart from Chapters 8 & 9, the work in this thesis was also validated internally via yearly stage reviews (Section 3.1), and externally through peer review (see the front matter of this thesis for a list of publications).

Among the constraints pertaining to thematic analysis, it should be noted that one of the main constraints regarded the presentation of themes to the would-be reader. To my mind, one of the reasons thematic analysis exists is that we live in an imperfect world where it is not possible for researchers to experience each others' data first hand in full resolution. If we did, most of thematic analysis would not be necessary. Instead, we are forced to compress our experiences and insights as researchers into themes, and compress the themes into vignettes, and present those vigenettes in static, mostly textual media forms, stuck inside PDFs, which themselves often have harsh page limits. In Chapter 8 I take the liberty of using as much space as possible to convey the DMI design sessions. In short then, the criteria for choosing vignettes was usually based on the page limit at hand, and otherwise this was simply about selecting the evidence that best encapsulated the proposed observational insight.

3.5 REFLEXIVITY

In Section 1.1, I shared historical and biographical details to help contextualise the motivations for this work. The definitions offered in Section 2.1 attempted to situate my position further still, and throughout this chapter I have elaborated further on my personal role in the research at all stages. I thus far have acknowledged these aspects mostly from an intellectual standpoint, but they are of course also entangled with the sociological, cultural and political contexts I have been exposed to during my life. Further, the opportunities that have led to this thesis being possible, in no small part result from privileges - class, gender and much else. For every benefit that these contexts and privileges have offered to me as a researcher, I regard them also as potentially harmful - to myself, my research participants, the research community, and society at large - in the way that they naturally lead to biases if accepted uncritically. In the end, every augmentation is an amputation[12].

In my case, I am a white male postgraduate researcher, who worked in a predominantly male engineering department in a European capital city. I acknowledge that there are harmful perspectives and behaviours systemically entrenched into myself and my institution, which will have impacted on my research in ways that I was not aware of, despite the best intentions. Potential avenues of harm touch on every aspect of my research: my research questions (Section 1.2) and framing (Section 3.1), my study designs, my participant cohort selections, and my interpretations of research outcomes (Section 3.4). I strive to become more aware of all causes of harm due to my biases, and am grateful for feedback and recommendations on this subject. In this regard, I am grateful for recent efforts in the NIME community to address gender imbalances [318], highlight women's contributions [255] and discuss women's labour [268], and celebrate contributions towards the discussion of diversity[13]. I also support the development of political [214], ethical[14] and environmental[15] awareness in the research community. In addition, the idiomatic linguistic style of theses produced in a context such as this one was, often exhibit normative framings and statements that are exclusionary towards non-European perspectives. I acknowledge that this research is inseparable from its localised sociocultural setting, and that any generalising claims require further investigation regarding their relevance and value in other cultural settings.

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12 This aphorism is often attributed to Marshall McLuhan, but I couldn't find a reliable citation.

13 https://wonomute.no/assets/downloads/Pamela-Z-Award-for-Innovation-NIME-2019.pdf

14 https://www.nime.org/ethics

15 https://www.nime.org/environment

The NIME ethics guidelines cited above call for researchers to address accessibility and inclusion, environment and socio-economic fairness, animals, and empirical aspects. Though these were introduced after this research was mostly completed, I see no reason not to attempt to address them. Firstly, I am sad to say that no animals were involved in this research. In terms of accessibility, I did not work directly with people who are typically marginalised in this way[16], however I believe my work does relate to accessibility in a few key ways. Throughout Section 2.2, I emphasised the deliterious impact of contemporary computers' focus on visual and symbolic capabilities over all other human capabilities, and how much talent and potential this excludes from DMI design. In combination with the future-leaning perspectives offered in Section 3.1, I optimistically foresee a world where computational handcrafts invite a much broader range of people into digital lutherie, and have attempted to demonstrate how this frontier might be explored in Chapter 7. Additionally, all of the probes in this thesis emphasise the latent expressivity and inclusivity of low cost crafting materials. Regarding inclusion, while I did attempt to balance participant cohorts in terms of gender, I did not achieve this, and this of course weighs negatively on the methodology and outcomes.

Environmental and socio-economic fairness have been considered throughout this work. Primarily, as mentioned in the preceeding paragraph, I have emphasised low cost, non-precious, recyclable materials during probe design. I have also engaged with open source projects as much as possible, and contributed to open source as well[17]

The NIME ethical guidelines raise important empirical issues as well. All of the investigations carried out in this work were subject to my institution's ethical review procedures which included approval of arrangements for gaining informed consent, and maintaining data privacy. Where possible, participants were renumerated for their participation in this research. Economically and practically, it was not possible in this research for participants to take lasting ownership over any of the probes, but given their speculative, largely non-functional designs, this was not an issue. No minors or vulnerable individuals participated in this research. This research did not explicitly feature decolonialising research methods, and in particular the focus on the violin as a canonical example of lutherie in Chapter 4, implies a need for future research to compare across more diverse traditions.

Further reflections on the specific methodologies that I have described in Sections 3.3 & 3.4 of this chapter, and their limitations, can be found throughout the discussion sections of the investigation chapters, and also in Section 10.2.3.

16 Those interested in this subject should explore my lab colleague Jacob Harrison's work on this topic [106].

17 See companion materials at https://jackarmitage.com/phd.

4 SUBTLETY AND DETAIL IN VIOLIN LUTHERIE

His first impression was one of eagerness, as if it were starting to make a sound even before he drew the bow across the strings. And when he did start to play, he said it was as powerful and as responsive as a racehorse, and so loud that is sounded almost like an electric instrument. He already had all the measurements he needed to make a copy, but at that moment he knew there was also an intangible quality to the Kreisler, something almost supernatural that he doubted he could ever capture. Many months later, Melvin gave Nikolaj Znaider the opportunity to try the copy he had made. The fact that Znaider, who had been playing the original Kreisler for years, immediately commissioned another copy for himself tells us all we need to know.

— Helena Attlee, *Lev's Violin: An Italian Adventure* [12]

This chapter is built on material from "The finer the musician, the finer the details: NIMEcraft under the microscope", by Armitage, Morreale, and McPherson, originally published in the proceedings of the International Conference on New Interfaces for Musical Expression, NIME 2017, Copenhagen, Denmark [9]. The violinist interviews featured in this chapter were originally conducted by Fabio Morreale [213].

In Section 2.3, we discussed a variety of issues in DMI design as observed through a microscope trained on its own literature. An alternative, telescopic approach to these issues is to compare the intangible aspects of digital lutherie [136], with those of established instrument making cultures, of which there are many to choose from. These cultures are models and precedents of practice-led craft culture that the DMI design community can turn to, to explore the personal, subjective, embodied and tacit aspects of craft practice. In this case, we turned to perhaps one of the most cogitated and enigmatic of these traditions, in violin lutherie. The anecdote in the epigraph above epitomises the legendary cultural status of violins and their luthiers, and the litany of such accounts affords digital lutherie ample and diverse entry points for critical self-reflection. Although violin lutherie is not equivalent to digital lutherie, there are relevant parallels, such as the existence of scientific knowledge in the community, and the practical application of guidelines and frameworks through tacit knowledge. There are also a great many examples of the two cultures cross-pollinating through hybridised and augmented violin making practices. Using traditional lutherie as a model, we conducted a series of interviews to explore how violin makers "go beyond the obvious", and how violinists perceive and describe subtle details of instrumental quality.[1]

4.1 INTRODUCTION

4.1.1 *Related research*

The violin has been the subject of interdisciplinary scientific research for centuries [93, 115, 116], and the obsession continues, abounding forward to this day. Theories of the acoustics of violins continue to accrue, with the cultural fixation consistently attracting advanced contemporary analytical methods [27, 317]. Hotly debated with equal fervour are the origin stories of specific violins as evidenced by their dendrochronology [289], and the historical inferencing of luthiers' geometrical techniques, previously deemed lost to history [323]. Disputes about the perceived quality of so-called golden age violins versus newly made ones also continues afoot, through blind studies with expert violinists [86], and the exploration of quantitative [266] and psycholinguistic [265] techniques for analysing their responses. The digital lutherie community has also been technologically reconstituting and reinterpreting the violin for decades, with recent examples contributing novel timbral spaces [232], and complexity management affordances for violin pedagogy [237].

And yet, despite this frenzy of curiosity and deliberation, one of the luthiers interviewed in this study quipped adamantly that "the violin is the most researched object in the world, about which we still have no idea". Is there an argument to be made that, similarly to digital lutherie, the tacit knowledge of practicing violin luthiers is understudied? Literature covering the issues described above is readily available, but detailed accounts of violin lutherie practice, such as those which might suit this thesis by focusing on the embodied craft of subtle details, are harder to come by. A prime example of what this might look like can be found in the anthropological works of Marchand, whose accounts of minaret building in Yemen [184], masonry in Djenné [183], and woodwork in Britain [181], are substantiated by the author's own apprenticeship into the cultures he seeks to expound on. The contributory embodied expertise (Section 2.2.1) that Marchand invests in, and his cross-disciplinary approach which incorporates embodied cognition, lends him a uniquely intimate vista from which to address his subject, one which would be ideal for the present aim.

While the scope of this chapter's investigation pales in comparison to Marchand's extraordinary multi-year efforts, it did seek to reorient the spotlight of attention from its usual focus on the violin, to highlight the practice of the violin luthier. Where in Section 2.2.4 we looked to Kettley's principles of craft practice [153] for inspiration in addressing

1 See Section 1.1 for more background context about this study.

subtle details in digital lutherie, here we looked to violin lutherie practitioners for their accounts of craft principles in action.

4.1.2 *Research questions and scope*

This study addresses Research Question 2:

What can the DMI design community learn from violin luthiers about the design of subtle details?

The study addresses this question by conducting interviews with violin luthiers about their practices. In particular this study addresses the following sub-questions of Q2 through the interview questions:

a. How do violin luthiers discuss subtlety and detail in violin making?

b. How do they learn to achieve subtlety and detail?

c. What impact do scientific and engineering tools have on their practice?

THE NEXT SECTION of this chapter describes the study methodology and interview topics. The chapter then presents findings from the structured interviews with luthiers and violinists exploring issues of craft in that instrumental domain. The discussion highlights opportunities and challenges for the DMI research community in sharing digital lutherie craft knowledge, which may not easily fit the parameters of typical publications. To conclude, the research questions are returned to and the outcomes and discussion are reviewed in terms of the overall thesis.

4.2 METHODOLOGY

4.2.1 *Participants*

In the first set of interviews, I interviewed six luthiers about a range of topics in violin making, which included their use of guidelines, comparison, measurement and analysis at various stages of the instrument creation process. In the second set of interviews, players were interviewed by Fabio Morreale in relation to a study on sensorimotor disruption [213], after playing four different violins, where one was known to be of lesser quality. The luthier interviews involved six luthiers who exhibited a range of experience. Half were either undergoing or had recently completed vocational training in lutherie (*L1, L5, L6*), and the other half had >25 years of experience as professional luthiers (*L2, L3, L4*). The player interviews involved seven professional violinists. In this instance, professional was taken to mean someone who had developed their playing over greater than ten years, and had significant experience participating in orchestras and ensembles.

4.2.2 *Interview and analysis method*

In the luthier study, the luthiers were interviewed in their workshop (2/6), at the author's laboratory (1/6) and remotely via video call (3/6). In each case they were asked to bring or have available an instrument in progress, or an instrument they had made already. The interviews were based on but not constrained to a script, and covered their development as luthiers, an instrument they were working on, and their methods in the context of realising the fine details of violins (see Appendix B).

The violin players were invited to the author's laboratory for interview, and brought with them their personal violin and bow. A week prior to visiting, they were given a short piece of music to learn. Before the interview, they were filmed playing three pieces on their personal violin and a provided factory-made violin. The first piece was from their repertoire, the second was the piece they had learned recently, and a new piece of music was also presented to them on the day. After playing, they were asked about their musical background, their relationship with their personal violin and bow, and to compare their playing experiences.

Both studies were thematically analysed deductively [32]. The luthier interviews were coded for references to the quality of violin function, behaviour and structure, descriptive clarity and valence (positive or negative), formalised knowledge (theoretical knowledge, explicit knowledge and analytical thinking) and practice-based knowledge (craft, implicit knowledge and design thinking). The player interviews were coded for which violin was being referred to, along with the same quality and description codes as the luthier study.

4.3 OUTCOMES

4.3.1 *Frameworks and goals as foundations*

An example of a lutherie framework is the architecture and geometry of violin body templating, which along with other foundations distill centuries of accumulated experience and set the overall constraints of making. The luthiers describe these guides and prescriptions as offering safety from failure:

L4: *This craft, in planning, in design, in making, it's all very safe. You cannot fail if you have a good guide. That's why the apprenticeship works so well, because you cannot fail if you do what you are told.*

L1: *You're working in the knowledge that whatever you do, within boundaries, it's going to sound good.*

Devising frameworks this specific is a difficult task that requires years of experience, especially in the numerical or parametric domain, due to the complexity of the violin:

L1: *Let's say I made these two violins and the elevation of this [pointing to violin 1] came up to 27mm on this and 25mm on this [violin 2]. Let's say this one sounded way better, or I preferred the sound of this one, then you could think 'Ok well, 25mm is obviously the thing to do. I'm going to make all instruments 25mm from now on.' But then you'll make another one identical, or what you think is identical, and have it 25mm and it won't sound as good.*

While frameworks insure luthiers against failure, goals are also necessary to drive them towards fine quality. The luthiers appear to deliberately set non-specific goals, due to the difficulty of setting out to fulfill criteria:

L3: *The goal is always the same, it's always a great instrument. Of course we could say we want something a bit brighter, a bit darker, a bit deeper, a bit rounder, but that is secondary.*

L1: *It's quite hard to start making an instrument with that goal, to say 'I'm going to make an instrument that's really easy to play'.*

Once the foundation and goal are in place and an appropriate plan has been made, the formal decision-making process comes to an end and the making begins.

4.3.2 *Tacit knowledge enables detailed craft*

Before luthiers can make fine instruments, they must spend substantial time acquiring the necessary tacit knowledge and crafting expertise:

L4: *Forget about knowing how to make a violin when you get out of school. You have to spend ten years before you can make a violin without asking for help.*

L3: *For five years at school, you learn to control your hands and you learn to see. You're given some tools and materials and you have to learn to see what's a bump, what's a curve, what's a bump within a curve. If I tell you remove this 1/10mm here that's what you need to do... Once you've done that, your eye starts to perceive things, and that's very difficult to define.*

There were similarities in the luthiers' descriptions of this process to practising a musical instrument, where repetition and flow are important factors for internalising the making process. As the luthier currently studying described:

L1: *For me it's like practising music. There's a lot of it that's quite like scales where you just have to put the work in. It's a weird sensation where you're switching off while being so concentrated and focused. Your brain starts to wander elsewhere but you're still focusing. It's similar to practising the same passage again and again.*

Frameworks are important for luthiers in training during this acquisition stage, since they are yet to gather the empirical experience necessary to feel their way through the process:

L1: *I have no idea if [a given violin will] sound better. I'm judging it purely on the fact that I was given a set of measurements to follow.*

Whereas the practical aspect of craft is transferable through tools and frameworks, the tacit knowledge required to apply them appropriately is not. This impacts their ability to progress throughout their careers:

L3: *I was in a school recently and looking at the students' work and trying to comment and help them to see, and they just can't see and they wont be able to unless they learn. There's no way to transmit this knowledge, to convey, to give, to communicate this knowledge. Even at my level when I've got a colleague that sees something on my work and tells me to look at something, if I can't see it they can't help me. They will never see anything until their brain is ready to get this knowledge.*

When asked to describe what it feels like to be in the moment of making, one luthier noted the limited capacity of deliberate, logical thinking versus embodied thinking:

L3: *Your hands are guided by your brain, but your brain is not clever enough to guide you through all those parameters, so it has to be subconscious. Your attention is fully in this automatic system, which is kind of the opposite of attention. To concentrate on something semi-automatic doesn't make sense. Somehow you need to get into the right frame of mind that allows your body to act.*

The same luthier was then asked whether they use any formal analysis techniques during the making process, answering that this approach cannot adequately guide their decision-making process:

L3: *I can't stand in front of thousands of doors knowing that if I open a door it might be the wrong one. That might stop me from going ahead. So I have to assume that I know something, or decide that I know something, decide that I might be wrong but I'm going in this direction. I'm relying on my feeling, what I feel when I make.*

4.3.3 *Tacit knowledge needs open comparative tools*

When asked about the influence of scientific forms of knowledge on their work, the luthiers described attempts to internalise them with varying results. The experienced luthiers had a desire to learn more, but described a lack of specific language that could be related to their making experiences:

L3: *I am still looking for a few keys that will help me understand how the box is vibrating.*

L2: *For people in my situation who had been studying making from a traditional point of view, there was no dialogue that people could use to explain certain phenomena about the behaviour of vibrating instruments.*

For example, all the experienced luthiers mentioned that visualisation had an impact on their understanding of their work, but that it was difficult to turn this knowledge into practical applications:

L3: *That's been very useful for me as a maker, to understand that every bit of the instrument is moving differently according to the frequency that is being played, and to understand the connection between the front and the ribs and the back. Being able to visualise it, having a slow movement, that was very useful for me.*

L4: *I like those graphs, they're full of colours! I just love it. It just doesn't basically say where to cut! They don't supply any instructions. That's my problem. I know many people in this branch of violin making; I ask them direct questions and they never answer, because they don't know. They speculate 'Why does this violin sound bad and this one good?' and they compare those two graphs and they are almost identical. But how to move this [acoustic] peak here, and this peak here [indicating two points on a violin plate]? I guarantee you they have no idea, because they're doing it the wrong way - measuring with computers. The computer is as clever as the guy who programmed it, unfortunately. We rely on our hands.*

The theme of frameworks as reassuring influences reemerged, but again in this context with limited actionable consequences:

L3: *I have colleagues that are quite into scientific approaches, which I think is a good way to reassure them. I'm afraid I haven't seen anything convincing in the serious research that's been going for 20 years apart from the visualising tool. The rest hasn't been very useful.*

One luthier had sustained an interest in using acoustic theory in their making. They reflected that familiarisation with it had integrated with their tacit knowledge, suggesting there are traceable links between them:

L2: *Some of us are struggling with just understanding the theory behind it, but actually coming to a point now where, for an instrument maker, it might not be necessary to understand totally the theory.*

L2: *It kind of remains tacit empirical ways of working. What seems to happen is that when your understanding of the physical behaviour of the thing increases, it doesn't necessarily mean for example that I am capable of describing very very accurately what is going on. But it's changing my total view of the way an instrument behaves, sort of through the back door, in a way.*

However, they found this relationship difficult to describe when asked to elaborate, despite their confidence of its impact on their work:

L2: *What I'm trying to say is that the knowledge gained through this kind of acoustic work, is not necessarily something I would be able to write very eloquently about. But it influences me a lot, and I know for a fact that is has improved the sound of my instruments.*

4.3.4 *Playing and testing as separate skills*

The luthiers were adamant that players were sensitive to violin quality in a completely different way to them, which made players mostly unsuited to the task of evaluating a violin. Despite undergoing far less training in instrumental practice than players, luthiers are able to test their instruments with simple but precise gestures:

L3: *Playing the cello for me means pulling the bow. I can still test, I have learned to hear. I have learned to define what works and what doesn't work, even with a shitty bow technique. If it works with my bow technique, it will work for the potential customers.*

At the core of this issue seemed to be a distinction between playing and testing instruments:

L4: *Musicians can differentiate. They cannot tell a good instrument if they don't have a good and a bad instrument. Give musicians three instruments, and after twenty minutes they would have no idea which one they played. It's so confusing, it's so demanding, you have to be trained. You have to have big stamina to do this.*

Stamina in the previous quote was referring to the luthiers' ability to test for long periods, and in doing so retaining the feeling of a comparison long after the sensory impression had faded. This was cited as a critical testing skill that was as hard won as any other in their work. There appeared to be a link between their desire to test in detail and their overall goal of fine quality:

L3: *I think you really have to go beyond the obvious 'yeah it's working, it's fine, it's a great cello'. It's never just great; you have to understand what is good and what could be better.*

Luthiers tested their instruments against idealised behaviour, which was claimed to be more particular than what a violinist would look for:

L3: *Some musicians are actually quite good at testing instruments, but they are quite rare because most of them haven't tried enough to know what we need to look for. They need to aim for this absolute, perfect sound.*

Feedback from different players can be ambiguous and fluctuates based on their level of experience:

L1: *'Projection' and 'ease to play' are meaningless words. I could find something easy to play that you would find horrible... The threshold [of quality] changes for everyone as well, based on your playing ability.*

As a result, one of the more experienced luthiers claimed to have gradually become less dependent on musician's feedback:

L3: *I don't rely on the musicians' opinion anymore to adjust my instrument, because most of them are not used to trying instruments. They are used to their own instruments and making them work for their needs. They are not used to playing for an ideal mechanism, an amplifier. They don't know what works with their instrument, they know they love it and they will never use anything else. The point is, when I demonstrate my instrument they have have to be impressed, shocked by the amplifying capacity, the link between string vibration and bow action.*

4.3.5 *Verbal player feedback misses details*

To investigate the limitations of player feedback as described by the luthiers, seven violinists were asked to compare their experience of playing a factory-made violin and bow with their own in quick succession (see [213] for more context about the main study these interviews were conducted for). As expected, all participants preferred their personal violin, citing lower quality aspects of function, behaviour and structure in the factory-made violin. 6/7 players mentioned the factory-made violin's strings as being poorly spaced due to the proportions of the bridge and neck, and connected this to difficulty and discomfort of playing experience:

P3: *What was a bit challenging, or annoying, is that the bridge is less round (flat). So I kept hitting D string while I was playing other strings. I tried to adjust to that, but still. My own violin has more curvature on the string.*

P5: *The string are not as close to each other. It's quite difficult to keep doing what you are used to with your own instrument, but you adapt. It requires more attention and you are more likely to make silly mistakes.*

P7: *I am quite familiar with that, I've played it a lot. They are a nice instrument. If you put a new bridge on that it could sound pretty decent... The bridges they come with are a bit fat and chunky.*

It seems plausible that the above comments could be turned into design changes with minimal interpretation. However, when the quality of the sound and playing experience are mentioned, the essential qualities seemed harder to describe and difficult to relate to physical properties or behaviours of the violin:

P3: *Well it's small sound. And it has the sour sound of new string. The sound I usually have on new strings on my violin. But I don't think these are new strings. So I think it just stays.*

P5: *It's basic. It plays but you can't work around too much. Not color, not feeling. You want an A, you get an A, but that's it.*

There appears to be difficulty in identifying appropriate words to describe these differences; P7 invented a term, *"bowy*, to describe their experience. Generally the interviews demonstrated a verbal pattern of comparisons made in a *goldilocks* form of "W is X Y than Z", where *W* and *Z* were the two violins, *X* a determiner such as *more, less, a bit*, and *Y* a violin feature. Another method of describing the factory-made violin was to use the idea of *"a good violin* (**P1**) as a counterexample, which has some similarities with the way luthiers' tacitly test against *"absolute, perfect sound*. Overall, this suggests a useful but limited contribution of verbal feedback from players.

4.4 DISCUSSION

Violin lutherie shows that frameworks can evolve over centuries, increasing in relevance over time. Frameworks prevent failure, provide guidance and bootstrap education. Where frameworks cannot guide, goals can provide direction when they are open enough to adapt to experience. There is no substitute to first-hand experience for acquiring tacit knowledge, which is not transferable as frameworks and crafting methods are. Tacit knowledge enables navigation of overwhelmingly large design spaces, where logical or analytical reasoning approaches can not. Scientific knowledge and tools can impact tacit knowledge, if they are designed to be open and comparative, since they need to afford subjective, empirical use. Playing and testing are fundamentally separate skills, thus players and designers will evaluate instruments with different outcomes. Whilst players do not have the acute awareness of instrument behaviour that designers do, player feedback can aid design evaluation through expression of preference and indication where possible towards design features. Fundamentally, player feedback is limited by the player's testing skill and the tacit nature of playing experience which is hard to describe.

Ultimately, violin makers do not rely on explicit means of creating or evaluating their work, such as evaluation criteria and player reports. Instead, they rely implicitly on their tacit, embodied abilities and experiences. Though these ways of knowing are often personal, subjective and unverifiable, they enable the realization of fine instruments. Similarly, in DMI design there are no explicitly "inviolable laws" [136], as Jordà states:

> *Digital lutherie should not be considered as a science nor an engineering technology, but as a sort of craftsmanship that sometimes may produce a work of art.*

DMI design frameworks, which are positioned as fundamental to DMI creation, commonly offer DMI designers analytical and descriptive ways of working only (Section 2.1.3). They do not support the craft aspects of DMI design, nor do they describe fine details or how to realise them. In Section 2.3 we defined the micro scale as the subtle and detailed nuances between otherwise identical instruments and their underlying design processes, to highlight this shortcoming, and to discuss how DMI designers as craftspeople can be better supported.

In this section we explore the implications of acknowledging the micro scale for DMI design frameworks, dissemination, crafting tools and evaluation.

4.4.1 *The micro scale in DMI design frameworks*

The outcomes of these interviews indicate that the tacit and embodied knowledge of instrument makers is paramount to the realisation of a fine instrument. The primary implication for DMI frameworks therefore is that they should consider accounting for and supporting the development of these forms of knowledge as described by Kettley [153]. Furthermore, at varied experience levels the violin makers applied frameworks in different ways, demonstrating an opportunity for DMI frameworks to target specific experience levels. In terms of utilising player feedback in design processes, our results show that DMI frameworks could better account for the differences in tacit knowledge between designers and players. For example, user-centric and participatory design processes risk assumptions about design intuition in non-designers [72], and overlook the heightened design intuition in designers compared to players, as in [18] where designer-centric evaluation is found to be related to technical details only. Frameworks alone can ultimately not support DMI design, and for this reason the field needs to understand how to discuss and disseminate the nonscientific aspects of instruments. Where frameworks are found to be insufficient or inapplicable, it is important to consider whether approaches that do not seek to alter or add new frameworks would be more suitable, as is discussed in the following sections.

4.4.2 *Dissemination of micro scale details in DMI research*

No infrastructure exists today that is exclusively focused on dissemination of micro scale details; fine details of instrument craft are often subjective and thus are declared unsuitable for inclusion in scientific papers, and performances exhibit only the final form of the instrument without reference to its design process. By comparison, violin making is centred around an apprenticeship model with a rigorous focus on acquisition of embodied design expertise, similar in intensity to studying in a music conservatoire. Jorda's teaching framework [137] appears to be a step towards a self-sustaining culture of DMI design practitioners, but there is clearly more to be learned from long-lasting instrument making cultures in this regard. Additionally, the violin makers emphasised the importance of continually exchanging craft practice in person and online. Given that the DMI design community is experienced with facilitating events and online communication, it could strive to develop means to support these vital activities.

4.4.3 *Micro scale digital luthier crafting tools*

Through inquiring as to the influence of scientific tools on violin making, our results suggest that some tools are better than others at supporting instrument craft processes. Particularly, the impact of tools that were created to support scientific or engineering knowledge were downplayed compared to slow motion vibration visualisation, which facilitated subjective interpretation through being relatable to embodied experience. Though many DMIs support embodied interaction by the player, the design tools for creating them take a scientific or engineering mindset that diminishes the role of the *designer's* embodied knowledge. Our results suggest that such engineering tools may be less than ideal for encouraging the development of micro scale design and crafting skills. Thus, we suggest the community should consider creating DMI design tools with the same attitude with which it creates instruments for musicians, by privileging the embodiment of the practitioner.

4.4.4 *Digital luthiers' evaluation of micro scale craft*

For professional violin makers, there appeared to be an indirect relationship between a player's indication of preference and violin structure and behaviour, leading the makers to develop and rely on their own internalised sense of quality. DMI evaluation instead frequently relies on an audience response to a performance, or a player's judgment [18]. Supplementing audience and player interpretations with the subjective evaluation of micro scale details by the DMI designer, and other designers, has the potential to create a more complete, nuanced and constructive instrument evaluation. This would have the added benefit of encouraging DMI designers to deepen their expertise in the evaluation of fine instrument craft.

4.4.5 *Scale-based ontology perspectives*

While looking for similarities across lutheries which can inspire reflection, applying our scale-based ontology of DMI design also highlights the distance between them in this case, which can also be useful. As Section 2.3 underscored, DMI designers are often dealing with macro and meso scale design spaces, which is seldom the case for practices focused on the art of replicating and finessing micro scale details. The violin is already culturally and historically constrained at the macro scale, and violin lutherie takes this for granted, leaving more time and energy for working at the micro scale. While this is also mostly true for the meso scale, there is also some diversity at this level in violin lutherie. On one level, this diversity exists in terms of the technological innovations required to conserve micro scale characteristics in the face of inevitable obsolecences and changes in material and economic circumstances. In our definition of the meso scale, this would refer to the configuration of the instrument. It also exists in terms of the taxonomical diversity of string instruments which some luthiers may choose to specialise in (for example Hardanger fiddles which include sympathetic strings). In our definition, this would refer both to the configuration and mapping of the instrument. It is important to emphasise however that in both instances, but especially in the latter case, these would be considered by luthiers as almost entirely different practices altogether due to the vast expanse of micro scale differences between them. That is to say that the space of micro scale details in violin lutherie, and lutheries of similar vintage, have over time become expansive landscapes requiring a lifetime's commitment to internalising through embodied craft practice. While some DMIs and DMI design tools have stabilised for a number of decades [217], these are still fledgling practices by comparison, and this should give the DMI design community pause for thought. As discussed earlier in this chapter, in Section 4.1.1, we suggest that the body of practical knowledge about micro scale details in violin lutherie, and other instrument making cultures, has a great deal to offer to digital lutherie, that far exceeds the account offered here.

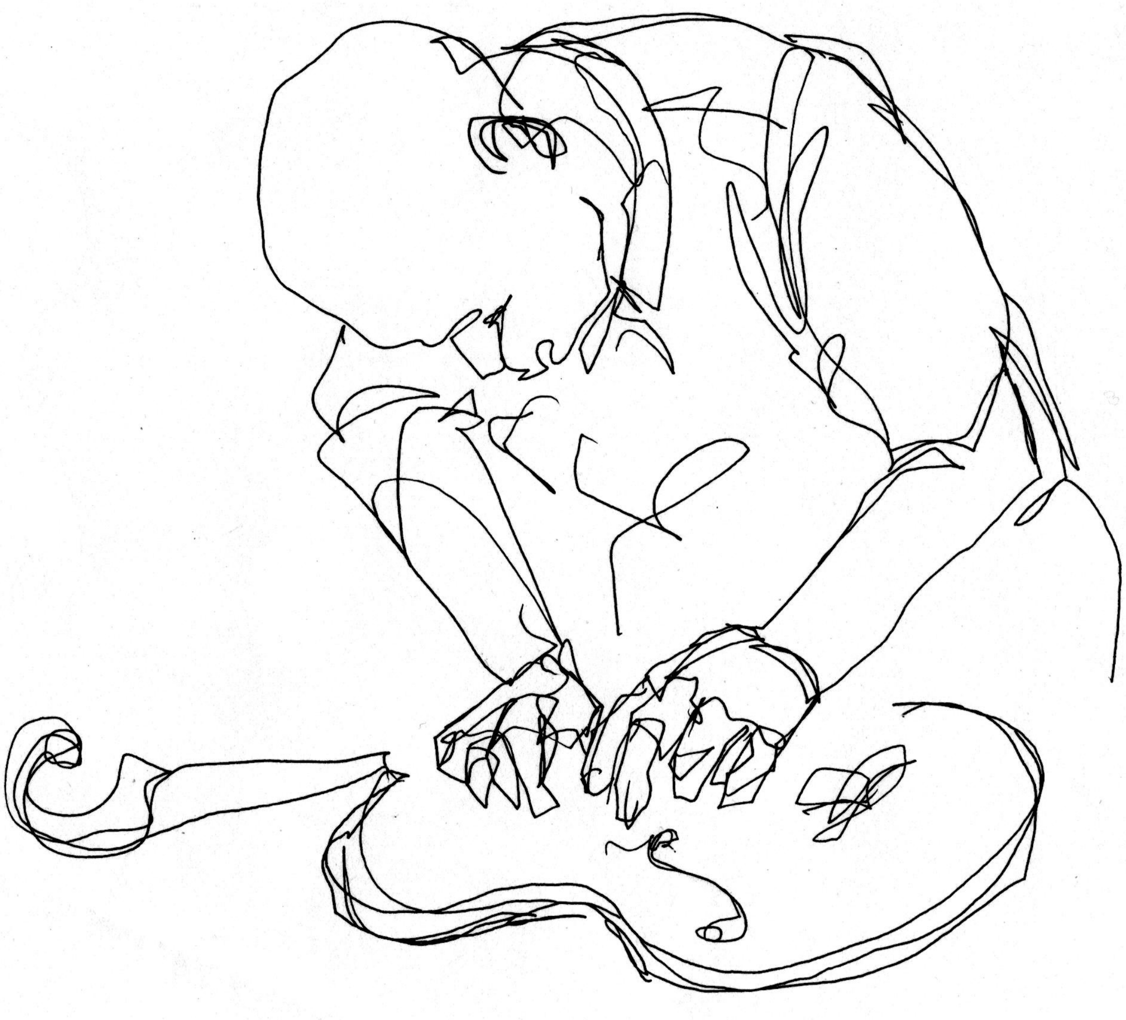
4.5 CONCLUSION

This chapter has presented a brief interview study conducted with violin luthiers, examining subtlety and detail in their practice, to provide a comparative account that can inspire critical reflection for digital lutherie. We have established traditional violin lutherie as a viable model of instrumental craft culture that the digital lutherie research community can learn from to improve its frameworks, dissemination, tools and evaluation. In doing so, we have explored the importance of an instrument designer's tacit and embodied knowledge. The outcomes suggest the need for more investigation in digital lutherie into micro scale differences across otherwise identical instruments and their underlying design processes. By highlighting micro scale details as an important factor in DMI design beyond familiar science and engineering processes, we encourage further discussion about how such skills and methods can be learned and shared.

THE NEXT PART of this thesis covers three practical investigations spanning four chapters. The words and attitudes of the violin luthiers as relayed in this chapter echoed in our minds throughout these investigations, with the outcomes and discussion themes inadvertently becoming our own set of guiding principles for designing DMI probes and scenarios. The next chapter describes the first such instantiation of our practical efforts.

Part II

INVESTIGATIONS



5 MACRO SCALE DMI DESIGN: COMBINING A DMI TOOLKIT WITH A KIT-OF-NO-PARTS

> *Manual sketching has advantages over other modes of fabricating images in the early design ideation phase [...] A certain amount of ambiguity enables greater freedom of interpretation of what the sketch means, and as a result, new information can be read of it and discoveries can be made, sometimes suggesting surprising new ideas. In addition, reasoning and learning involve more than our brains: the body, in this case the hand, helps encode information, and therefore active exploration with kinematic expressions such as sketching and gesturing is helpful, too.*
>
> — Gabriela Goldschmidt,
> *Manual Sketching: Why Is It Still Relevant?* [96]

This chapter is built on material from "Crafting Digital Musical Instruments: An Exploratory Workshop Study", by Armitage and McPherson, originally published in the proceedings of the International Conference on New Interfaces for Musical Expression, NIME 2018, Virginia, US [7]. The NIME workshop that the paper was based on was collaboratively designed and ran by Andrew McPherson, myself, Astrid Bin, Fabio Morreale, Robert Jack and Jacob Harrison [197].

Having defined subtlety and detail in DMI design from our perspective (Chapter 2) and explored related issues comparatively through interviewing violin luthiers (Chapter 4), the next step of our research was to open up the discussion to the NIME community in the form of a workshop [197]. This chapter describes the workshop design and outcomes, in which a room of groups of attendees participated in discussions and a practical activity centred around reflecting on subtle details in DMI design. In the activity, the groups were given a "template" DMI which we named the *Unfinished Instrument*, along with a DMI design toolkit and a wide range of crafting materials with which to explore it. Since this was a community event where we aimed to foster engagement and dialogue, the probes and materials that we provided were open-ended, and the overall atmosphere was not too serious. As this chapter's title and epigraph allude to, we interpreted the outcomes that emerged as being predominantly macro in scale (Section 2.3.4), with high-level sketching of the form and function of DMIs taking place, despite the framing of the event. The resulting instruments were as ambiguous and open to interpretation as the materials that we provided, and in this chapter we reflect on the various reasons for that, and how they impacted our ideas about eliciting subtle and detailed DMI design processes going forward.

5.1 INTRODUCTION

5.1.1 *Related research*

Rosner et al. describe design workshops as social research methods as "interventionist projects" which play multiple roles, operating simultaneously as "field site, research instrument and research account" [264]. Reflecting on their own collaborative sewing workshops, they note "we found that introducing a loosely structured event to an ongoing community of practice exposes the blunt instrument of the design workshop", citing how "members aligned anticipated outcomes in opposition to our guidelines and abandoned projects due to personal obligations". This bluntness connotes an exercise in herding cats, which could indeed defeat the purpose of some workshops, but in other circumstances, embracing these ensuing entanglements could be desirable and beneficial [261, 310]. In the context of NIME, workshops involving practical activities have tended to be purely pedagogical, but more recently the community has embraced the "productive contradictions" of critical making [41, 160, 253, 254]. Given the personal and subjective aspects of craft practice (Section 2.2.4), and the tacit and embodied aspects of attending to subtlety and detail (Section 2.2), a hands-on and open-ended approach seemed necessary for this workshop.

As a workshop is ultimately a thematised context, with fixed temporal and material constraints, there are always limits to how open-ended responses can be. On the other hand, the tools and materials in a practical workshop can potentially mediate too far in the other direction, by not providing enough potential for appropriation [60], and authenticity in crafted responses [154]. Perner-Wilson and Satomi challenge this issue by describing a "kit-of-no-parts", where the low entry bar of modular components with pre-determined purposes common in STEM disciplines, is eschewed in favour of "a diverse palette of craft materials" which emphasise personalisation, transparency and skills transfer [239]. This position has influenced the design of kits for e-textiles and paper electronics [251, 279]. Such kits, they contend, invert the usual paradigm where toolkits "constrain what we build and how we think", and instead promotes "personal expression" through engagement with "aesthetic, decorative and material qualities" rather than "technological concepts" [239]. These benefits can be considered in relation to material ambiguity, which Gaver et al. frame as a highly generative design resource [90]. Similarly, Goldschmidt describes "tolerance to ambiguity, inaccuracy and incompletion" as being advantageous in idea generation, leading to "greater freedom of interpretation" which generates "new information" and "discoveries" [96].

What happens when kits-of-parts are combined with kits-of-no-parts, however, is not a scenario which has been explored in the literature. What might be expected to occur under such circumstances? Would the no-parts take on a decorative role, while the parts dominate structure and function? Or would the no-parts encourage recontextualisation of the parts?

5.1.2 *Research questions and scope*

This workshop was not approached as a study, nor was there necessarily any intention to interpret the outcomes (Section 1.1.2). However, the outcomes diverged enough from our expectations that it was felt that we should try to make sense of them. With this in mind, we formulated research questions to guide our observations and frame our findings. As such, this study addresses Research Question 3:

How does a community of DMI design researchers respond when encouraged towards subtle and detailed design of a gestural DMI via a physical design kit and crafting materials?

In particular, this study addresses the following sub-questions of Q3:

a. How do participants explore in an environment featuring both a kit-based instrument and crafting materials?

b. How do they balance material constraints against their own ideas?

c. What scale of detail do participants spend most of their attention on?

THE NEXT SECTION of this chapter describes the workshop design. Subsequently, an overview of the outcomes are reported, and a thematic analysis based on exploration, gesture, sound and materials is presented and discussed. We conclude by reflecting on their possible consequences for combining instrument design tools and methods.

5.2 WORKSHOP DESIGN

A digital lutherie workshop focusing on craft practice was held during NIME 2017 [197]. It was free and open to anyone registered for NIME, and no submission was required (Appendix C.1). We expected but did not require participants to be digital luthiers, and participants with experience in traditional or acoustic instrument making or non-musical crafts were also welcome. The organisers gave an introduction to the subject area, where they introduced a theme of craft in NIME [9] as a starting point for discussion. We devised a crafting activity that would compliment discussions and reflection about craft in NIME, and how it can be shared in the community. The instruments and probes used in this study are reported in detail in Appendix C.

5.2.1 *The Unfinished Instrument*

The goal of the activity was to facilitate open-ended crafting of a prototype instrument, that could appear to be "unfinished" and subjectively reinterpreted. This process is illustrated in Figures 5.1 and 5.2 and started with appropriating [60] and un-crafting [218] an existing instrument called the AirHarp[1] developed by Chris Heinrichs in C++ using the Bela platform [202], chosen for its flexible synthesis of virtual string sounds using audio-rate sensor inputs. Its physical model excited by an accelerometer was replaced with up to eight low-cost microphone capsules. This offered a high-bandwidth connection between physical behaviour and sonic response, necessary for facilitating gestural interaction using a wide variety of materials.

To provide a contrast to previous workshops and integrate with the crafting materials, we focused on mechanical instead of software and electronic modularity. Simple and repeatable prototypes were developed using the microphone capsules, that would facilitate physical modification via materials available from a craft modelling store. Two gestural interactions were offered as demonstration: a plucking configuration featuring wooden tines clamped across the microphone cavity, and a tapping configuration which allowed different surface materials to be clamped across all the microphones to form a surface.

These two example configurations were then generalised in terms of their physical structure, such that both could be made from the same basic components. Introducing flexibility into the design required trial and error to strike a balance between openness and robustness; for example the microphones had to sit firmly in place but still be movable, and the physical structure featured slots instead of holes where possible to make it adjustable. The final design[2] was presented to participants along with its two pre-explored configurations (pluck and tap).

5.2.2 *Crafting environment*

The room consisted of tables for small groups of 2-5 to sit around facing each other. There was a long table at one side of the room displaying a variety of tools and crafting materials. The organisers presented the opening discussion from a projector at the front and provided technical support around the room.

Materials were selected for their familiarity and tactile and acoustic variety, and included rods of aluminium, brass, wood and plastic,

1 Search AirHarp in http://github.com/bela/belaplatform
2 http://bit.ly/theunfinishedinstrument

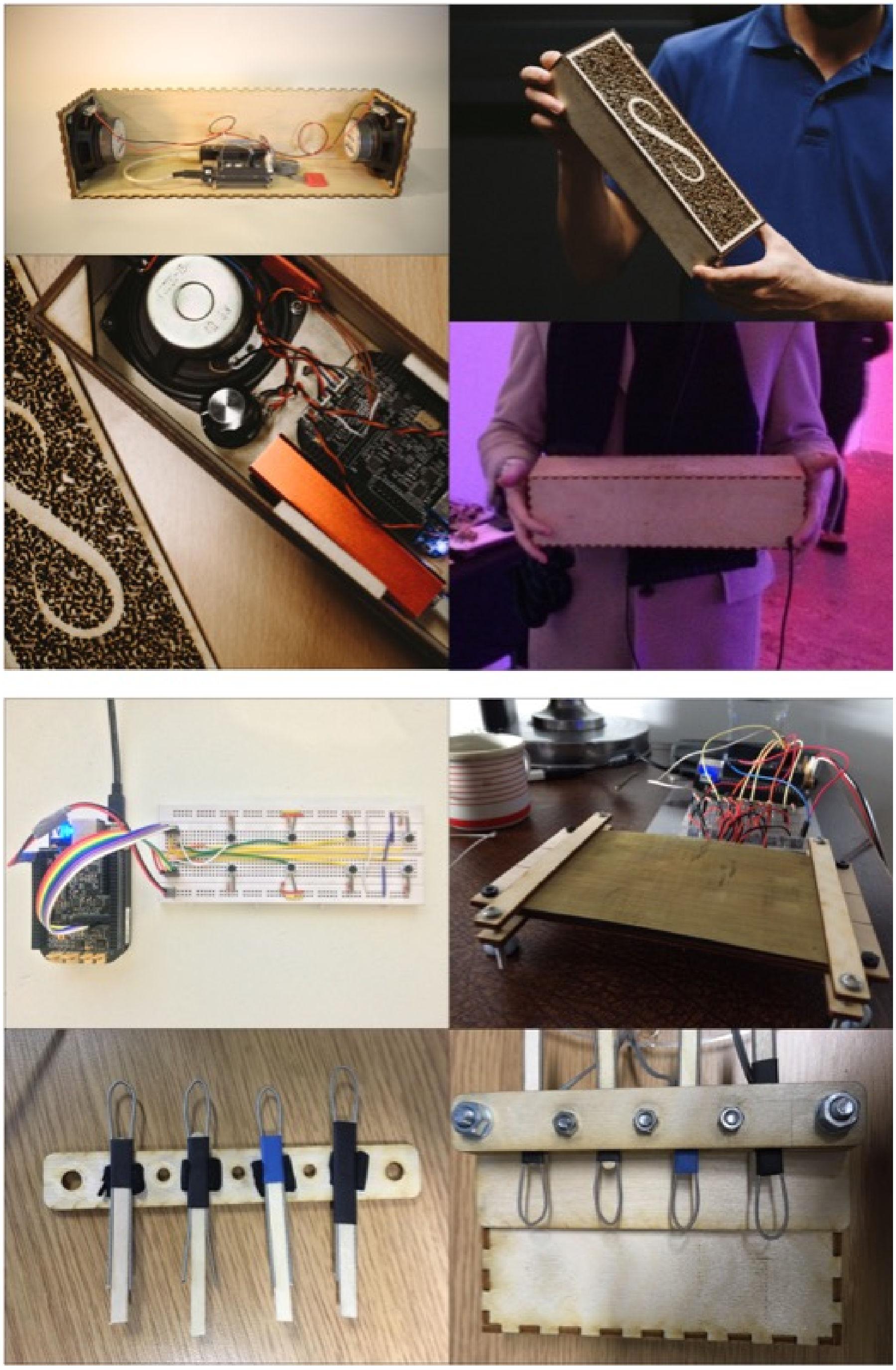


Figure 5.1: Un-crafting [218] the 'finished' *AirHarp* into the *Unfinished Instrument* $\frac{1}{2}$. Above: The *Airharp*. Below: deconstructed versions of the *AirHarp*. Top left to bottom right: capsule microphones on a breadboard; microphones clamped between wooden plates; microphones underneath plucking tines; iteration of the plucking tines.

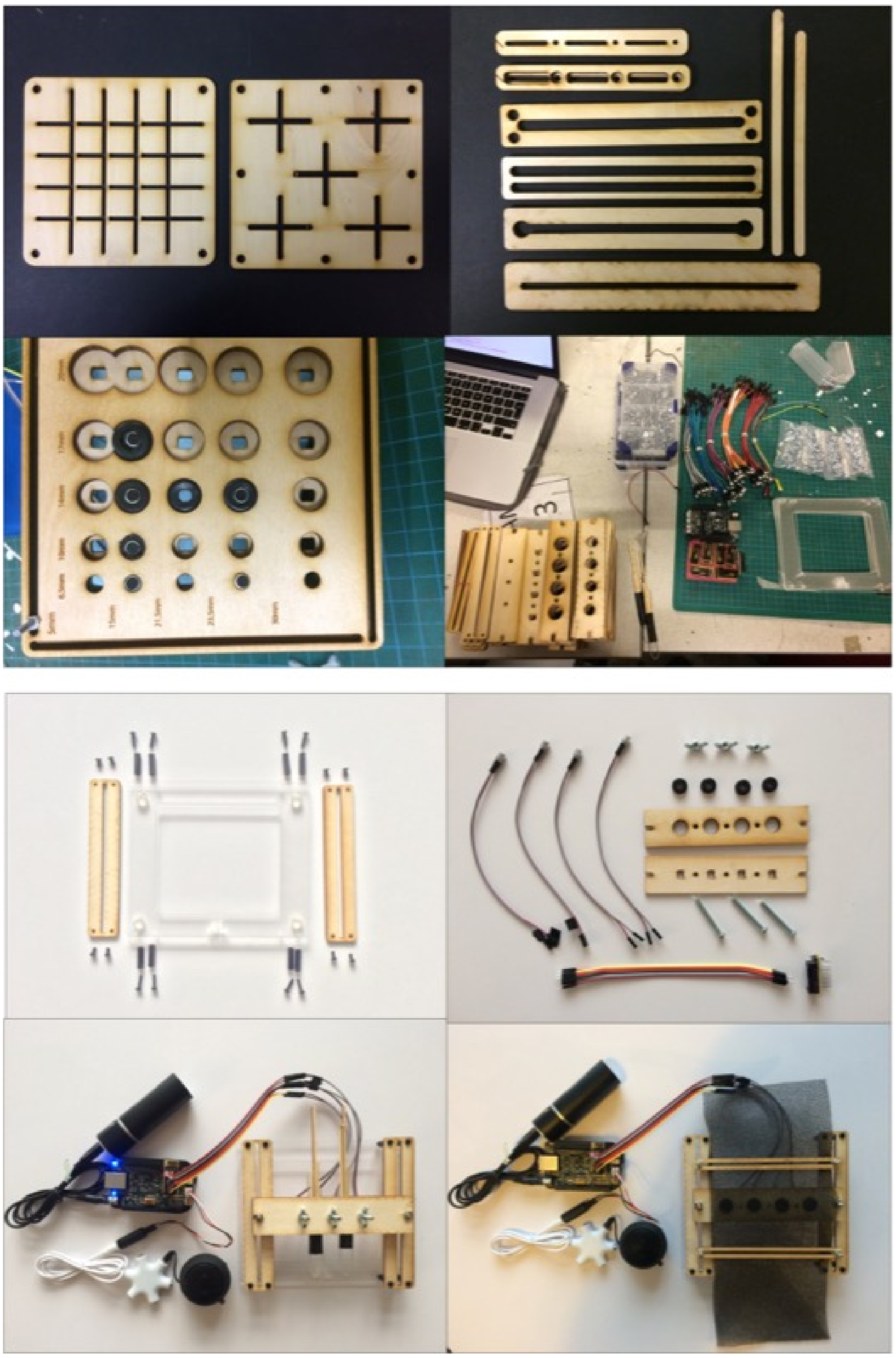


Figure 5.2: Un-crafting [218] the 'finished' *AirHarp* into the *Unfinished Instrument* $\frac{2}{2}$. Above: Developing the *Unfinished Instrument* kit. Below: final build photos and suggested configurations for the *Unfinished Instrument*. Top left to bottom right: base of the instrument; sensor bars for plucking and tapping configurations; pluck configuration; tap configuration.

sheets of various foams and metal meshes, paper, corrugated card, thick card, cork balls and granules, folding clips, and googley eyes. Tools included scissors, wire cutters, jewellery pliers and cutters, adhesives, double-sided tape and foam tape, duct tape, blu tack, notepads, pens and miniature cameras. Each group had at least one camera which they could use to document their crafting (consent forms were signed for filming). Tools and materials could be used in any quantity by any group at any time.

5.2.3 *Data collection and analysis*

Immediately before and after the activity, participants shared their reflections on their own craft practice and their crafting experience. Notes and observations were taken during this time by the workshop organisers. During the activity, audiovisual footage was being taken by the participants on an ad-hoc basis, and luckily the conference's photographer dropped in. After the workshop ended, more photos of the final instruments were taken. In the days after the workshop, reflections and feedback were gathered from participants via in-person interviews on an ad-hoc basis and an online survey. The data above has been thematically analysed according to the description of this method in Section 3.4.

5.3 OUTCOMES FROM THE NIME WORKSHOP

The workshop had 20 participants encompassing research, instrument design, teaching, composing and performance. They were split into four groups (**G1-4**) but were given no brief for how they should collaborate. In this section, the groups' crafting process and outcomes are described. Participants' reflections are then thematised based on the topics described in Appendix C. An emergent theme of collaboration process is also presented.

5.3.1 *Opening discussion responses*

After the opening remarks by the conveners of the workshop, three questions were posed to participants as a means to open up the discussion[3]:

1. What precisely do micro scale details encompass, and how are they distinct from engineering or musical aspects of DMI design?

2. How can we systematically compare micro-scale differences between otherwise identical instruments?

3 In the workshop we used the neologism *NIMEcraft* [197], which we have replaced here with the phrase *micro scale details* for consistency.

3. How should knowledge of micro scale details best be represented and shared in the community?

The responses added new perspectives on micro scale details that were not covered in our paper [9] or workshop proposal [197]. One of the workshop organisers took notes during this discussion, which are briefly summarised here.

A participant in **G1** opened by stating that crafting for others versus themselves has a significant effect on how they work and what they make. Crafting for others means understanding, empathising and designing for their needs and making appropriate changes to suit the end user. Pragmatically, robustness has to be increased in instruments designed for others to use, since they are less aware about design limitations and more likely to discover and use hidden affordances.

A participant in **G2** offered reflections based on DMI design workshops they had led, where participants were designing the layout and mapping of synthesiser controllers. Similarly to this workshop, the participants were given identical instrument 'scaffolds' with the same hardware and software. The participants took great interest and care over the interface elements, com- paring their tactile responses and look and feel, and trying out many configurations before committing to a design.

Another participant in **G2** stated that they refrained from publishing iterations on instruments in the form of academic papers. Despite these iterations being rich in micro scale crafting details that improved instrumental quality significantly, they believed this information was not 'paper-worthy' and would be rejected as such. This was reaffirmed by one of the workshop organisers, who had previously felt the need to reject such papers when reviewing. It was suggested that the decisions taken during these later stage iterations were artistic in nature, and could be exhibited alongside musical examples as part of a series of updates on projects originally presented as technical research.

A **G3** participant remarked that since NIME is a highly dynamic field, that perhaps micro scale details are also highly related to adaptation towards creative needs, which makes documentation and sharing complex. Another **G3** participant related micro scale details to the skill, sensitivity and care required of the maker in order to make 'something beautiful', and that this quality of the maker was recognisable but also subjective.

A suggestion was made by a participant in **G4** that micro scale details are inherently tied to other contextualising factors such as personal attachment to an instrument, which in turn affects the way instruments are played. Audience engagement was also cited as a contextual factor impacting crafting decisions.

5.3.2 *Overview of each group's DMI(s)*

Group 1 split into two subgroups and worked with two separate instruments (termed **G1A** and **G1B**).

G1A: *It started out with the elastic bands in the way of it just being easy to get a string effect on the string sound and do multiple sensors at once. Then we started with duct tape and getting the sound of pulling the tape off the other tape to get the kind of like [ripping] sound which was really nice. And [redacted] suggested velcro which kind of wound up in this way [scrapes velcro] where you can play it like a plucked harp like thing. And then it's also just really fun to whip it [with a giant foam stick].*

G1B: *We just split different microphones onto separate layers so you can play them. And it could be like a multiplayer sort of instrument [two players demonstrate]. And we thought about developing different materials for each layer to get different sounds. That's pretty much it.*

Group 2's instrument was demonstrated as two versions. The first was described as a 'feedback organ' where cardboard tubes could be telescopically lengthened to produce different timbres of feedback, with each microphone isolated.

G2: *One group member suggested something where we could throw objects into it and they would rattle around. Then, we decided that the tubes were cool, but would feel more like an instrument if they were different lengths, even though that wasn't necessarily functional.*

The second was based on striking the cardboard tubes, and featured a code modification affecting timbre.

G2: *We changed the code in an attempt to make the instrument slowly change octaves, but mis-judged the size of the buffer so we created an extremely fast arpeggiator (like 8-bit video game polyphony) instead, which turned out to give our instrument a unique sound.*

Group 3 split into two subgroups working with two separate instruments (G3A and G3B). G3B separated their instrument into four sub-instruments, three of which were demonstrated.

G3A: *We tried to figure out the different parameters of the mass damping but we sort of got slightly lost and got some help to reboot the project. With 30 seconds left we switched to the pluck model so all it does is just do the original pluck thing. So musically it's very uninteresting [...] But what we've got is this nice little visual representation of the evolution of the instrument.*

G3B: *We tried to extend each single microphone and explore a single microphone, and I think as a whole it would have been [the idea] to come together at the end. We explored different kinds of sound aesthetics, trying to understand actually what those mics could do and it was quite limited. In my case I've made this sandwich and inside it there's the microphone and some bolts, so if you shake it hard, then you get some sound.*

"This [second sub-instrument] is even more basic, well you can do this [plucks string against mesh] and [scrapes mesh]. I think the acoustic sounds are more interesting than those coming from the loudspeaker. One way to use this instrument would be to combine these two sound sources.

"Here's one final rudimentary part [third sub-instrument]. It doubles as a crucifix, it's a tapping mechanism, you can slightly hear it if you twist it around, that's what I came up with.

Group 4 found the initial instrument frustrating and also used feedback as a jumping off point for what became a highly performative process:

G4: *I guess at first we were frustrated with having limited notes, so we tried a lot of things. Somehow the feedback seemed to be inspirational and we started to come up with ways of thinking about the whole animal. We added speaker rattles and we looked at ways to create effects acoustically [the group begin performing]. This is the subtractive synthesis bit [microphone attached to a hacksaw]. So the same idea as [G3B] to mix the acoustic sound.*

5.3.3 *Plenary discussion responses*

During the plenary, the three questions from the opening discussion were returned to, with participants being asked to comment on them with respect to what they had just experienced during the crafting activity. It was observed that the crafting was not exclusively focused on micro scale details, which would make a systematic comparison difficult. Others expressed doubt that any such systematic comparison could be made due to the complexity and subjectivity involved. More suggestions were made as to possible venues for exhibiting and sharing NIMEcraft including design masterclasses. Overall, it seemed difficult for the participants to make direct connections between the questions and the results of the crafting activity, or that the crafting activity did not immediately stimulate novel responses to the questions.

5.3.4 *Session themes*

5.3.4.1 *Exploring constraints*

Most participants said they intended to explore the instrument and materials rather than start with a specific goal. This extended to setting aside our suggestion about focusing on subtle details.

G2: *Our intentions were quite geared towards the exploration side anyway so that continued throughout.*

G4: *What was interesting was to discover an instrument and to basically try to make music with it. So I would say even though maybe the goal was not*

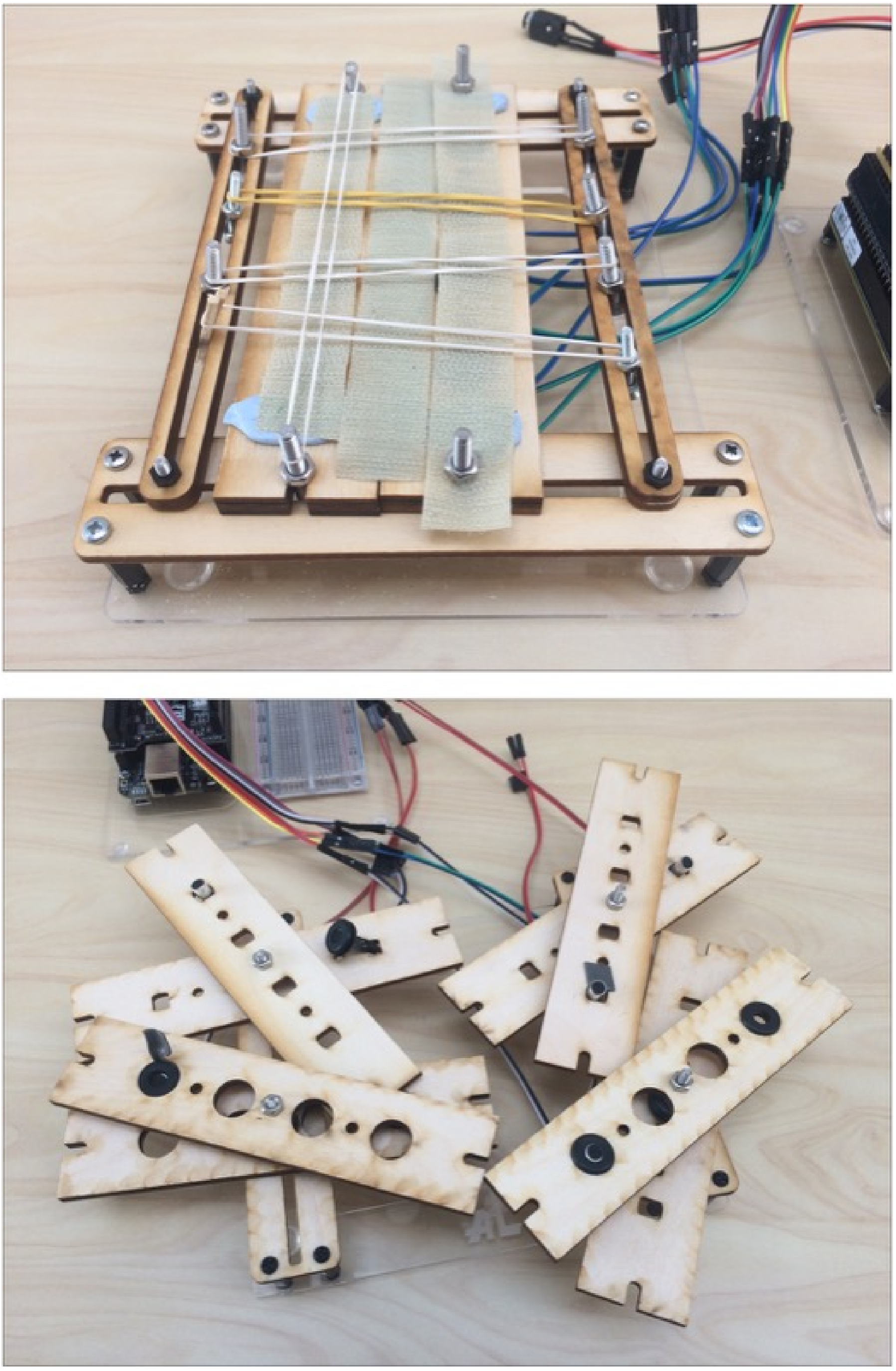


Figure 5.3: Group 1A and Group 1B's *Unfinished Instruments*.

Figure 5.4: Group 2's *Unfinished Instrument*.

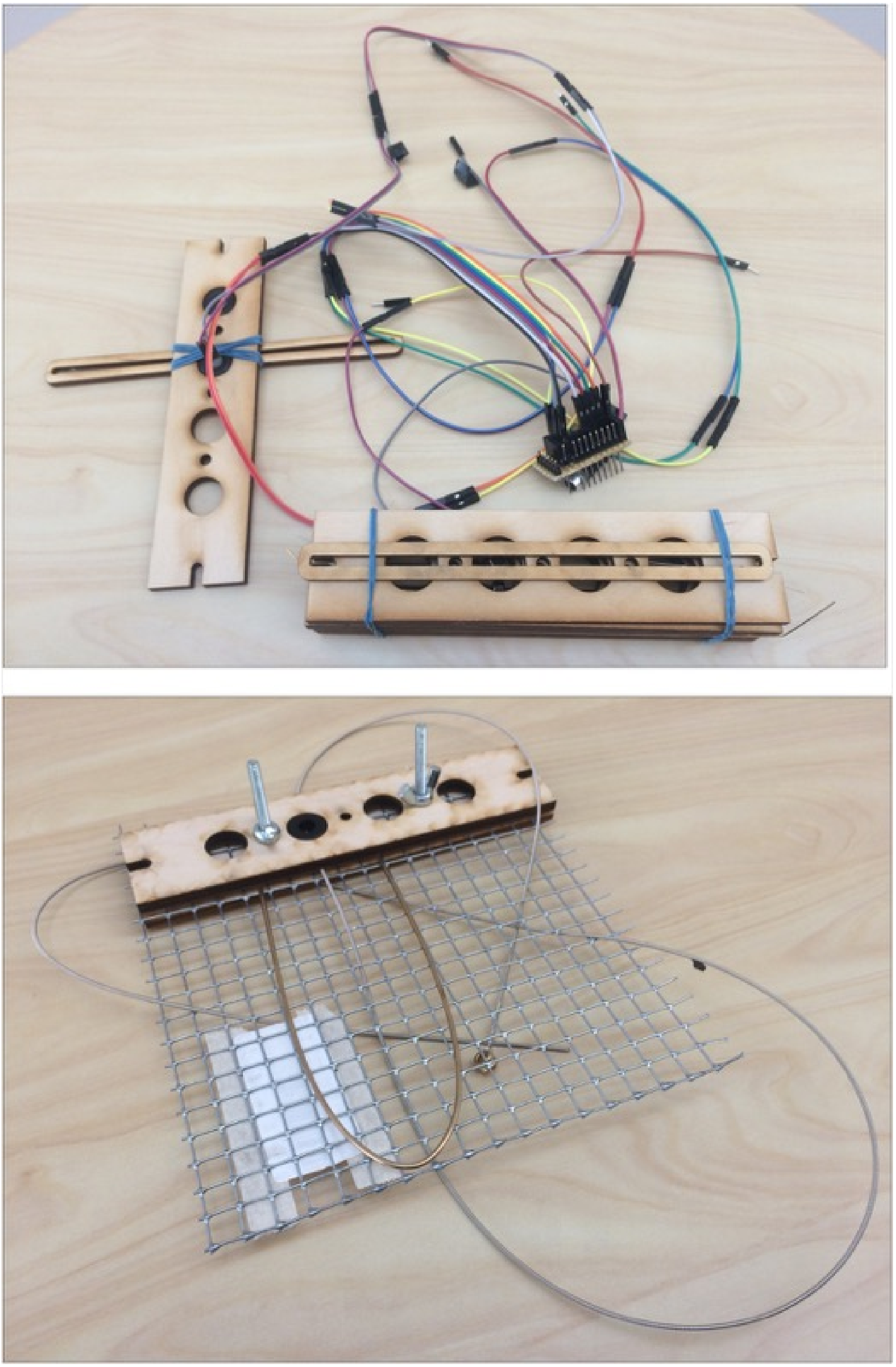


Figure 5.5: Group 3A's *Unfinished Instrument*.

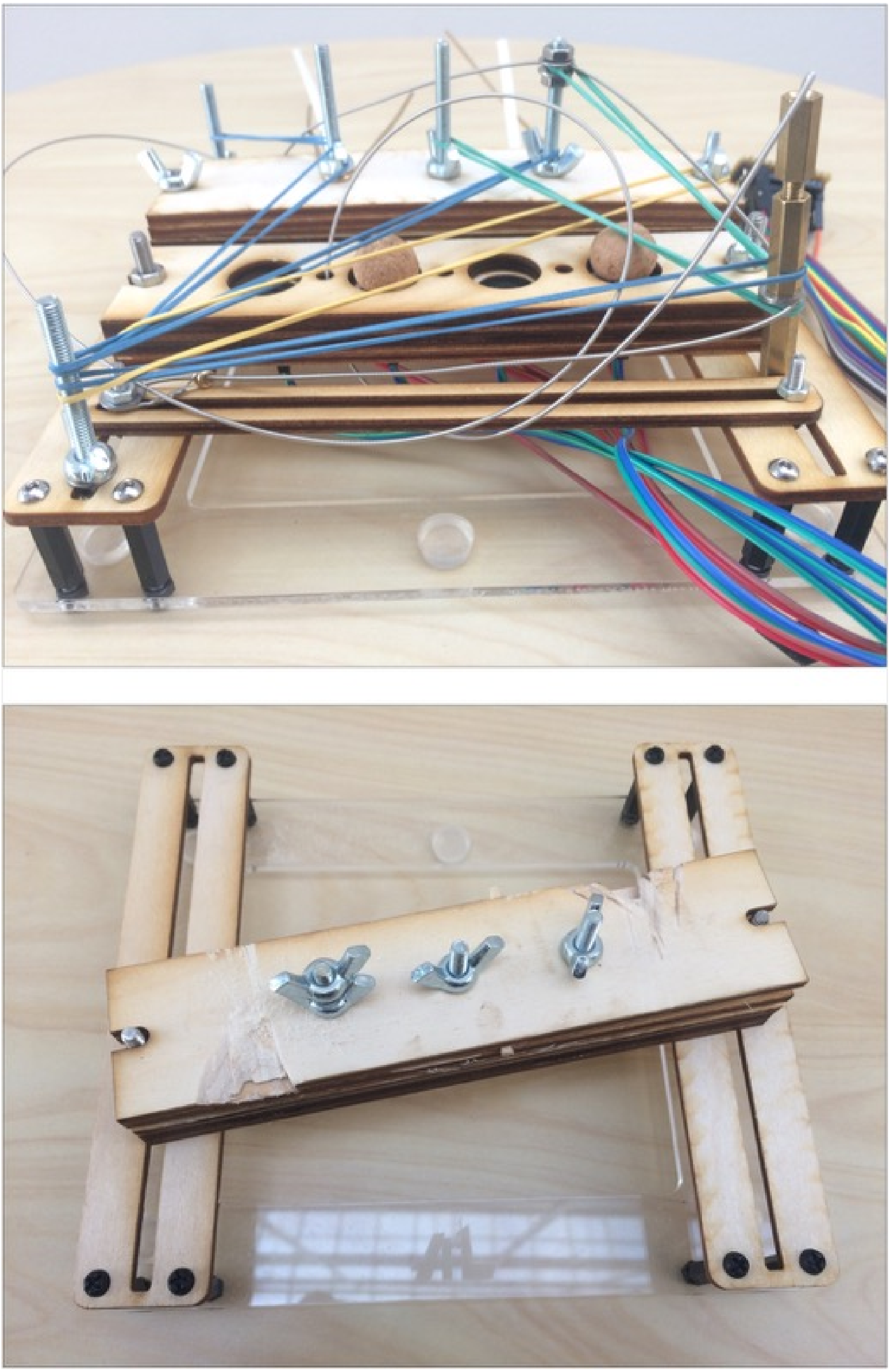


Figure 5.6: Group 3B and Group 4's *Unfinished Instruments*.

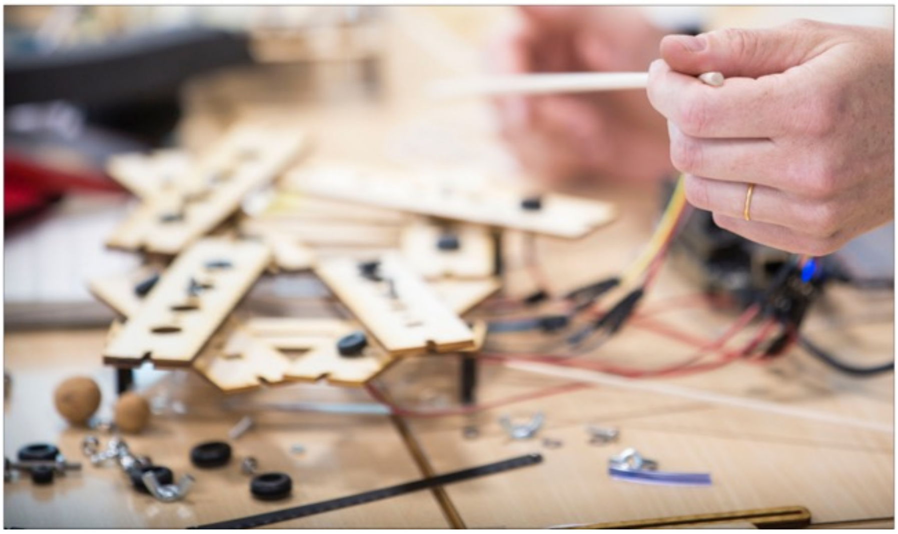


Figure 5.7: Craft process in Group 1A and Group 1B.

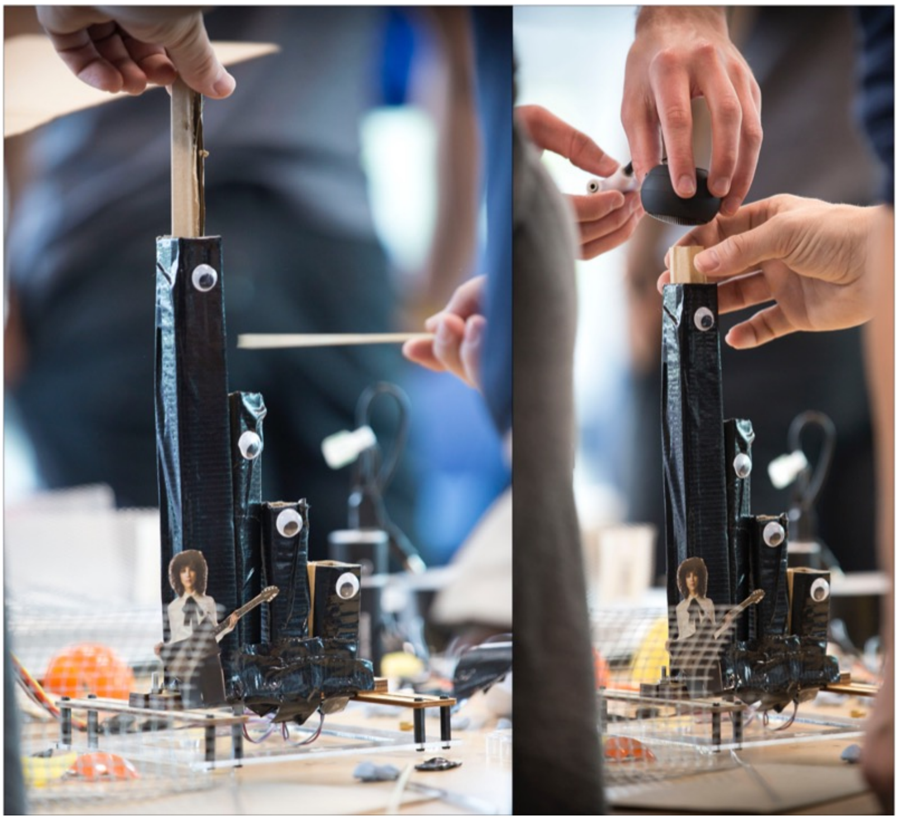


Figure 5.8: Craft process in Group 2.

announced like that, we didn't try at all like theoretically thinking about how to improve this instrument [...] we just tried to kind of okay we have this situation let's try to make music.

G2: *I think we wanted to do something different from what the other groups did. I don't think we said that explicitly to each other, though.*

Where initial ideas were pursued, it sometimes turned out that the design constraints were not supportive.

G3: *We had this grand idea of having this sort of spring reverb that was going to allow us to pluck it whilst these [strings] would carry on vibrating and then the balls would continue that in a physical way.*

G3: *The thing that I wanted to achieve is to get away from this pluck stuff and this was my only idea [pulling string through mesh].*

While the initial conditions of the instrument did not thrill, and the option to modify the code was there, participants still mostly preferred to continue exploring.

G1: *I personally made a conscious decision that I was not going to try to change the code that was running on the device because I didn't want to be in that headspace.*

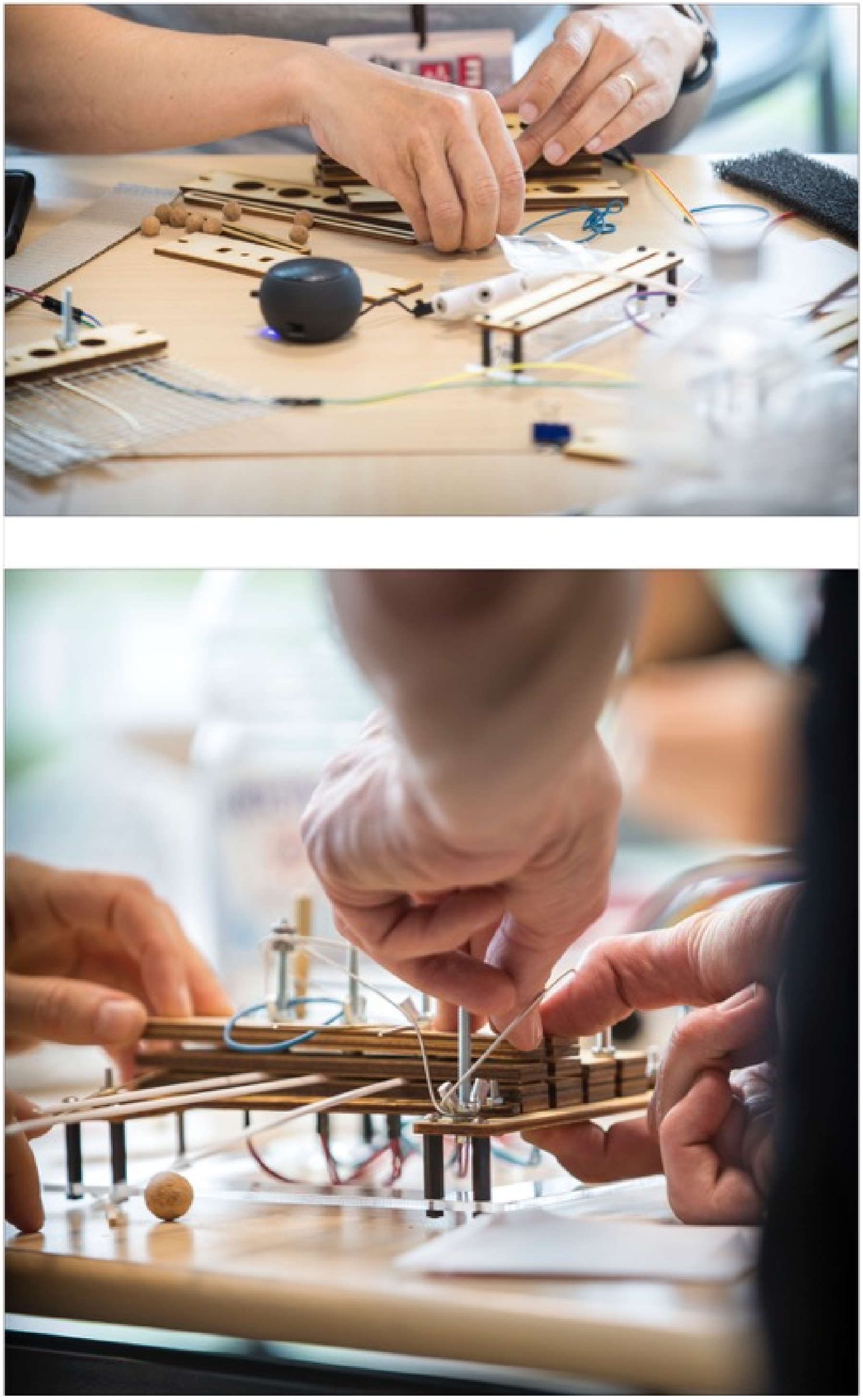


Figure 5.9: Craft process in Group 3.

Figure 5.10: Craft process in Group 4.

G1: *Once you get into trying different things with it, you don't really think about that aspect of the instrument so much, which I think is important. Because you can spend all this time tuning the sound, but then you need to spend some time tuning interaction or exploring interaction as well.*

Once the participants became more familiar with the constraints, they explored through a succession of making, playing and continuous iteration.

G1: *There was an aspect for me that is like it wasn't so precious, it wasn't like a thing that I had built up in my head as being like, oh I really want to try this specific thing.*

G1: *Coming into it not really having a clear goal or a clear expectation made the exploration more fun and lighthearted, I think it's analogous to music making.*

G2: *We were free to really think about the physical interaction and the visual details that would influence how the instrument was played.*

G2: *We were all very quick to discard something if it didn't look right.*

G3: *[It was] more or less chaotic, which is a good thing if you wish to expand the design space.*

As this process developed over time, there were points of little verbal discussion and instead a shared focus on doing.

G4: *We specifically acted and we interacted in and not too much discussion but like, oh you did that let me let me add that, or you did that let me cut that.*

G2: *It's kind of just like a feedback system just like idea bouncing back and forth.*

G2: *It ended up being implemented through playing modes.*

G4: *I actually never experienced like those things, it was like hmm so I'm doing as I'm experimenting as I'm in doing.*

G2: *It felt like it was very responsive; I am coming with one idea and and we could just, yes try it out, oh no it doesn't work, uh-huh okay [...] It wasn't any like darlings that you want to keep and very like quick to come up with some new ideas when something wasn't working.*

One participant in G4 reflected on the divergence away from the brief.

G4: *Because everyone in the room was creative, it came to not at all micro differences but huge differences even in the philosophy of music making or instrument building and the results themselves. Actually I loved many of the instruments that the other groups did and they were super different.*

5.3.4.2 *Sound, gesture and materials*

In their initial explorations, groups tested out the behaviour of the instrument, and in some cases these trials were dissatisfying or unrewarding, but groups later returned to the same gestures.

G3: *One of our first problems was that it was really quiet, so we first of all tried to make a more directional cone so we could turn up the gain without it feeding back. That wasn't entirely successful.*

G2: *One group member suggested something where we could throw objects into it and they would rattle around. We worked for a while trying to make that work (cardboard tubes, plastic eggs, different materials thrown in) but we didn't have the right materials to get a good bounce.*

G2: *In my head my ambition was more the acoustic sound [...] but I didn't think it through that it was actually destroying the sources [microphones]. One of the other things that quickly annoyed me was how responsive it felt [...] it sounds so the same every time [...] so we went looking for more variation.*

It was not long before the groups had accumulated differing collections of materials at their tables. The open layout of the table seemed to suggest ideas.

G2: *It's good to actually arrive there and have all this broad range of material and to experience the freedom you know like the creative freedom that it provides.*

G1: *It was interesting to have this is a kind of playground to explore different kinds of tactility that was then serving as inspiration for something totally different.*

New gestures often resulted from the incidental combination of ideas, and failed ideas resulted in raw materials being reused in new ones.

G1: *[G1 participant] was interested started out with ripping tape off and then that developed to the velcro, and then at first we just tried to put the two side-by-side and then kind of by accident realised that they complemented each other [...] like fret noise on a guitar, there's a bit of a lead up and then a more definite pluck sound.*

The process of combining and transforming materials and gestures were compared to sketching and sculpture, and happened more rapidly as materials accumulated on tables.

G4: *I found the bass string and some metal and that give me like a rough idea to try to sketch.*

G2: *[The process] became very much focused on the sculpture.*

G4: *At the end we were always kind of performing with it or trying it to make sound that was really interesting.*

5.3.4.3 *Collaborative process*

The groups diverged in their approach to collaboration (see Figure 5.11), and took advantage of the flexibility of the instrument's design to re-configure as their collaborative style required.

G1: *You specified to collaborate in groups but you didn't really go beyond that with the detail of how to collaborate, so it was really nice to see how the different groups came out with very different ways of working together. We kind of split it in half and made two instruments between four people.*

G3B: *Initially because there was four of us working on it we tried to extend each single microphone and each explore a single microphone, and I think as a whole it would have been [the idea] to come together at the end.*

G1: *The activity and the group environment was super inspiring, to see what everyone else came up with from the same initial state.*

G2: *Sometimes we would each take a particular task [...] and sometimes one of us would decide to experiment with a new idea while the others worked on something else.*

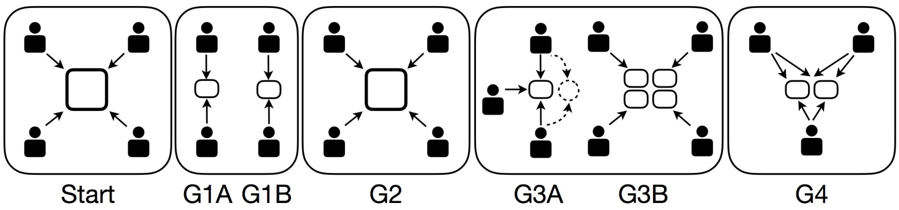


Figure 5.11: Variation of group organisation and instrument structure compared with starting point.

Across groups, ideas were shared explicitly and implicitly.

G1: *Someone else actually pointed out that connection and then it made it a little bit more usable.*

G2: *This kind of feedback idea was very collective idea so it wasn't one person's.*

G2: *It was interesting because I never made an instrument in a group process like that.*

5.3.5 *Activity by scale of detail*

Reviewing the photographs of the instruments reveals that no two looked the same by the end of the activity, neither did they bear much resemblance to the template that was initially provided. Some instruments made disparate organological references to pipe organs, percussion sets, spring reverbs and sound sculptures. From the perspective of the scale of detail, comparisons across the instruments could only really be made in terms of their overall role, form and function, indicating divergent macro scale differences (Section 2.3).

This corroborates with the participants' own statements referring to expanding the design space, and also with their creative processes, with ideas being transmitted across the room, and design blending fluidly with performance.

Although the instruments were not strictly comparable in terms of their meso and micro scale details, owing to their macro scale differences, this is not to say that each groups' instruments did not explore these scales within themselves. The initial trend across the room seemed to be to first explore the template DMI's micro scale affordances, by exploring tactile phenomena and auditioning musical gestures, and then subsequently exploring its macro scale using the craft materials. It seemed that the kit and materials implied macro scale reconfiguration, and that this was also felt to be necessary for the groups to establish individuated responses, given the mediocre quality of the template's initial micro scale details.

There was little convergence across the groups from then on. In some cases, like in **G2**, a stable macro scale form quite clearly emerged, which the group proceeded to explore and refine, in such a way that if they replicated their efforts there would likely be identifiable details to discuss. While in others, such as **G4**, macro scale instability of the DMI achieved performatively appeared to be the entire purpose of the material assemblage. Across all cases however, the detailed phenomena that were being explored, though in some ways similar due to their common material origins, are ultimately incomparable based on our definition of micro scale details, due to their higher-level differences. Referring back to the difference between micro scale design details and Jordà's micro-diversity of interaction described in Section 2.1.3, many of the DMIs involved quite micro-level interaction techniques, but did not necessarily query micro scale design details.

5.4 OUTCOMES FROM OTHER WORKSHOPS

5.4.1 *NIME 2017 Unconference*

This event was open to the public, with attendees free to wander between different tables and stalls where they could play with instruments, and in the case of this table, they could craft their own instruments based on the available kit.

Four instruments were made available on one large square table, such that participants would be facing each other whilst crafting. During the session, participants visited the different exhibitors and spent some time there. In addition, exhibitors were encouraged to hack together integrations between their systems. There was no introduction, opening or plenary discussion.

The format of the Unfinished Instrument, with its electronics and software constrained, meant that it was possible for members of the

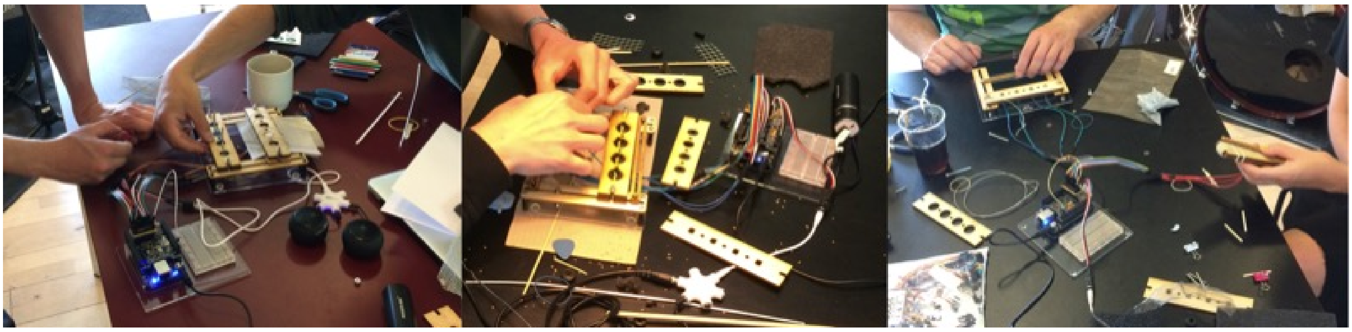


Figure 5.12: Rhythmic Music Conservatory students crafting their DMIs.

public to craft the instruments with no previous experience. Notably, a participant of senior age, with no experience with digital musical instruments, was perfectly able to craft the instrument.

One particularly interesting instrument that came out of this session involved suspending wooden sticks between rubber bands, which created a pendulum effect where pushing the sticks down would cause them to bounce up and down. The layout of the table with the participants facing each other with their own instrument, and the format of the unconference encouraging participants to move around the various exhibits, led to some surprising interactions. Participants were talkative and shared comments and ideas about their instruments with each other. When participants moved onto another exhibit, they would leave their instrument not as they found it, meaning people were crafting on top of each other in an exquisite corpse manner. There was one instance where multiple instruments were connected together across the table by a guitar string, which made the instruments 'networked' according to one participant, prompting questions about how to network them wirelessly.

5.4.2 *Rhythmic Music Conservatory in Copenhagen*

An additional workshop was held with music students from the Rhythmic Music Conservatory (RMC) in Copenhagen (Figure 5.12). Four instruments were made available on four separate tables during this workshop. A summarised version of the introduction was given to contextualise the themes, and discussion was held informally throughout the workshop. Compared to the primary workshop, the musicians overall exhibited less exploration of the design space, and appeared to struggle more with understanding how the microphones and virtual string model were configured and functioning. However, some similar ideas appeared, such as in one group which disassembled the instrument to make separate handheld versions. One novel variation of the rubber band as a string idea was to wrap nuts and bolts in the rubber band above the microphone cavities, which both exhibited novel use of construction materials as interact elements and subsequently increased the gestural richness of the instrument.

During a break from crafting, the participants asked why there was no explicit requirement to perform as part of the workshop, stating that this would be an obvious goal for them. Indeed, their crafting style involved more emphasis on performance than the digital luthiers. One participant started out creating a means to filter the sound of them blowing into the microphones, and ended up developing singing techniques where they interacted with acoustic feedback and the pitches of the virtual strings. At the end of the workshop, the participants requested an introduction to Bela, the platform the instruments were based on, so that was given instead of having another discussion.

5.5 discussion

In this discussion, we return to the session themes described in Section 5.3.4, and subsequently reflect on the workshop design.

5.5.1 *Exploring constraints*

The brief presented the workshop as an opportunity to reflect on subtle differences between outcomes given an identical starting point, however this was mismatched with the unconstrained environment. Instead of responding to this brief, most responded to what emerged from their ideas and engaging with each other. Although this scripting of the workshop was light and open responses were welcomed, it inadvertently motivated playful subversion and appropriation. To engage with subtle differences of craft, an alternative strategy could involve participants presenting and comparing their own instruments that have similar functions, forms or design processes.

The goal of un-crafting [218] the AirHarp into the Unfinished Instrument was to present something complete in terms of synthesis and sensors, but open to interpretation in terms of performance and gestures. While the instrument could only be “re-crafted” so much in one hour, the instruments exhibited personality and style, and they inspired collaboration and discussion. Some participants wanted the code to be more accessible, and some were generally dissatisfied with the resulting artifact itself, but still saw value in how it represented their group process. The shortcomings of the instrument’s sound and sensors, and the potential for its parts to be recombined or reinterpreted, seemed to just about balance frustration with motivation.

5.5.2 *Sound, gesture and materials*

The workshop environment encouraged mixing a variety of approaches including design, bricolage and performance. The layout of materials across a long table inspired ideas through visual survey, and their abundance and malleability led to their combination and destruction as needed. Participants were aided by not being attached to materialised ideas, perhaps due to the familiarity and low cost of the materials. This contrasts with circuitry-based workshops where participants interacted in a cautious and apprehensive manner [195]. The instrument parts were used and repurposed in surprising ways, sometimes fictitious ones as in G2's instrument. Some groups distinguished between instrument parts and crafting materials, while others blurred this line completely.

After initial disappointment with the instrument's lack of responsiveness, participants discovered stroking, hitting, scraping, throwing, twisting, pulling, pushing, sawing, singing, shaking, whacking, dropping and more. The hands-on way of working offered fast iteration of testing gestural ideas and sharing and critiquing the results, to the extent that many ideas were explored simultaneously. A notable pattern of activity across groups was the curation of a portfolio of gestures, which were continuously refined as new materials were incorporated into the instrument. When demonstrating their instruments to each other at the end of the workshop, participants were not required to perform, however this was vital to some groups. The outcomes indicate that "making the instrument malleable" [3] is not only applicable in fictional model-making scenarios.

5.5.3 *Collaborative process*

One of the more surprising aspects of the workshop was the diversity of collaboration it afforded the participants, as depicted by Figure 5.11. Even the more experienced participants commented that this workshop offered them a way of working that their current practice and community does not. There were no apparent barriers to dynamically configuring group organisation, roles and process, or any notable friction between verbal and non-verbal communication, or overtly performative or design-led activity. The workshop facilitated participants to use their existing skills, experience and interests, or simply respond to what emerged, without dividing labour in the group or enforcing rigid role-play. Exploring the design environment's affordances was a shared experience across groups, as observing an idea contributed to one's own understanding. Some ideas were felt to be collectively owned, such as feedback. The environment's openness allowed different collaborative styles to emerge.

5.5.4 *Reflections on the apparatus and activity*

In Section 5.3.5, we considered the processes and outcomes of the workshop from the perspective of our three scales of DMI design.

Despite the workshop design's considerations described in Section 5.2, the outcomes did not present us with the opportunity to compare micro scale details. Such an outcome was predicated on the DMIs' created exhibiting identical macro and meso scale features, whereas in reality these diverged completely, barely five minutes into the activity. The combination of a modular DMI toolkit with open-ended crafting materials (Section 5.1.1), along with only a light brief about subtle details, were both necessary to meet the workhop's community engagement goals, but clearly contributed to the divergence exhibited.

In effect, due to the way the tools and materials, the brief, and the groups were set up, we interpret the outcomes as indicating that the macro and meso scales were unconstrained, and that the macro scale in particular was the most engaging. Macro scale engagement was fueled primarily by the open-ended nature of the crafting materials, and the general excitement that propagated across the groups. Not only this, but the relatively low technical quality of the DMI's microphones and speakers meant that by contrast, the micro scale details that we were attempting to draw attention to were in effect tightly constrained in a creatively disengaging way. Even where some groups did seem to settle on some specific ideas and start to refine them, the lack of discrete iterations or prototypes, and the lack of replication, would prevent detailed comparison. From this perspective, the outcomes are hardly surprising in hindsight.

In terms of design processes, the groups' were similarly incomparable with any precision, but compounding this was the lack of clarity of the data. The hands-off approach of allowing each group to manually operate their cameras suited the occasion, however the captured video did not lend itself to detailed review. This would have been interesting to scrutinise, as it may have been possible to identify aspects of design convergence in some groups towards the end of the activity, and compare the temporal progression of each group on an individual basis.

5.6 CONCLUSION

In this chapter, we reviewed the outcomes of a hands-on NIME community workshop themed around reflecting on the craft of subtle details in DMI design. In contrast to the theme, the activity that we provided, along with the workshop's context, motived participants towards high-level exploration. The process of exploring gesture in digital lutherie involves a complex interplay between what an instrument can do versus what its creators and players would ideally like it to do. Tools and methods often address these issues through two styles of exploration; toolkits encouraging exploration through constraining actual instrument behaviour, and sketching and model-making encouraging exploration guided by imagination. While independent exploration of these issues is beneficial, we sought to investigate the potential of supporting designers to explore them concurrently through a craft-inspired workshop method. We found that reformulating an existing instrument to have a modular mechanical structure and combining it with crafting materials enabled rapid, open exploration of gesture. Groups also restructured the instruments' form to suit their gestural ideas, and the group setting of the workshop fostered diverse collaborative process. Further investigation is needed to identify how this method compares with those that inspired it, and where in a larger scale design process it might be appropriate and effective. In terms of our original aims, this study revealed the valuable perspective of interpreting the workshop design as featuring constraints and affordances that effect macro, meso and micro scales of DMIs and their underlying design processes differently.

6 MESO SCALE DMI DESIGN: PURE DATA PATCHING BETWEEN FORM AND DETAIL

> *While the essence of the artist is reflected in their work, it is rooted in skill - skill which is hard earned, and therefore worthy of respect by the instrument builder, or 'luthier'. But it is precisely these same skills which are so poorly captured by most computer-based tools. I maintain that the skills (and therefore needs) of the artist are different from those of, say, an accountant. Yet, based on the tools used, when I walk through Disney Feature Animation, I can hardly tell if I am in the accounting or character animation department.*
>
> — Bill Buxton, *Artists and the Art of the Luther* [35]

> *The worst thing about the computer keyboard is that it's not a real keyboard.*
>
> — Marvin Minsky, *Communications of the ACM* [152]

This chapter is built on material from "Bricolage in a hybrid lutherie context: a workshop study", by Armitage and McPherson, originally published in the proceedings of the 14th International Audio Mostly Conference: A Journey in Sound, AM'19, Nottingham, United Kingdom [8].

In the previous chapter, our initial efforts to elicit micro scale design activity instead resulted in high-level exploration of instrumentality, where the outcomes were only comparable at the macro scale. Seeking to better understand the impact of our workshop design decisions on these outcomes, we ran similar workshops again with digital luthiers, only this time making two significant changes to see if the outcomes would be more or less detailed than previously. First, we hosted individual groups of participants in our media arts laboratory space, rather than co-locating groups together. Second, the physical crafting materials were replaced with a Pure Data [250] patch, which we expected would result in more detailed responses, or at least provide an interesting comparison case. While the outcomes were not as high-level as before, neither did they exhibit comparable micro scale details, leaving meso scale differences as the main point of comparison. All groups sought to use the DMI's microphone signals to control behaviour in complex ways, but found even apparently simple mappings difficult to realise within the time constraint. We describe the difficulties they encountered and discuss emergent issues with software tinkering. We conclude with further questions and suggestions for designers and technologists regarding embedded DMI design processes and tools.

6.1 INTRODUCTION

6.1.1 *Related research*

In discourse on interaction design, design processes are often differentiated based on whether the media involved are physical or hardware, versus graphical or software based [195, 297]. Hardware processes are typified as being led by tinkering, or what Vallgårda and Fernaeus refer to as "bricolage practice" [297], and software processes by more conceptual approaches [195]. DMI designers increasingly engage with hybrid approaches [98, 292], where varied processes take place concurrently, or where the aforementioned distinctions break down. It is important to understand how tensions between hands-on tinkering and conceptual design are navigated in digital lutherie, in order to inform the design of tools and media suited for hybrid processes [136]. Software design workflows for embedded DMIs are in the early stages of development [64, 212], and while new software tools are frequently proposed, little data exists to guide them forward.

An advantage of embedded DMI design platforms that are capable of running powerful operating systems, is that they can be programmed using existing sound and music computing languages. Languages including SuperCollider [191] and Pure Data [250] provide high-level abstractions and "live" development workflows [282], which are considered more approachable for novice DMI designers, who can also rifle through decades' worth of examples and resources. In Section 2.3.3 however, we critiqued these tools and the supporting "mapping" literature around them, as professing to be blank canvas, non-mediating DMI design mediums, whereas in practice they most readily afford meso scale design. To summarise: at a high-level, they rigidly enforce the macro scale decisions of their creators, and at a detailed level, they do not support micro scale design processes, particularly where embodied crafting is concerned. Their material "grains" [120] actively shape the aesthetics of works produced using them, unless practitioners endeavour to overcome them at noteworthy expense.

We surmise that the impact of these affordances and constraints on DMI design practice is not well understood, and that DMI design technologists especially would benefit from a clearer picture of the repercussions of their choices. This lack of understanding is further hindered by the lack of research methods specialised towards the observation and interpretation of DMI design activity with sound and music computing environments. As such, this study attempted to produce evidence for and explore approaches for communicating the impact of, in this instance, Pure Data patching on the embedded DMI design process, in the context of a group-based activity.

6.1.2 *Research questions and scope*

This study addresses Research Question 4:

How do groups of DMI designers respond when encouraged towards subtle and detailed design of a gestural DMI via Pure Data patching?

In particular this study addresses the following sub-questions of Q4:

a. How much does workflow liveness affect the creative process?

b. What impact does working as a group with a Pure Data patch have on the process and outcomes?

c. What scale of detail do participants spend most of their attention on?

THE NEXT SECTION describes the workshop design, including a comparison with the previous design described in Section 5.2. This is followed by the outcomes, which are described group-by-group, and then subsequently thematised in different ways. Finally, we discuss the outcomes in relation to the DMI design issues highlighted already in this chapter.

6.2 WORKSHOP DESIGN

6.2.1 *Workshop activity & environment*

The instruments and probes used in this study are reported in detail in Appendix D. A one-hour workshop activity was designed where groups of three DMI designers respond to a probe called the *Unfinished Instrument* (Figure 6.1a), which was deliberately simple and required creative and technical intervention to make it more playable and interesting. The goal of the activity was to facilitate open-ended exploration of the instrument and development of its character towards the aesthetic inclinations of the designers. Our motivation in facilitating this was to gain insight into how the different elements of the material environment — the physical instrument, sensors, electronics and software described in more detail in the next section — affected design idea generation, exploration, decision-making and development.

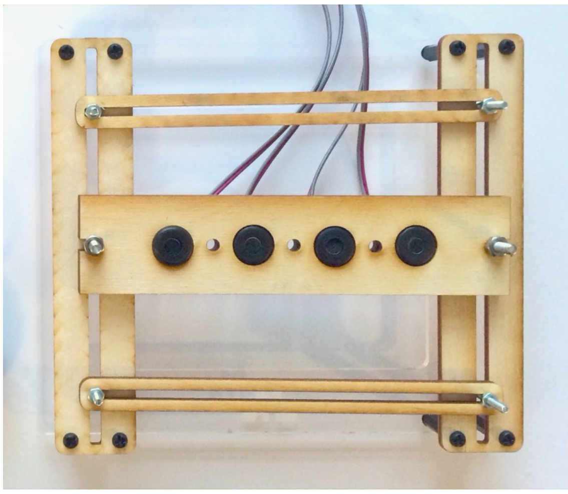
The instrument and workshop environment are depicted in Figure 6.1. Participants gathered around a table facing the instrument and two computer monitors displaying the Pure Data patch and the browser-based Bela oscilloscope [202]. In terms of sound output, participants could choose between a loudspeaker or individual headphones. The software was configured such that each time the Pure Data patch was saved it would be compiled and run on the Bela board, and the changes would be saved into a timestamped log. The Pure Data patch was neatly laid out by the author, and was annotated with comments describing the patch and how to modify it. Supplementary materials were available to encourage discussion and exploration, such as a print list of Pure Data objects, a system diagram of the Karplus-Strong string synthesis algorithm [145], a Pure Data reference textbook [76], a whiteboard, pens, pencils and A3 paper. Towards the end of the one-hour activity, participants were asked to summarise and demonstrate the results of their work. Afterwards they filled in a brief survey, and were debriefed about the research project.

The instrument was previously deployed in a NIME 2017 workshop facilitating crafting with physical materials [7, 197], described in Chapter 5, and as such it is based on a simple modular physical structure. In contrast, in this workshop a separate set of participants were given the same physical instrument, but instead they work with a Pure Data patch for one hour. Pure Data offers a visual data flow programming environment where objects and connections are represented by text boxes and lines between their inputs and outputs [250]. The specific Pure Data patch is described in the next section.

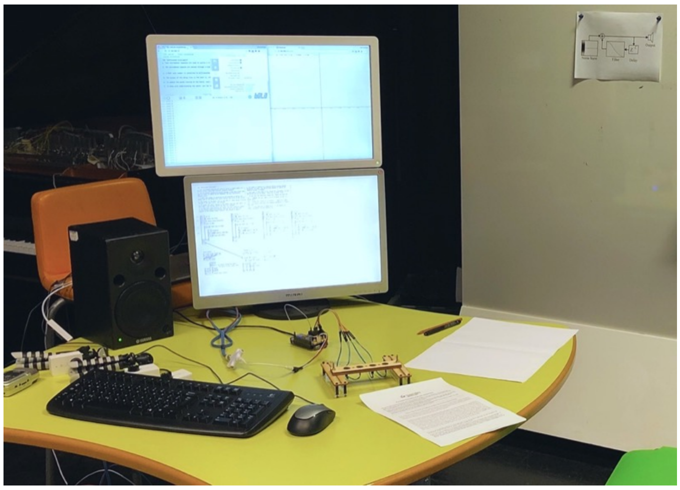
6.2.2 *Instrument design*

The design of the *Unfinished Instrument* was previously described in Section 5.2.1. To recap, the *Unfinished Instrument* was constructed from simple laser cut, modular parts which enabled many possibilities for arranging its overall form and the positioning of the inputs (Figure 6.1a). Four low cost microphone capsules are housed inside rubber grommets, which were connected to a Bela device running a Pd patch (Figure 6.1b). When the player taps or otherwise interacts with the mics, the signal was used to excite four Karplus-Strong [145] vibrating string models. In the Pd patch, each mic signal was pre-processed with a high pass filter, gate and gain factor (Figure 6.1c). The mics were clearly visible so that the designer was aware of what kind of sensor they were working with and how they could approach it [242]. The patch mixed the four string sounds together, and in addition provided debugging facilities for printing and visualising via the Bela platform's browser-based oscilloscope (Figure 6.1d) [64].

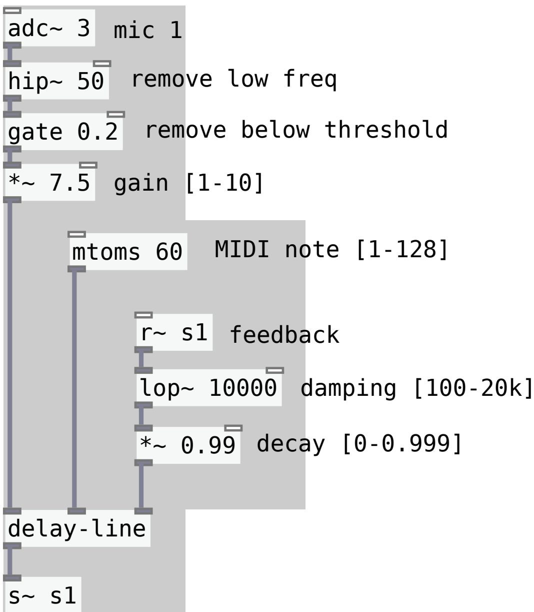
Pd does not feature a formal spatial syntax, meaning the spatialisation of objects and connections are left to the author as a secondary notation [192]. Perhaps more so than textual code comments, the layout of a Pd patch can communicate a great deal about the patch and its author(s). In this workshop, it was desirable that the patch be as transparent as possible to a broad range of experience levels, and that



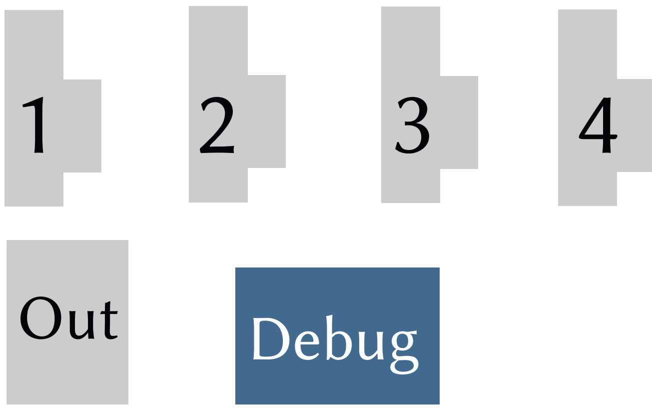
(a) Top view of the *Unfinished Instrument*.



(b) Instrument and software tools in situ.



(c) Pd patch detail of mic-to-string algorithm with visual outline for reference.



(d) Visual overview of Pd patch with four mic-to-string algorithms, audio output and Bela IDE in grey and debugging utilities in blue.

Figure 6.1: Above: instrument (left) and workshop environment (right). Below: Pure Data patch mic-to-string algorithm detail (left) and patch overview (right).

it be modifiable without too much concern for encapsulation, duplication and deduplication. At a high level, the patch was separated into six distinct blocks, which were connected via send and receive objects rather than graphical connections to highlight their separation. Four of these were mic-to-string algorithms, duplicated left-to-right to mimic the physical design of the instrument, and the two other blocks were for audio outputs and debugging tools. The mic-to-string algorithm can be visually broken down into mic processing, MIDI note to pitch input, and feedback input.

6.2.3 *Instrument editing workflow*

When referring to Tanimoto's liveness levels [282], Pd can be described as having Level 4 properties (a live editable flowchart where program data is continuously displayed and is manipulable). Objects and connections can be added, edited or removed while the program is running, with the caveat is that there can be glitches when the signal graph changes. As a result one might elect not to make graph changes during an artistic performance, however during design iteration graph changes are usually frequent. Pd also support graphical user interface (GUI) elements such as sliders, buttons and plots, for direct manipulation of program data. In this case however, the Pd patch was running on a remote device, Bela, so the workflow for editing the patch differed to the regular live editing workflow. While the patch is edited live in the standard desktop application, edits are not reflected on the instrument in real-time, neither are changes to program data via graphical interface elements such as sliders. Instead, the update procedure, which was measured to take around seven seconds for the given patch, is as follows:

1. The user edits the patch using the desktop Pure Data application.
2. When they want to update the instrument, they save the patch.
3. The instrument stops running while the patch is automatically copied to the embedded device and recompiled.
4. Once the patch has been recompiled, the user can continue to interact with the instrument.

6.2.4 *Comparison with physical materials workshop*

The common elements between the physical crafting workshop described in Chapter 5 and [7, 197], and this workshop were the *Unfinished Instrument*, and working in small groups for one hour with access to technical support. The unique elements of the physical crafting workshop were the physical crafting materials (rods, meshes, foams, sheets, handtools, etc.), and groups being co-located in one large space, situated in a research conference (*New Interfaces for Musical Expression 2017*). The unique elements of this workshop were the software crafting tools (Pure Data, Bela IDE console and oscilloscope), and groups working one at a time situated in a research lab. The outcomes of the physical crafting workshop [7, 197] involved a high degree of divergence in the form, identity and gestural language of the instruments. We were motivated to see how the processes and outcomes would differ in this workshop, with participants being constrained towards crafting the instrument's software.

6.2.5 *Participants, grouping and data collection*

Participants responded to an open call published on mailing lists and social media. They were required to have at least some experience with at least one sound and music computing language. Participants were matched into groups to balance out experience, such that every group had at least one participant with some Pure Data or Max/MSP experience. In total, 15 participants were grouped into five groups of three. After four groups had participated, the conditions for the final group were altered such that both Pd and physical crafting materials were available. This group's activity is highlighted using the abbreviation **PM** for (*Physical Materials*). This change was made for two reasons: first, the previous study [7]) described in the previous chapter also had four groups, and second, the outcomes of this study by G4 had started to become predictable.

Participants self-reported their experience before the activity (reported fully in 6.1) and were grouped in threes into two more experienced groups (G1-2) and three less experienced groups (G3-5). Participants within each group are labelled A, B and C. Workshop sessions were documented with video and audio recordings. Each patch update was automatically version controlled, and the final patches were visually annotated based on object movement, editing, deletion and addition. Each participant completed a brief post-activity survey covering their impressions and reflections on the activity, and the collected data was thematically analysed by the authors (Section 3.4).

6.3 OUTCOMES

This section is split into four parts. The first gives a brief overview of what each group did, and the second then goes into further detail for each group. The third part then reviews commonalities across the groups, and finally the outcomes are reviewed again from the perspective of the scale-based ontology described in Section 2.3.

6.3.1 *Overview*

In this section, overviews of the outcomes are given in terms of the experience levels of the participant cohort, the states of their Pure Data patches at the end of the activity, and their activity over time.

6.3.1.1 *Cohort*

	G1			G2			G3			G4			G5		
Experience	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Playing DMIs	>5	1-3	1-3	>5	>5	>5	>5	1-3	1-3	>5	>5	>5	1-3	>5	≤1
Making DMIs	>5	≤1	≤1	3-5	>5	3-5	1-3	≤1	≤1	≤1	>5	>5	1-3	≤1	≤1
Max/MSP	≤1	-	≤1	3-5	1-3	3-5	≤1	≤1	1-3	1-3	>5	1-3	-	≤1	≤1
Pure Data	-	≤1	1-3	3-5	>5	1-3	≤1	1-3	1-3	>5	>5	-	1-3	>5	-
Other lang(s)	>5	3-5	-	3-5	>5	>5	>5	1-3	≤1	>5	>5	>5	≤1	>5	-

Table 6.1: Group experience in years, self-reported.

Table 6.1 displays the results of the pre-activity survey. In summary:

Group 1 were least experienced with Pure Data.

Group 2 each had at least one year of experience.

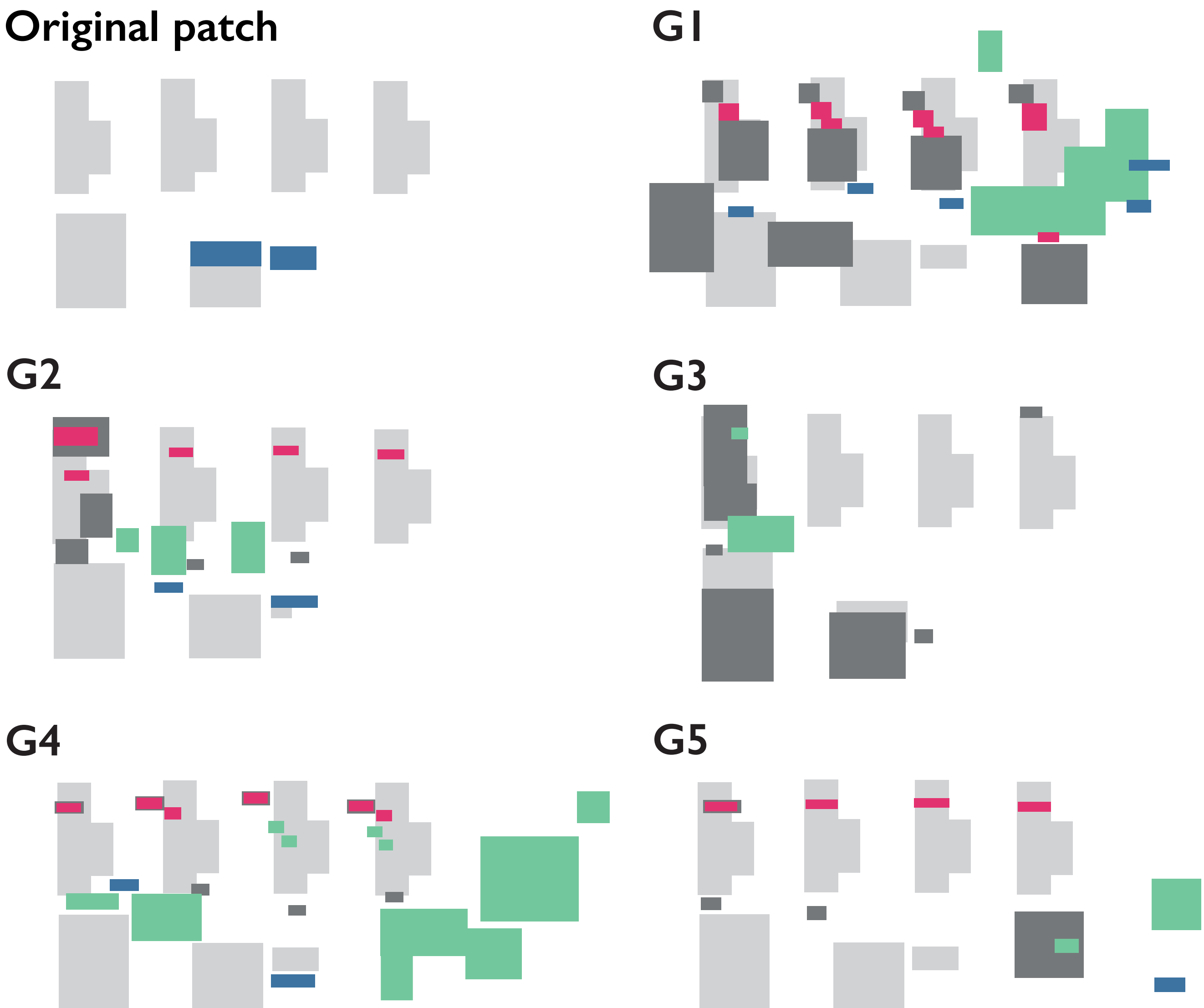
Group 3 each had some Pure Data experience.

Group 4 had two out of three participants with experience.

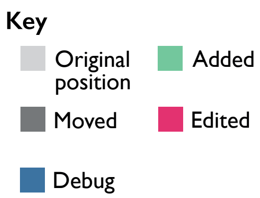
Group 5 (**PM**) were second-least experienced.

6.3.1.2 *Final states of Pure Data patches*

Figure 6.2 depicts the final states of the Pure Data patches for each group. The overall architecture of the patches remained unchanged. Groups 1, 2 and 4 used the debugging facilities (blue) of the Bela IDE. Groups 1, 2, 4 and 5 (**PM**) edited (red) the threshold of the sensors to achieve greater sensitivity. Groups 1 and 2 attempted to turn sensor signals into control structures (green), and Group 4 added extra delay lines (green). Group 3 also attempted to add extra delay lines (green), but deleted their work before the end.



(a) Pure Data patch visual summaries for each group.



(b) Key for Figure 6.2a.

Figure 6.2: Visual summary of the final states of the Pure Data patches for each group, except for Group 3 which is in its penultimate state, since the group deleted their additions at the end of the activity.

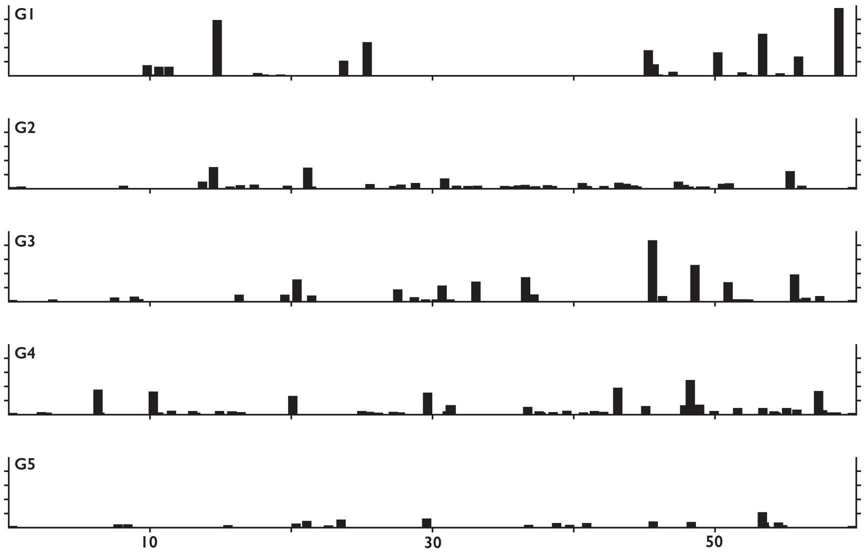


Figure 6.3: Pure Data patch updates over the 60 minute activity period for each Group. The height of each bar represents the size of the update.

	Total updates	Updates / min	Avg. size	Comp. time (%)
G5	19	0.31	12.7	3.7
G1	21	0.35	52.0	4.1
G3	30	0.50	32.5	5.8
G2	44	0.73	11.5	8.6
G4	46	0.76	20.5	8.9

Table 6.2: Summarial statistics for each group, ordered by number of total updates (first column).

6.3.1.3 *Pure Data activity over time*

Figure 6.3 and Table 6.2 describe the frequency and size of patch updates over the 60-minute activity. Few updates were made in the first ten minutes, and the rate and size of updates generally increased towards the end of the activity. Groups were fairly consistent in their frequency and sizing of updates apart from Group 1.

Group 1 made infrequent and large updates, almost as few as Group 5 **PM**, and stopped editing for almost 20 minutes in the middle of their session. Groups 2 and 4 made the most updates, but Group 4's were of almost double the size of Group 3 on average. Group 3 had the second-largest average update size. Updates took around seven seconds from saving the patch to hearing the output, so Group 4 spent almost 9% of their session waiting for updates to happen. Group 5

(**PM**) made the fewest updates and spent more time working with the physical materials.

6.3.2 *Outcomes by group*

6.3.2.1 *Group 1*

Group 1 were least experienced with Pure Data (Table 6.4a). They were initially frustrated with the quality of the instrument and the speed of the workflow. They experimented with optimising sensitivity, and changed the tonality of the pitches from major to minor.

First impressions

A: *[...] patch was a big influence (not necessarily positive!) on our work*
B: *Looked interesting [...] but actually sloppy (mics didn't seem to work well).*

Goals at the outset

A: *Find a fun way to play the physical thing, adapt to that*
C: *More melodic, harmonic control*

Mid-way through the session, they turned to pen and paper to sketch out their idea and its implementation (see the gap in the middle of Figure 6.4b). This period lasted 20 minutes, after which they struggled with debugging their implementation.

Group process

A: *Difficult [...] in the flat hierarchy there was a tendency for agenda pushing.*
C: *Efficient, once we realised the limitations [...] we found a common goal.*

Crafting process

A: *Slowly! [..] Tried to use audio gain to control octave.*
B: *It ended up a multi-interactive instrument rather than a hit instrument.*

They tried to turn a sensor signal into a control signal by thresholding it, such that it would control a pitch shifting effect (Figure 6.4c). They ended somewhat frustrated with their result, reporting that the process was too slow, or they needed more time.

Outcome

B: *[...] ended halfway of what we actually wanted to get.*
C: *[...] we did the most we could with the slightly broken equipment.*

Workflow

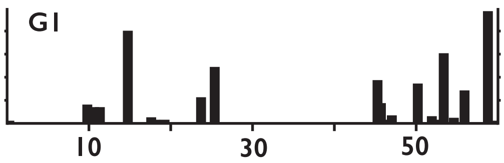
A: *There was a tendency to focus on screen, rather than playing.*
B: *Slower than desired. Pd became too high level for some operations.*

Reflections

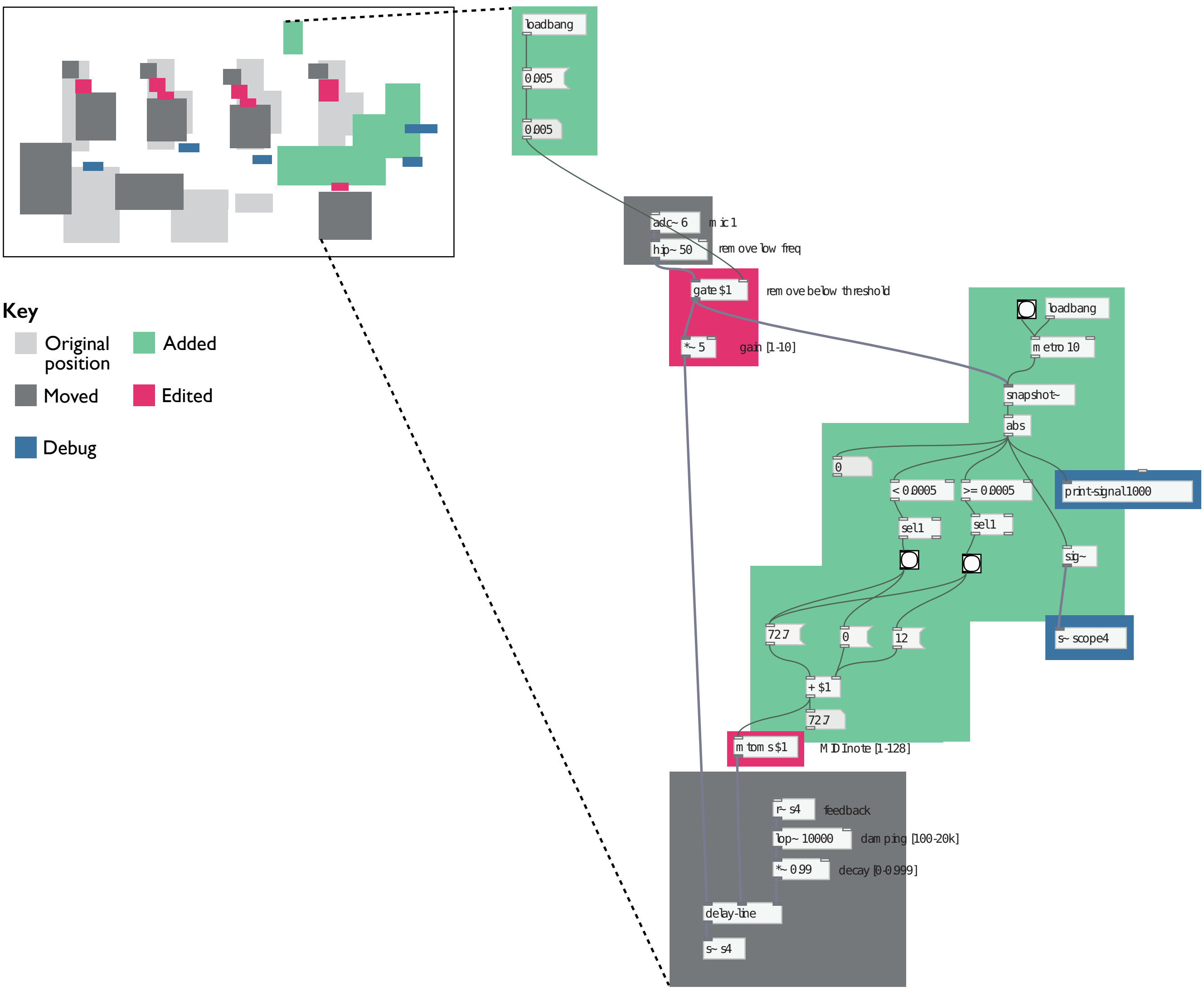
A: *Long feedback loop made it difficult to iterate.*
B: *[...] we didn't have time to develop our ideas and experiment.*

Experience	A	B	C
Playing DMIs	>5	1-3	1-3
Making DMIs	>5	≤1	≤1
Max/MSP	≤1	-	≤1
Pure Data	-	≤1	1-3
Other lang(s)	>5	3-5	-

(a) G1's experience levels.



(b) G1's activity over time.



(c) G1's Pure Data patch, with detail.

Figure 6.4: G1's experience level, activity over time, and Pure Data patch. See Section 6.3.2.1.

6.3.2.2 *Group 2*

Group 2 each had at least one year of experience with Pure Data (Table 6.5a). They were initially dissatisfied with the sensor response, but were positive about exploring the instrument.

First impressions
B: *Input control fidelity very limited.*
C: *I thought it was ok but not very interesting - not many different sounds.*

Goals at the outset
A: *Just to explore and see what's possible.*
B: *Find out what could be interesting.*

They cross-mapped sensors together to enrich the sound, but struggled to derive control values from the sensors. They achieved variety by reducing the delay time, altering the string pitches, and experimenting with acoustic feedback (Figure 6.5c).

Group process
A: *Some brainstorming, some scoping and a bit of implementation.*
C: *We all took turns to explore the instrument and added ideas on each topic.*

Crafting process
A: *It went from a karplus synthesis engine to a feedback machine.*
C: *It developed through small changes [...] Little steps at a time.*

By the end, they felt they had made some progress, but that the group process and the update procedure slowed things down.

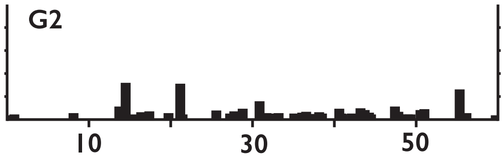
Outcome
C: *I like the instrument more now... But we didn't get to the final creation. We succeeded in brainstorming an idea but not making it.*

Workflow
A: *Compile stage limited flow. A desktop patch w/ OSC streams would be good.*
C: *I usually work alone. The group element affected the ideas being made.*

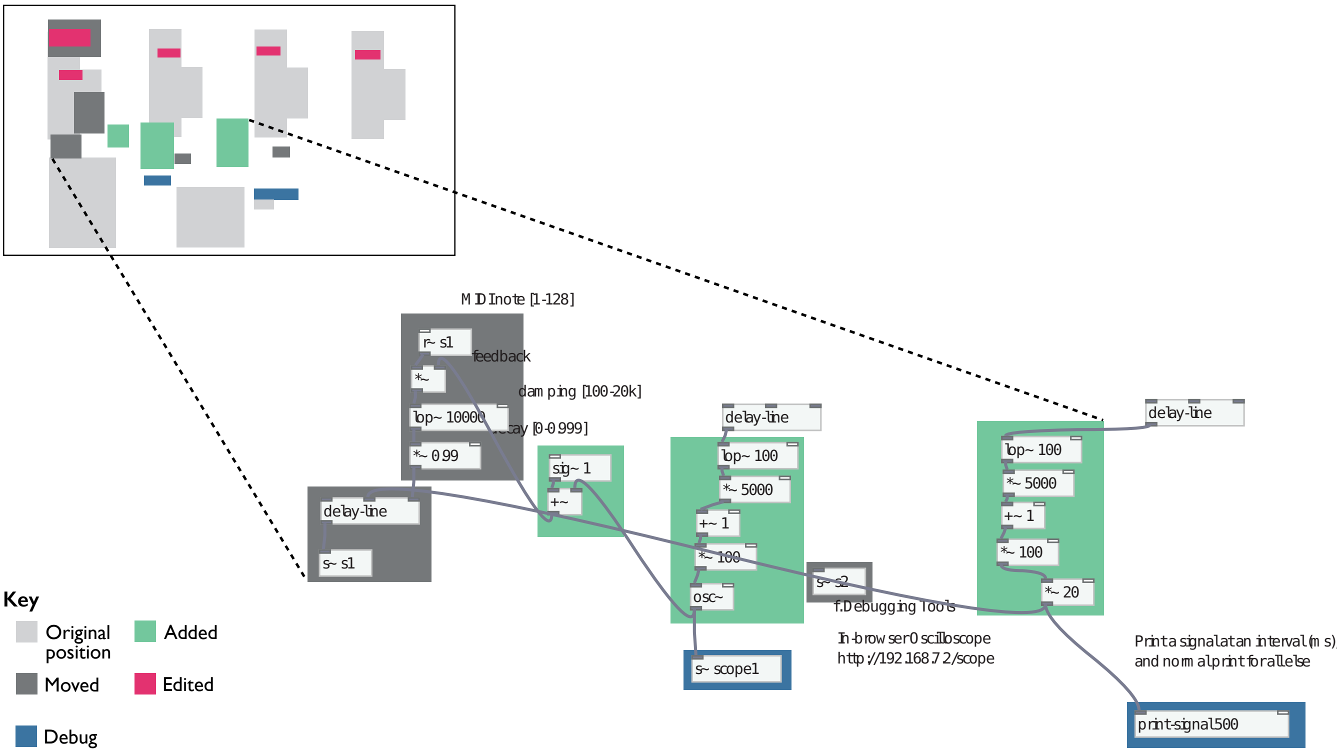
Reflections
A: *Brainstorming amongst experienced people is helpful for this kind of project.*
B: *Tricky in one hour.*

Experience	A	B	C
Playing DMIs	>5	>5	>5
Making DMIs	3-5	>5	3-5
Max/MSP	3-5	1-3	3-5
Pure Data	3-5	>5	1-3
Other lang(s)	3-5	>5	>5

(a) G2's experience levels.



(b) G2's activity over time.

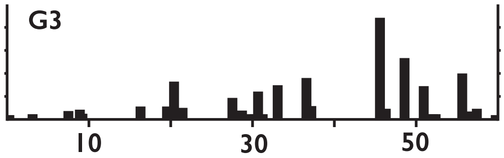


(c) G2's Pure Data patch, with detail.

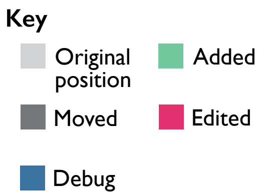
Figure 6.5: G2's experience level, activity over time, and Pure Data patch. See Section 6.3.2.2.

Experience	A	B	C
Playing DMIs	>5	1-3	1-3
Making DMIs	1-3	≤1	≤1
Max/MSP	≤1	≤1	1-3
Pure Data	≤1	1-3	1-3
Other lang(s)	>5	1-3	≤1

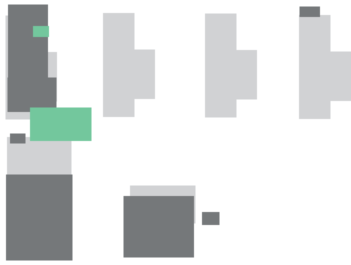
(a) G3's experience levels.



(b) G3's activity over time.



(c) Key.



(d) G3's patch summary.

Figure 6.6: G3's experience level, activity over time, and Pure Data patch. See Section 6.3.2.3.

6.3.2.3 *Group 3*

Group 3 each had some Pure Data experience (Table 6.6a). They analysed the instrument architecture and discussed ideas for modifying it.

First impressions

B: *As it was before modification [...] It had some potential for renovation.*
C: *Not very responsive. "Ordinary" interaction not very inspiring.*

Goals at the outset

A: *Our goals focused on the interaction (how to play the instrument).*
B: *Improve existing "problems" (unresponsive to touch) and create new sounds.*

Verbal discussion was prominent in their group process, which sometimes seemed to produce hesitation and withdrawal. They were at times silent and did not interact with the instrument. Their main idea involved combining discrete and continuous interactions to produce a rich and sustained sound.

Group process

A: *Partly based on a deterministic approach. Partly a "trial/error" method.*
C: *Tried to test [ideas] fast and decide based on the results.*

Crafting process

A: *From a keyboard to an instrument with continuous and discrete interaction.*
C: *We found some interesting ideas, but returned to our first one due to time.*

Overall the outcomes were judged to be insignificant, and the technical aspects of the activity seemed at odds with the collaborative aspects. Without prompt, they deleted some of their patch additions just before the end of the session (restored in Figure 6.6d).

Outcome

B: *Hour didn't seem long enough to make significant changes to synthesis.*
C: *Only a minor improvement compared to the starting point.*

Workflow

A: *Part of our efforts was put in figuring out how to implement our idea.*
B: *The need for approval of team meant that ideas were held back.*

Reflections

B: *Perhaps better suited to working independently.*
C: *Frustrating that we didn't manage to build something different/better.*

6.3.2.4 *Group 4*

Group 4 had two out of three participants experienced with Pure Data (Table 6.7a). They explored in detail the interaction possibilities of the instrument. Unlike Groups 1-3, they took particular interest in the physicality of the instrument.

First impressions
> **A:** *Exciting - blank canvas of possibilities.*
> **C:** *Curiosity, desire to play, experiment, explore.*

Goals at the outset
> **A:** *To make interesting sounds with a definable interactive capabilities.*
> **C:** *Explore sounds and interactions made inspired by the physical setup.*

Participant C, who had no Pure Data experience, decided to take the role of a performer while A and B modified the patch. They were quick to ideate, and were the only group to make a significant patch update in the first ten minutes (Figure 6.7b). They aimed to create sustained sounds, which led them to explore adding delay lines (Figure 6.7c) and acoustic feedback.

Group process
> **A:** *Discussion on how to achieve something technically, then implemented.*
> **C:** *I ended up being the player, the others were focused on the design.*

Crafting process
> **B:** *It developed however lack of debug lead to some issues.*
> **C:** *We found ways to actuate the sensors tapping w/ pencil, singing, etc.*

Participants A and B felt that they made progress but did not have time to refine their work. Participant C offered their performer-centric account of the activity.

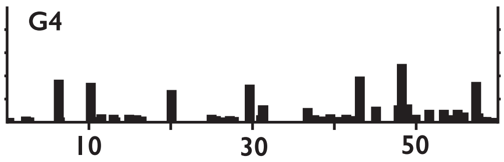
Outcome
> **A:** *Would have loved more time. Didn't even start on pitch manipulation.*
> **C:** *Interested in using it in a jam [...] with other instruments and musicians.*

Workflow
> **B:** *Functionality was built but not really fine tuned.*
> **C:** *Much more intentional and planned with the group than if I was alone.*

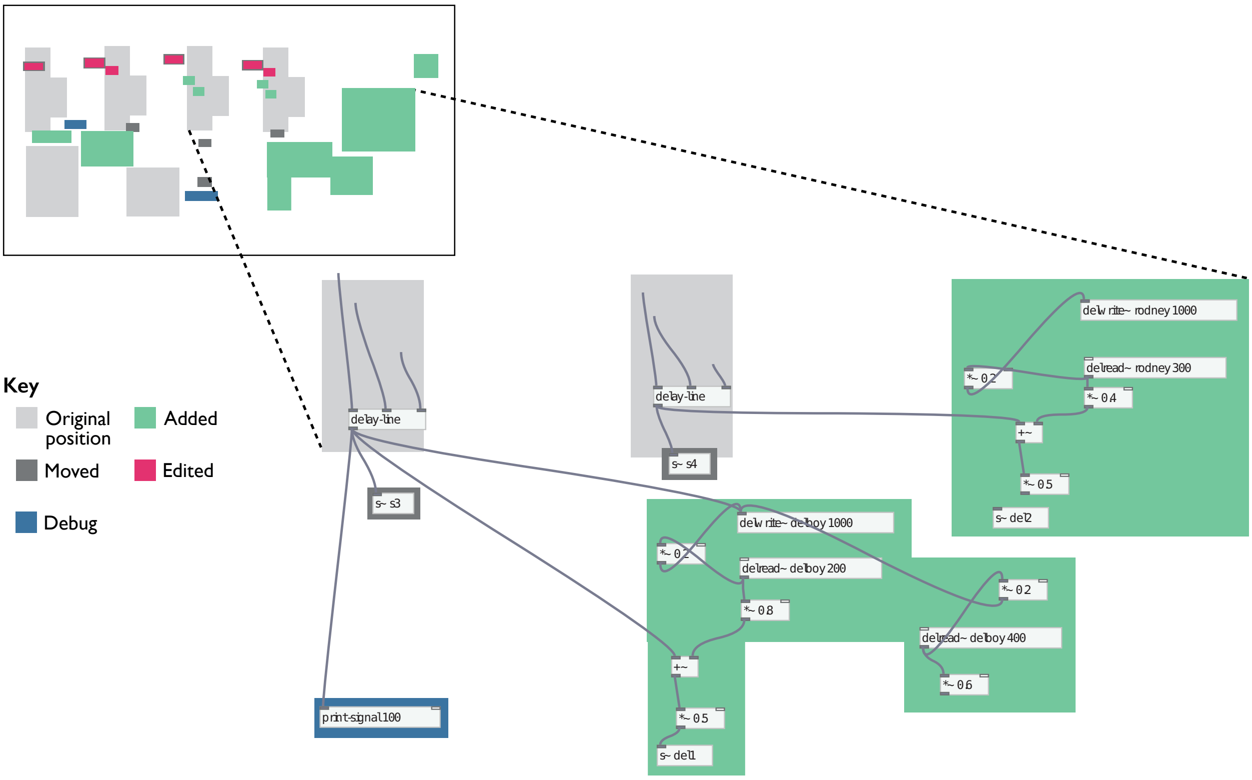
Reflections
> **A:** *I like working in a group, although workflow is slower.*
> **C:** *Makes me want to play with physical acoustics more for making music.*

Experience	A	B	C
Playing DMIs	>5	>5	>5
Making DMIs	≤1	>5	>5
Max/MSP	1-3	>5	1-3
Pure Data	>5	>5	-
Other lang(s)	>5	>5	>5

(a) G4's experience levels.



(b) G4's activity over time.



(c) G4's Pure Data patch, with detail.

Figure 6.7: G4's experience level, activity over time, and Pure Data patch. See Section 6.3.2.4.

6.3.2.5 *Group 5*

Group 5, the *Physical Materials* (**PM**) group, were second-least experienced with Pure Data (Table 6.8a). They initially investigated the Pure Data patch, exploring its affordances and constraints.

First impressions

A: *An effective way of playing string sounds using low tech components/build.*
B: *Interesting but difficult to draw expression from it as a musical interface.*

Goals at the outset

A: *I would have liked to retune it so that it played just intonation chords*
C: *Basically I wanted to create a physical system that produce vibration*

After initially modifying the sensor response in the patch, they gradually ignored the patch and focused towards physical exploration (Figure 6.8b). They eventually discovered the use of credit cards as plucking tines and optimised this design (Figure 6.8e). There was an attempt to further modify this sound using a *voltage controlled filter* object, but this was abandoned.

Group process

A: *We all played with the materials and jointly decided what changes to make.*
B: *Determined skillsets, bounce off people's ideas, play with tools/materials.*

Crafting process

A: *We changed the gate to increase the sensitivity of the microphones, then added credit cards to be plucked and vibrate on the microphones.*

The group noted the difference between the physical and digital materials, and felt their limited time was better spent working with the former.

Outcome

A: *It would've been interesting to use one sensor as a modulator for the others.*
C: *I liked the result [...] of bringing physicality to software sound generation.*

Workflow

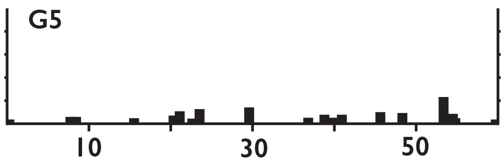
B: *It was slow to develop the digital audio part so that was left unchanged.*
C: *Definitely it lead us to gain better results in shorter time.*

Reflections

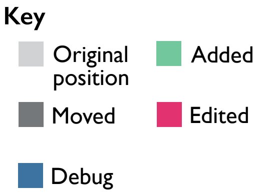
A: *It would have been interesting to see the results if there was more time.*
B: *Working with physical objects is a lot more engaging, it had a LEGO type aspect to it. Very open ended.*

Experience	A	B	C
Playing DMIs	1-3	>5	≤1
Making DMIs	1-3	≤1	≤1
Max/MSP	-	≤1	≤1
Pure Data	1-3	>5	-
Other lang(s)	≤1	>5	-

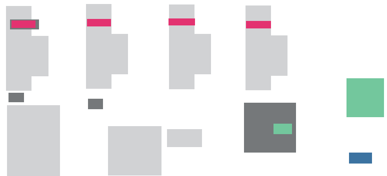
(a) G5's experience levels.



(b) G5's activity over time.



(c) Key.



(d) G5's patch summary.

(e) G5's instrument with plastic card plucking tines, adorned with eyes.

Figure 6.8: G5's experience level, activity over time, Pure Data patch, and instrument. See Section 6.3.2.5.

6.3.3 *Session themes*

This section presents observations made about the workshop in an approximately chronological way, beginning with familiarisation and ideation, implementation patterns, evaluation and iteration, and finally demonstration of outcomes by the groups. The topic headings suggest discrete transitions from one type of activity to the next, but the actual activity was fluid across them. Some groups were already ideating while familiarising, and some skipped discussion of ideas and went straight to experimenting with implementation. Some groups stuck to implementing a few key ideas generated early on, while others continued to broaden their exploration throughout.

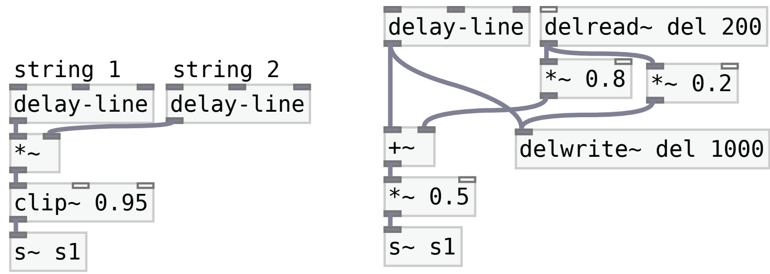
6.3.3.1 *Familiarisation and ideation*

After being introduced to the workshop brief and materials, the groups showed little hesitation in accepting their task and assessing the possibilities available. The initial activity across the groups involved exploring the instrument's responses to different gestural interactions with the mics, which included tapping, hitting, rubbing and scratching. From this, the groups perceived the mic response to be lacking sensitivity, and accordingly they adjusted the mic processing parameters to alter the response. Having made these adjustments, the groups also became familiarised with the procedure for editing the Pd patch and updating the instrument. They concluded overall that the Pd patch and thus the overall instrument was "minimal" (G4), "basic" (G4), "limited" (G2), "simple, essential" (G3) and while not necessarily "inspiring" (G3), it showed "potential" (G4) as a "blank canvas of possibilities" (G1) and a "good starting point" (G4). Subsequently, the groups engaged briefly in ideation through discussion, referencing gestures they were making with the instrument, making comparisons to their own experiences and seeking out common frames of reference.

6.3.3.2 *Mapping across the patch*

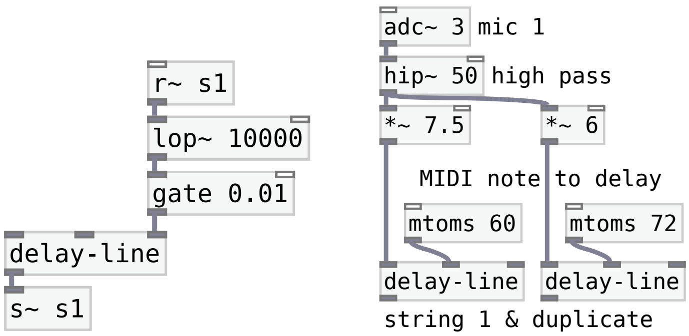
Rather than accepting the Pd patch structure as a given and working within it, in most cases the groups took advantage of its flexibility and explored making new connections across the structure. Here we describe four specific example mappings (Table 6.4, Figure 6.9) and then reflect on their use of the patch as an ideas canvas. Two examples come from Group 1 (G1 A & G1 B), a more experienced group, and two examples come from Group 3 (G3 A & G3 B), a less experienced group.

In example G1 A (Figure 6.9a), G1 multiplied the outputs of String 1 & 2 together. They mentioned that this approach was referencing *frequency modulation*, where one string could act as a carrier and another a modulator. In example G1 B (Figure 6.9b), G1 inspected the 'delay-line'



(a) **G1 A**: Audio multiply String 1 & 2.

(b) **G1 B**: Delaying a string.



(c) **G3 A**: Gating string feedback.

(d) **G3 B**: Duplicating in unison (1oct).

Figure 6.9: Pure Data mappings across mics and strings (laid out and commented by the research author).

abstraction, and added a similar extra delay to a string. Adding further delays to other strings, they created implicit relationships between them by giving them different delay times.

In example G3 A (Figure 6.9c), G3 took the 'gate' abstraction used to eliminate background noise from the mic inputs, and inserted it in place of the decay parameter of a string. This reduced the feedback signal much more rapidly than the decay parameter, creating a much more percussive envelope. In example G3 B (Figure 6.9c), G3 duplicated String 1 and connected Mic 1 to its input, decreasing the input gain of the mic and increasing the string pitch by one octave, creating a unison effect. With this move, they were proving the concept of triggering chords or harmonies from a single input.

	Input(s)	Transform(s)	Output(s)	Impact
G1	Mic 3 & 4	Audio multiply plus MIDI note	String 3 & 4 pitch	More timbre complexity
G2	String 2 & 3	Low pass filter & scaling audio signal	String 1 decay & pitch	Transient sound, complex timbre
G3	Mic 4	Audio envelope	String 4 excitation	Implementation unsuccessful
G4	Mic 4	Audio as control data & addition	String 3 & 4 pitch	Brighter timbre
G5	Mic 4 & String 1	Low pass filter & scaling audio signal	Additional filter cutoff	Audible filter sweep

Table 6.3: Attempts to turn a signal into a control structure.

	Input(s)	Transform(s)	Output(s)	Impact
G1 A	String 1 & 2	Audio multiply & clip	Audio output	Inaudible
G1 B	String 3 & 4	Add extra delays & scale gains	Audio output	More sustain & polyrhythmic delay
G3 A	String 1 output	Audio gate (taken from mic input)	String 1 feedback input	No sound produced
G3 B	Mic 1	Audio addition	String 1 duplicate +1oct	Brighter timbre

Table 6.4: Other mappings created by the groups.

6.3.3.3 *Audio signal-based control structures*

Most groups became interested in the idea of using the audio-rate sensor data to manipulate control data in the patch. However, implementing the low level operations for translating between the audio and control domains were a point of friction. This suggests a certain inherent desirability about this type of idea, and that reducing the friction around it would prove useful.

Each group attempted at least once to use the mic input audio signal in or as a control structure (Table 6.3, Figure 6.10). This could have been motivated by the lack of real-time patch editing capabilities and the lack of additional physical inputs, but equally also by extraneous factors. What was observed in each case was that the participants did not find this process intuitive, regardless of their level of experience. In this section, we highlight three examples of difficulties they faced and discuss their impact on the groups' design progress.

G1 used Mic 3 & 4 to control the pitch inputs of String 3 & 4 (Figure 6.10a). They wanted to "knock the pitch a bit", and added an extra gain control ('[*~5]') to experiment with this. The resulting effect was a transient timbral effect, which while interesting was different to their idea which was imagined to be affecting the pitch on a longer timescale. Despite this, they did not consider an implementation affecting the temporal shape of the signal and stuck with a simple math operator.

G2 filtered and scaled the outputs of String 2 & 3 to control the decay and pitch inputs of String 1 (Figure 6.10b). They wanted Mic 2 & 3 to modulate String 1 such that the player would need to excite three inputs simultaneously. They chose to use the string outputs rather than the direct or processed mic inputs. Their approach was to low pass filter, scale and translate the string signals, trying parameter values ranging over a number of orders of magnitude. They were somewhat satisfied with their result, but could not compensate for the low mic sensitivity.

G3 used Mic 4 to generate a ramp that was combined with Mic 1 before reaching the excitation input of String 1 (Figure 6.10c). Their idea was to give the player control over the amount of "drone" coming from String 1, via Mic 4. They attempted to use an envelope follower to trigger a ramp, but used the output from the high pass filter and omitted the signal scaling multiplier, meaning the ramp was not triggered. Eventually they abandoned this implementation effort.

G4 used relational operators based on discrete samples of Mic 4 to control the pitch inputs of String 3 & 4 (Figure 6.10d). They originally wanted to control the pitches using a horizontal slider object in Pd, but realising this was not possible with the non-real time workflow, they tried to implement a control structure that would allow pitch to vary based on Mic 4 input. The figure shows their working implementation, but prior to this their patch spent some time in a state where zeroes were being sent to the string pitch input, causing a repetitive clicking sound which they assumed was occurring in time with their metronome. Their initial threshold values were several orders of magnitude too large, which they discovered after converting the control signal back into an audio signal and visualising it on the oscilloscope.

G5 processed String 1 with a voltage-controlled bandpass filter, with a filtered and scaled Mic 4 as the centre frequency (Figure 6.10e). They wanted to use Mic 4 as a breath controller for String 1. Unlike other groups, they started by visualising the Mic 4 signal on the oscilloscope. They were able to create an audible effect, but were not completely satisfied with the level of control.

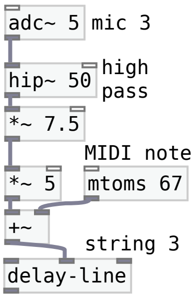
In each of these cases we could summarise these approaches, which were recalled from memory rather than discovered for the first time, as having memorable ingredients, but forgettable recipes. The elements required to turn a signal into a control (filter, scale, etc.) were not difficult to remember, but we did not observe an effective and repeatable approach to devising their ordering and parameterisation for a less than ideal sensor. Such a recipe might have included more extensive and consistent use of debugging tools, which was only observed to a degree. Overall, these difficulties impacted the pace of design progression in the groups and led to some frustration, as these tasks were perceived to be simple stepping stones to the more sophisticated ideas they were attempting to realise.

6.3.3.4 *Evaluation, iteration and final demo*

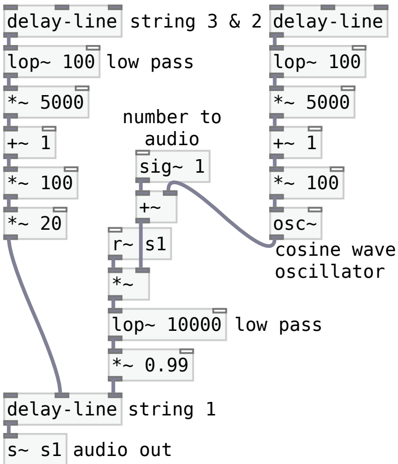
Opportunities to evaluate the instrument came at regular intervals due to the nature of the software update process. At these intervals, the groups would typically play, listen, consider and discuss before deciding what to do next. There were various evaluation outcomes and decision-making at each stage.

Firstly regarding evaluation, the groups decided that either the implementation was working as planned or not, that in either case the result itself was interesting or not, and if any surprising outcomes occurred that were worth considering. Secondly, decisions had to be made as to what to do next. If an idea was working and interesting, they could go forward and refine, reimplement or add extra features, and if not they had to decide whether it was worth persevering. If an idea was working but uninteresting, or not worth pursuing further, they could go back to older ideas or propose new ones.

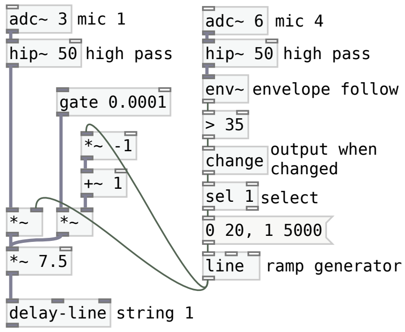
In all but a few cases where discarded ideas were deleted from the patch, the groups scattered their ideas across the Pd patch. Some used different mic-to-string algorithms to trial different ideas. In this way, multiple ideas were often represented simultaneously either explicitly or implicitly in the patch (through orphaned objects for example), like in a sketchbook. The final patches represented a snapshot of their process in some cases, as much as a specific design intent.



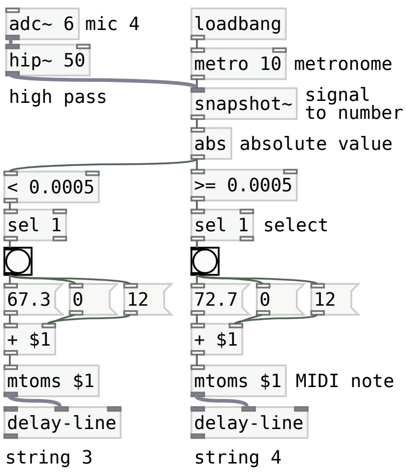
(a) **G1**: Mic 3 & 4 controlling pitches of String 3 & 4



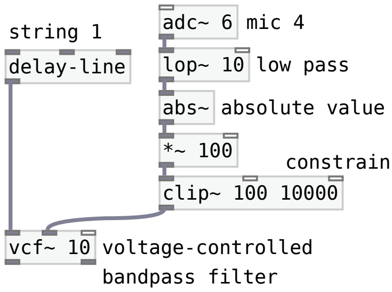
(b) **G2**: String 2 & 3 to String 1 decay & pitch.



(c) **G3**: Mic 4 ramp combined with Mic 1 exciting String 1



(d) **G4**: Mic 4 to String 3 & 4 pitch select.



(e) **G5 (PM)**: String 1 to filter input, Mic 4 to filter centre frequency.

Figure 6.10: Pure Data patch excerpts of signal to control structures (laid out and commented by author).

The groups were asked briefly at the end to summarise their activity. G1 commented on the time limit as a stringent constraint: "it feels like you would need a lot of time [...] even a day would be good [...] you could even plan it a bit". G2 made a cogent reflection about their process: "realising the limitations of the inputs and then scale the design to match something that could be interesting with those inputs". G3 described that initially they "analysed the system, and we outlined its parts, and then we decided on which part to focus our work", although the outcomes did not follow the plan they formed. G4 felt their attention was drawn to timbre: "we had to stick to the more timbral qualities of each individual sound. Because that was the avenue of real-time-ness if that makes sense". G5 appreciated that the hybrid design context "kind of brings a reality because the sound produced in the end is a result of a physical system".

6.3.3.5 *Support probes mostly ignored*

Various support probes were provided in the crafting environment; a system diagram of the Karplus-Strong model, whiteboard, paper, printout of Pd objects, and utilities in the patch for using the oscilloscope and printing signals to the console. Some groups used paper to aid in sketching out and communicating an idea before testing it, and some groups used the Pd objects printout. Some groups used the oscilloscope and console, but much less than expected. No groups annotated the model or used the whiteboard. Overall, it felt like groups could have made more use of the design aids around them, yet they chose not to. Maybe they were not familiar with the value of the design supports, or their value was not worth the switching cost of using them. The groups must have felt overall that their verbal communication was strong enough to see them through, however the communication issues present would appear to contradict this.

6.3.4 *Activity by scale of detail*

Overall, there was an absence of macro scale design exploration across the sessions. The visual summaries of the Pure Data patches demonstrate this, where the original template materials are mostly left intact (Figure 6.2). Macro scale interventions may have included rearchitecting the patch, altering the existing abstractions or creating new ones, or transforming the physical model's structure and parameters. This suggests that this particular scenario was poor at facilitating these types of operations, or that the groups were not motivated in that direction for other reasons, though the two could be related. Nonetheless, the lack of interaction with the damping and decay parameters was suprising, as they were relatively accessible leverage points for dramatically altering the timbre and envelope of the sound.

The most common types of design intervention lay at the meso scale regarding mappings. As described in Section 6.3.3, examples of these included creating control signals from audio signals and using them to alter mappings, cross-mapping sensors and delay lines together, and adding extra delay lines and mapping those on top of the existing patch. Some of these changes did make affect timbre fairly radically, but the resulting DMIs were still similar enough across the group to be able to compare them at the meso scale. Patching wires semi-randomly requires almost no forethought, is easy to do, and can result in novelty, which may go some way to explaining the motivation for this type of activity.

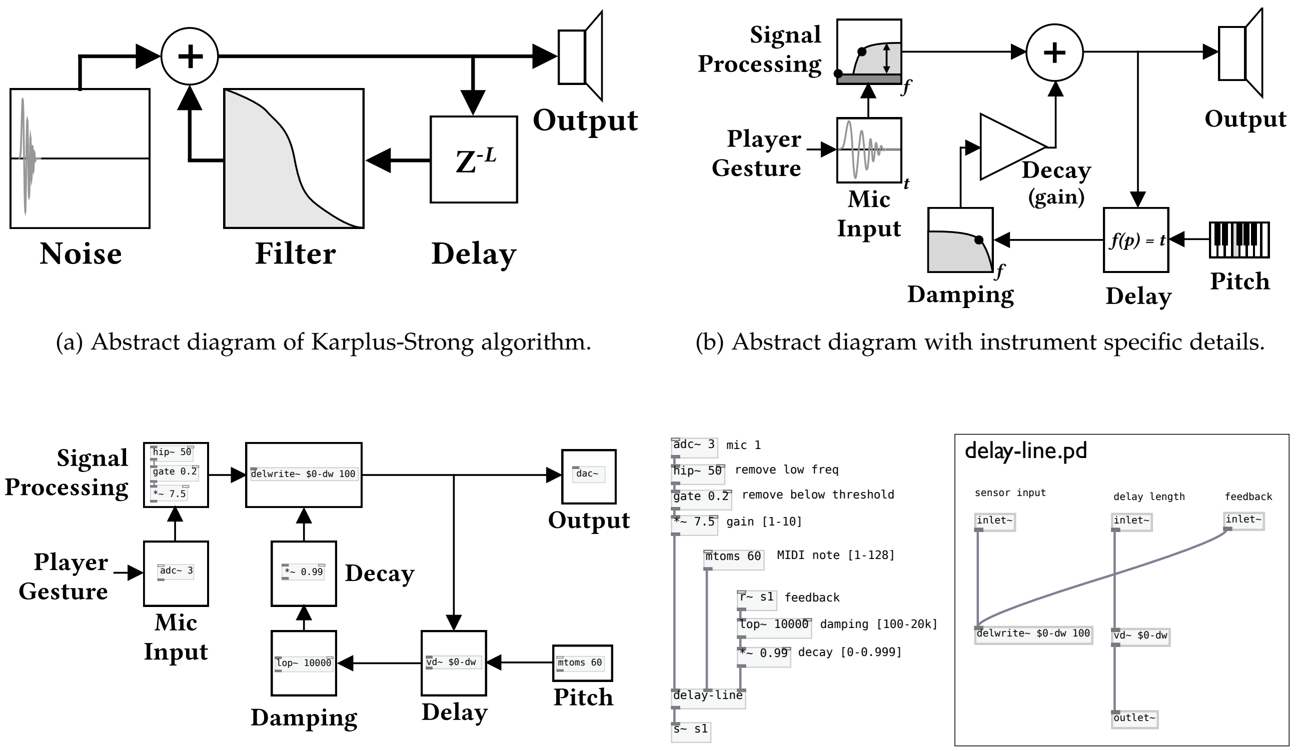
In terms of micro scale details, four out of five groups edited the input signal processing parameters, in an attempt to improve the response of the inputs (highlighted in red in Figure 6.2). All else being equal, this response would be comparable at the micro scale across the groups, however in all cases, the groups did not explore any further than tweaking the parameters for gate threshold and gain and so on. This could be because they felt the improvements achieved were 'good enough' to continue on with, and that there was much more patch to explore in the short time frame. Either way, this was not a significant sum total of design activity upon which to base detailed analysis. And while there were some instances of groups settling on some meso scale changes and then attempting to refine them further, they did not progress very far with them, and neither were these meso scale changes ultimately comparable at the micro scale across the groups.

6.4 DISCUSSION

6.4.1 *Bricolage and tinkering in a hybrid craft context*

Vallgårda and Fernaeus' bricolage explicitly encapsulates the non-digital aspects of interaction design [297], nevertheless this hybrid workshop's outcomes follow her descriptions of bricolage practice. Similarly, tinkering approaches with physical DMIs have been described as sharply contrasting with software-based explorations [195], and yet we also identify certain similarities. We believe these processes share a situated exploration of the design patterns and changes that are most immediately reachable, regardless of whether the tinkering is occurring with physical or digital tools.

It is from one perspective common sense that any complex process must be composed of simpler steps, and that the simpler steps are by definition one step away from the previous step. However, at each step the materials being used — in this case mostly Pd — exert a creative pull [126], and in these workshop outcomes we saw design patterns reappearing frequently that hint at this influence. Frequently the participants' design moves were composed of individual steps, as



(a) Abstract diagram of Karplus-Strong algorithm.

(b) Abstract diagram with instrument specific details.

(c) Abstract diagram with Pure Data objects used.

(d) Pure Data implementation of Karplus-Strong algorithm.

Figure 6.11: Intermediate stages of interpretation by an instrument designer when implementing the Karplus-Strong algorithm in Pure Data, informed by language idioms, aesthetics and other contextual factors.

part of an iterative process where a step was taken, re-evaluated and new steps were chosen. The programming system's representations seemed to highlight or encourage connecting disparate parts of the Pd patch experimentally, inspiring a tinkering approach which previous work has argued is more exclusive to hardware-based processes.

Another aspect of bricolage that we felt was present was the growing of a *treasury* or inventory of design ideas and implementation experiences. Examples of contents in the groups' treasuries included interaction gestures, interaction ideas, their shared Pd vocabulary, and the disconnected Pd patch parts that were kept rather than deleted. Frequently the treasury was indeed returned to when deciding how to iterate based on particular evaluations. Although the "signs" Lévi-Strauss referred to were conceived as half-way points between concrete images and abstract concepts [163], it could be considered how programming environments can aid users in building, tracking and recomposing their treasuries.

6.4.2 *Diverging human and machine representations*

For the given activity and time constraint of this workshop, and the complexity level of the ideas the participants wanted to tinker with, it appears that the level of abstraction of Pure Data was perhaps too low. To illustrate this, Figure 6.11 shows the mentally complex transformations required to go from a high-level system diagram of the Karplus-Strong algorithm, to a working implementation in Pure Data. If the participants were having to do these kinds of transformations at some level of awareness, on a more or less constant basis, then it seems reasonable to assume that their cognitive overhead during the activity would have been fairly high.

The consistency across groups of attempting audio-signal based control by filtering and scaling, and the struggle they faced in achieving this, might suggest a latent set of primitives for audio-rate sensing oriented embedded DMI design platforms. These primitives would condition audio-rate signals into control signals, smooth them out and scale them into desirable numerical ranges, perhaps offering different interpolation methods. In some sense they would encode the recently accumulated knowledge of digital luthiers over the past two or three decades regarding effective mapping methods, and instantiate that knowledge similar to how animation tools instantiate Disney's twelve basic principles of animation [284].

Victor argues that a programming environment should enable an author to "create by abstracting — start concrete, then generalize" [303]. In our workshop, we did not witness anyone creating their own abstractions explicitly, although it could be argued that copying and pasting small programs they created could be considered as a form of implicit and weak abstraction. We did not poll participants about abstractions, so we can only speculate that the available methods for composing and decomposing abstractions were too costly in time, labour and cognitive overhead to be worthwhile in this context. In turn, we suggest the need for methods of abstracting to become more responsive and contextually aware to facilitate rapid and commonplace usage.

6.4.3 *Workflow liveness and iteration time*

Recalling Tanimoto's liveness levels described in Section 6.1.1, the update procedure in this workshop, which was measured to be approximately seven seconds in duration from saving to hearing the patch again estimates how long each group waited for compilation, shifted Pd from liveness Level 3 (or 4 if using GUI objects) to 2 — a non-live executable flowchart. The positive outcome of this trade is the increased level of performance and integration of the resulting instrument, which can run standalone, at low latency, and with high-bandwidth sensing, such that the designer or performer can evaluate the instrument holistically and in-situ [212].

In trading off liveness for integration, the digital luthiers gains certain advantages. For example, once they became familiar with the mics' physical responses, they used them to rapidly and holistically evaluate changes. They used their musical and tactile skills to quickly feel out the behaviour of the instrument, internalise it, and reconcile their expectations of the program's behaviour with the actual behaviour they observed. Based on this, we suggest that the availability of high levels of integration during the design process affords the digital luthier the ability to engage directly with instrumentality which Hardjowirogo defines as "that which defines a musical instrument as such", "the essence of the musical instrument", and "specific instrumental quality" [105].

Equally, there were a number of disadvantages to the decreased liveness level of the workflow. The seven second save-upload-recompile-run stage, which replaced live program editing, felt costly ("It was slow to develop the digital audio part of the instrument, so it mainly was left unchanged" — G5) to the groups. Any change, no matter how large or trivial, required the same amount of effort to experience, which required an entirely different approach than the participants were familiar with. Based on these outcomes, we suggest that when workflow liveness in DMI design contexts is decreased, the impact on design thinking is both quantitative and qualitative: less design moves are possible in the same window of time, entire categories of ideas are rejected, and other categories are not thought about at all.

One of the more experienced participants from G2 commented that they would rather work offline without the instrument in order to reverse the trade off of liveness and integration ("What I would normally do here is just work with not with that controller for a bit but just in Pd normally just listening to it in real-time"). For this participant, and perhaps others who noted the workflow speed, seeking liveness instead of integration would have been worthwhile.

6.4.4 *Reflections on the apparatus and activity*

As described in Section 6.2.4, the main two differences between the apparatus and activity in this study versus the previous one (Chapter 5), were switching from co-located groups to individual groups, and from physical crafting materials to Pure Data patching. Overall the media lab setting was more focused towards design rather than blending design with performance as was observed previously, probably because there was no 'audience' to perform to. However, working in groups still clearly impacted the outcomes a great deal.

More so than previously, the groups were dealing with issues of creative consensus. Each individual participant had their own way of approaching this activity, but the groups operated politely and democratically, with usually a single Pure Data 'operator' being the final arbiter. This meant that each design step was subject to discussion and agreement before proceeding, and given the time constraint this limited depth of exploration. The need to verbally communicate about proposed changes also slowed down the process. Discussing the Pure Data patch often required explicit and technical language in order to be clear. As a result, responses were constrained by what could be articulated, unless the Pure Data operator made a unilateral decision. In some cases communication was less verbal, however this is hard to quickly establish with strangers. Overall, the group structure itself limited depth of exploration in a number of ways.

An advantage of working with singular rather than multiple groups was that loudspeakers with higher power could be used without disturbing anyone else. Keeping the rest of the DMI kit the same, to be able to compare with the previous study, meant that once again the DMI's input sensitivity proved to be an issue. The groups did try to optimise the DSP to improve sensitivity, but didn't get very far as mentioned in Section 6.3.4, and this similarly reduced the satisfaction of exploring micro scale details. From this we can conclude that the quality and richness of the detailed features of the DMI/DMI kit are extremely important for motivating engagement with micro scale details.

6.4.5 *Comparison across studies*

In Section 4.4.5, we discussed how violin luthiers are able to focus on micro scale details largely due to the macro and meso scale cultural constraints on their practice. This enables violin luthiers to constantly pursue methods to make micro scale details more familiar and flexible, the experience of which accumulates as embodied expertise (Section 2.2.2). In contrast, in both this study and its predecessor (Chapter 5), there were no explicit external constraints on the macro or meso scale, since the briefs were suggestive rather than tightly constraining. Whether participants chose to focus on macro or meso scale features depended on their backgrounds and motivations, and what kind of leverage — low cost actions with high impact results — the design materials provided. In Chapter 5, the physical crafting materials provided leverage for macro scale changes, whereas in this chapter the Pure Data patches provided leverage for meso scale changes. In both cases, the participants quickly identified and exploited these leverage points.

The extent to which they could exploit them also depended on their familiarity with the materials, which, in the case of the physical craft materials in Chapter 5, was extremely high. Participants focused on macro scale features because of the macro scale flexibility of the design environment, and the lack of constraints on macro scale design. Though they were able to modify the DMI's software and mappings, these were far less accessible and flexible. In this study, participants focused on meso scale features (mappings), because of the relative meso scale flexibility of the design environment compared to the macro or micro scales. Making macro scale changes to the Pure Data patch was time-consuming and error-prone, whereas alternative mappings could be explored with relative ease. Participants' everyday tacit knowledge was less applicable with Pure Data, contributing to a slower pace than in the previous study. Group 5 (PM) had access to both the physical materials and Pure Data patch, and responded to the increased macro scale flexibility of the instrument compared to the meso scale flexibility of the software. In other words, they found higher leverage in the macro scale flexibility and familiarity of the physical compared to the Pure Data patch.

These outcomes from the first two investigations point towards scale-based constraints as being critical to motivating micro scale design activity. Our reflections suggest that participants will only focus on micro scale details, if they accept macro and meso scale inflexibility of the design environment due to some external constraints; micro scale flexibility is only pursued in earnest as a result of macro and meso scale inflexibility. If participants accept external constraints on macro and meso scale features, they would then direct themselves to discover ways to increase familiarity and flexibility of the design environment at the micro scale. They would be supported in these efforts if they can make use of pre-existing expertise, which is the case with familiar crafting materials. However, if the materials are unfamiliar, they will find it difficult to perceive and manipulate micro scale details, resulting in reduced motivation and design progression.

6.5 conclusion

This chapter has presented the outcomes of a group-based DMI design activity involving manipulation of a Pure Data patch, which was designed to contrast with a previous study involving physical crafting materials instead (Chapter 5). In both activities, participants were encouraged towards micro scale design activity, but in this case the scenario did not seem to readily lend itself to either micro or macro scale design activity, and meso scale design activity was most commonly observed. Despite the prevailing motivation towards meso scale activity, the groups experienced a number of difficulties. Given an 'unfinished' DMI and a Pure Data patch for one hour, the five groups all showed the desire to directly control the patch using audio signals, but struggled to realise the interactions they envisioned. Translating their ideas about gesture and sound into signal processing and synthesis code was made especially difficult by the decreased liveness of the software environment and workflow. Our interpretation of these outcomes is that both the group-based scenario and the materials used obstructed micro scale DMI design activity. On reflection, we concluded by suggesting that constraining the macro and meso scales of a DMI design apparatus and activity might be a viable way to encourage sustained micro scale activity.

THIS CONCLUDES our investigations with the *Unfinished Instrument* and group-based DMI design workshop activities. Though it did not reveal micro scale DMI design activity, it taught us a great deal about how we might do so. Over the next two chapters, we put our conclusions to the test.

7 MICRO SCALE DMI DESIGN I: APPARATUS FOR SCULPTING DIGITAL RESONANCE MODELS WITH CLAY

I have tried to preserve in my relationship to the film the same closeness and intimacy that exists between a painter and his canvas. This is rather difficult, for in one case only a stick of wood with a tuft of camel hair intervenes between the maker and the finished result. And in the other an elaborate series of optical, chemical and mechanical processes, which become a perfect breeding ground for a lack of intimacy, frustrations, ill-feeling and hostility between the artist and his finished work. So I decided to throwaway the camera and instead work straight on the film with pens and ink, brushes and paint. And if I don't like what I do, I use a damp cloth, rub it out and begin again.

— Norman McLaren, *Creative Process* [203]

This chapter is built on material from "An experimental audio-tactile interface for sculpting digital resonance models using modelling clay", by Armitage, originally published in the proceedings of the <Programming> '20: 4th International Conference on Art, Science, and Engineering of Programming, Porto, Portugal [6].

This chapter describes the design of an apparatus for micro scale DMI design, inspired by the outcomes of Chapters 5 and 6, and used in a study described in Chapter 8. An accompanying demonstration video of its features and workflow is available online[1], and a glossary of terms can be found in Appendix E.1. The apparatus takes the high-dimensional parameter space of a digital resonance model and makes it amenable to sculpting with commonly available modelling clay, with the results being performable on a simple tuned percussion DMI. It achieves this through measuring the impact of the clay on the vibration of an acoustic plate and mapping this onto the digital resonance parameters, and provides the luthier with interfaces for navigating the sculpted resonance models they have created. The result is a simple interaction between the luthier and the sculpting clay, reminiscent in spirit of McLaren's practice of inscribing film directly. However, the analog acoustic input and resonance mapping algorithm imbue the process with a complexity evocative of handcraft in violin lutherie as described in Chapter 4.

1 Audio-tactile sculpting demo, `https://www.youtube.com/watch?v=EtJrk9LywWI`

7.1 INTRODUCTION

7.1.1 *Related research*

In Section 2.2.3, we argued for the centrality of the hands in embodied expertise, which was further supported by the accounts of violin luthiers in Chapter 4. Handcraft is a primary site of interest for investigating subtle and detailed design processes (Section 2.2.4), and craft HCI provides a wellspring of examples for how so-called digital, post-digital and hybrid crafts can explore handcraft's rich possibilities (Section 2.3.2). Arriving at study probe design for DMI design research from this angle, the issue of materiality becomes crucial for guiding the design of new craft materials with suitable "grain" [120]. Whereas desirable material properties are often "given to us for free by nature" [167] in the case of acoustic instruments, with hybrid crafts, material experience is a large part of the design space [17, 144]. Decisions have to be taken about what the hands will be doing, and what this doing will practically mean in terms of digital representations and manipulative affordances [270].

In the case of the probes described in this chapter, their main design decisions fell out of our critique of the material experience of our previous probes (Chapters 5 and 6) with regards to subtle and detailed design. While our previous probes did take advantage of the Bela embedded DMI design platform's low latency and high-resolution sensing capabilities [212], neither the microphone inputs nor the Karplus-Strong string synthesis [145] that we chose inspired micro scale responses from participants. Design decisions related to these issues will be explained shortly, but especially relevant is our exchanging of string synthesis, a model with a few high-level parameters, for resonant filter banks with many low-level parameters [129, 209]. These two digital materials both enable physically-inspired sound synthesis, but the latter kind does not encode a rigid idea of how any given combination of resonances would be produced by a physical object, and this openness proved a vital resource in the study that follows.

An aspect of hybrid crafts that makes them hybrid and not anachronistic, is that digital representations of craft processes and artifacts can be stored, copied, displayed and navigated.The use of such affordances is often conceptualised in design research under the term case-based reasoning [54, 94, 178], but can also be related to craft practice via Lévi-Strauss' notion of the bricoleur's *treasury* [163].That digital materials can provide such facilities, means that researchers can explore their impact on craft processes, for example by investigating scenarios where 'undo' is not necessarily strictly possible in a traditional digital media sense [195].

7.1.2 *Research questions and scope*

This study addresses Research Question 5:

What methods and processes emerge when instrument makers encounter a subtle and detailed design space?

In particular this study addresses the following sub-questions of Q5:

a. What motivates instrument makers and creatives to focus on subtle and detailed design or not in a one hour activity?

b. How do instrument makers and creatives from different domains approach subtle and detailed design?

c. What kinds of comparative activity are present when subtle and detailed design is taking place?

THE NEXT SECTION provides an overview of the apparatus in terms of the interfaces, workflow and system architecture. Following this, successive sections describe in detail the digital tuned percussion instrument, digital resonance sculpting tool, resonance mapping algorithm and session workflow interfaces. Technical detail is offered in this chapter for the sake of the reader's understanding of the study that follows in the next chapter; our approach may well serve no other practical purpose than to answer the specific questions that we set out to address. To avoid misinterpretation, we do not believe that what follows should be regarded as a recipe or technological foundation, since it was not designed to solve any problem other than those encompassed by our research questions. A reader may nevertheless take forward some technical inspiration, in which case we ask them to critically consider such a decision, via for example Postman's six questions for new technologies [248].

7.2 OVERVIEW

7.2.1 *Interfaces*

For this section's glossary, see Appendix E.1.1.

The interfaces that made up this apparatus are depicted photographically in Figure 7.1, and illustrated from the participant's point of view in Figure 7.2. A tuned percussion instrument consisted of four identical wooden blocks each with a piezoelectric vibration sensor mounted underneath. A resonance model sculpting tool consisted of a suspended wooden panel with a piezoelectric vibration sensor and a vibration transducer mounted underneath. The tangible user interface based on a *Sensel Morph*[2] device controlled the sculpting process, and

2 https://morph.sensel.com/

Figure 7.1: Photos of the interfaces. Left: digital tuned percussion instrument (above) and tangible user interface (below). Right: sculpting surface (above left), sculpting tools (above right) and sculpting clay (below). Described in Section 7.2.1.

enabled navigation of previous sculptures along with the graphical user interface. The graphical user interface displayed three panels of information about session state, instrument state and sculptures state.

7.2.2 *Sculpting workflow*

Sculpting in this activity referred to using the sculpting surface, clay and tools to manipulate the digital resonance models that were excited via the tuned percussion blocks. This process was discretised into *Sculptures* which were made up of a sequence of individual *Sculpts*. A *Sculpture* took an existing resonance model and calibrated it to the sculpting surface, and then allowed the participant to manipulate the model based on further changes to the sculpting surface, recorded as *Sculpts*. A *Sculpt* consisted of a frequency response measurement of the sculpting surface, and a new resonance model, created by mapping differences in frequency response to model parameters.

For each *Sculpt*, the mapping algorithm compared the current frequency response with the calibration frequency response, and mapped differences between them to the parameters of the selected preset resonance model, to generate a new model (Section 7.5). Thus, each *Sculpture* represented a set of variations on a specific preset resonance model, related by the physical *Sculpts* that took place.

The sculpting workflow had four steps which were demonstrated during an introductory tutorial, and numbered on the tangible user interface (Figure 7.3):

1. *New Sculpture*: this step created a new sculpture and added it to the session.

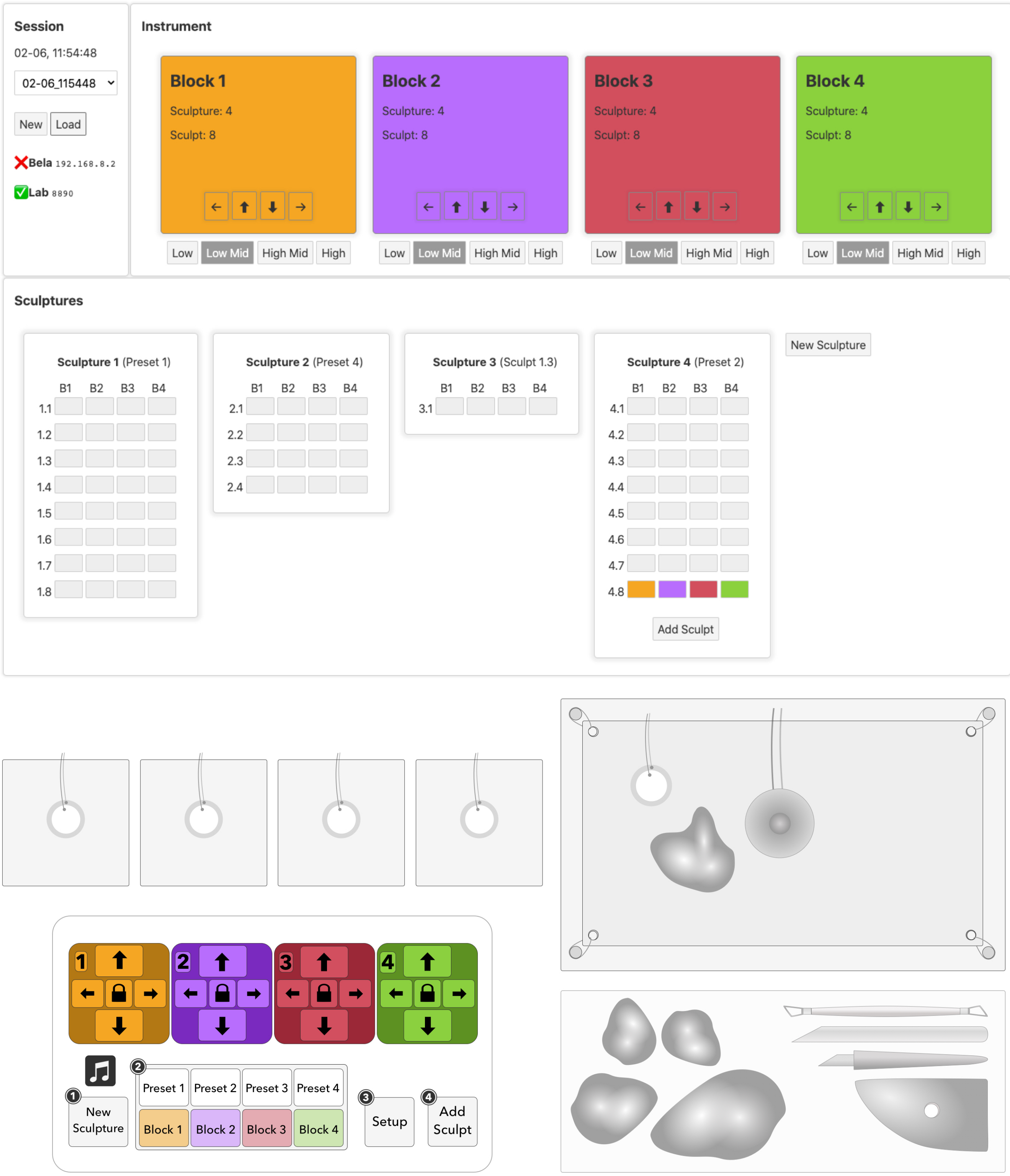


Figure 7.2: Graphic of the workshop's interfaces, as seen from the participant's point of view. Top: graphical user interface. Middle left: tuned percussion instrument. Bottom left: tangible user interface. Middle right: sculpting surface. Bottom right: sculpting clay and tools. See Section 7.2.1.

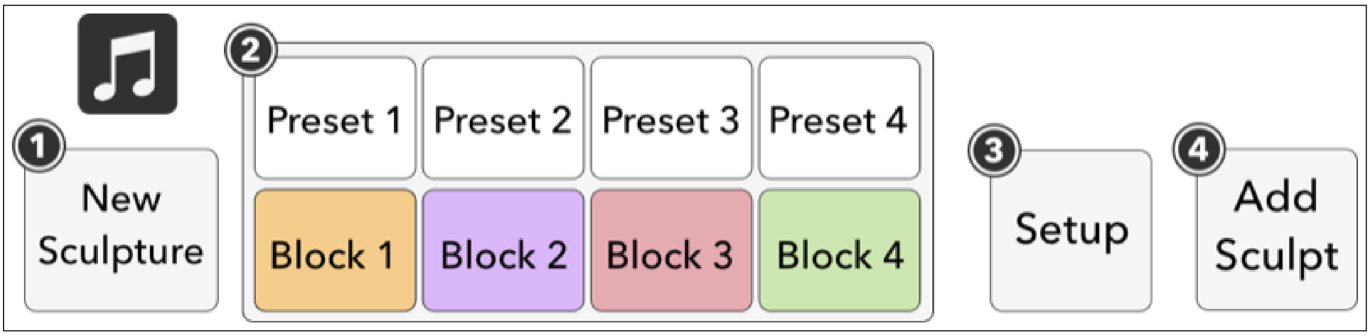


Figure 7.3: Detail of the tangible user interface controls for the sculpting workflow, enumerated to remind the participant of the four steps: *New Sculpture*, *Preset Selection*, *Setup* and *Add Sculpt*. The musical note button toggled the pitches of the tuned percussion blocks between five states: all *Low*, all *Low Mid*, all *High Mid* and all *High* and spread pitches (default). See Section 7.2.2.

2. *Preset Selection*: the participant was prompted to select a resonance model for this new *Sculpture* from four presets. As an advanced feature, existing *Sculpts* could be used as presets by using the block selectors (Section 7.5.4).

3. *Setup*: this step took a frequency response measurement of the sculpting surface as a reference, which thereafter was used by the mapping algorithm to produce new models.

4. *Add Sculpt*: this step was repeated iteratively, and compared new frequency response measurements against the *Setup* measurement to map the resonance model.

7.2.3 *System architecture*

The system architecture is depicted in Figure 7.4. The aspects of the system encountered by the participant were the *Percussion Blocks*, *Sculpting Surface*, *Session GUI* and *Session TUI*. Internally, the tuned percussion instrument ran on a *Bela* embedded system, and the *JupyterLab* scientific computing environment controlled the sculpting surface sampling and mapping processes. The logic required to coordinate interactions between these two subsystems, and handle user inputs, ran in a *Svelte.js Web App*, with a group of *Stores* propagating state changes as needed.

The main constraint driving this architecture was the frequency response measurement. If this was instead performed on the *Bela* device, this would obviate the need for the *JupyterLab* environment and the web application to coordinate them. However, the complexity involved in implementing the measurement and mapping process, and the minimum quality of measurement required for a usable sculpting process,

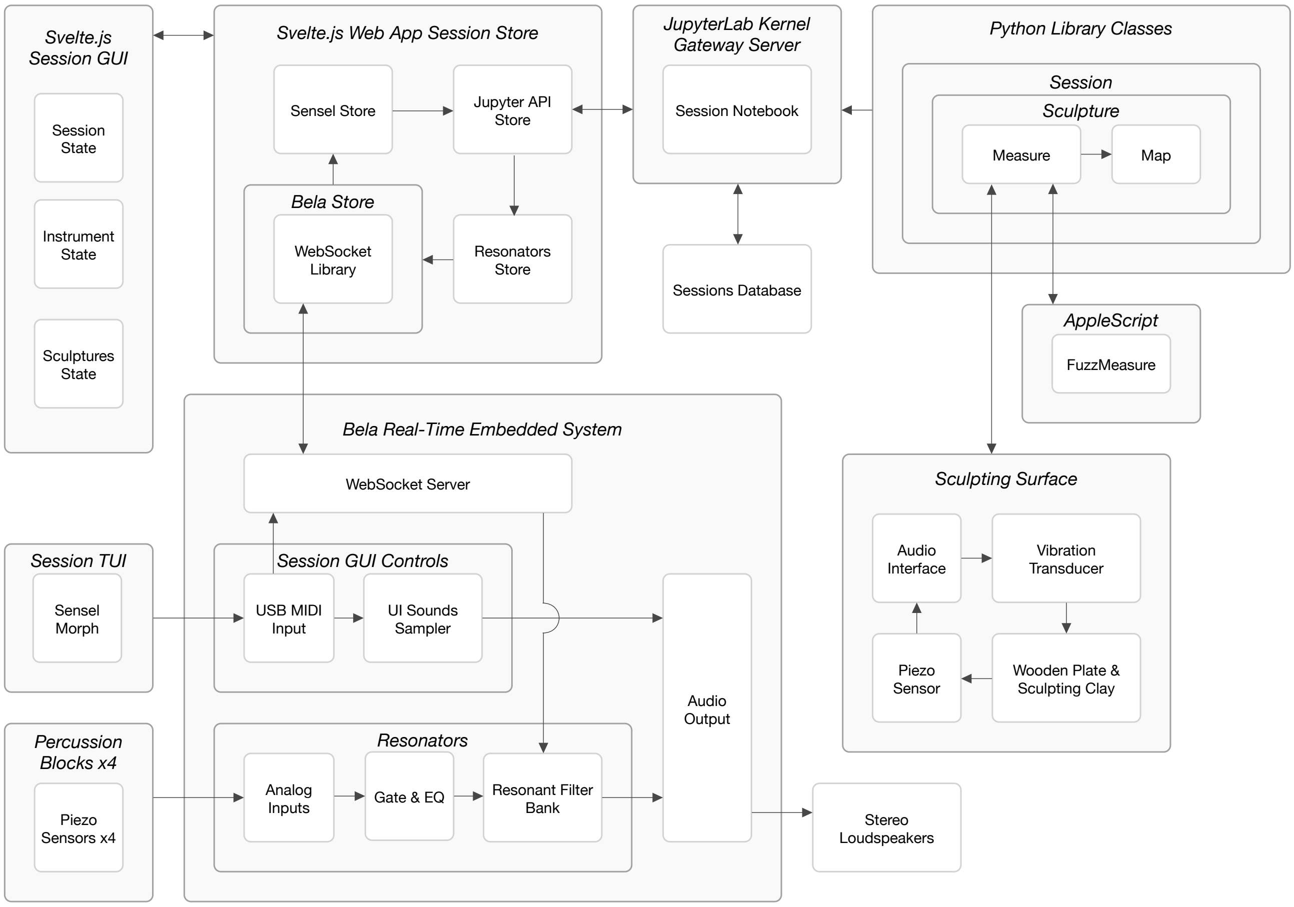


Figure 7.4: System architecture diagram. Described in Section 7.2.3.

meant this was better implemented using specialised equipment and software.

Another constraint that favoured this approach related to the tuned percussion instrument. This approach meant that the resource constrained *Bela* could focus on synthesising larger digital resonance models, giving the tuned percussion instrument higher timbral resolution, and the user more subtle details to work with. As such, the *Sculpting Surface* took measurements using a dedicated *Audio Interface*, and the measurement data was analysed using the *FuzzMeasure* software[3]. The subsystems and logic of the system are described in further detail in Sections 7.3 and 7.4.

7.2.4 *Pilot studies*

Informal pilot studies were conducted at various stages of the design of this apparatus to test its features and assumptions. In these sessions, the participants - mainly nearby university colleagues and friends - would have the apparatus demonstrated to them, and then they would be allowed to freely explore it for 5-10 minutes. Especially in the earlier stages of design, the issues were high-level enough that no detailed interpretation was necessary - for example physical components falling apart obviously needed to be more robust. As the design came together, pilots provided more nuanced feedback, enabling fine tuning of mapping algorithm parameters, and workflow streamlining. The pilot studies are mentioned in this chapter, but below is a list of the main areas of the design which were improved through testing:

- Curation of preset resonance models (Section 7.3.4).
- Improved robustness of the physical interfaces (Section 7.4.3).
- Mapping resonance model decay parameters (Section 7.5.1).
- Fine tuning parameter scaling (Section 7.5.1).
- Streamlined the workflow and improved clarity (Section 7.6.1).
- Improved the GUI design (Section 7.6.2).

7.3 DIGITAL TUNED PERCUSSION INSTRUMENT

For this section's glossary, see Appendix E.1.2.

This section describes the digital tuned percussion instrument, in terms of the major design decisions, build of the percussion blocks, the sensor signal processing, digital resonance model synthesis, and model synchronisation mechanism.

3 https://www.rodetest.com/

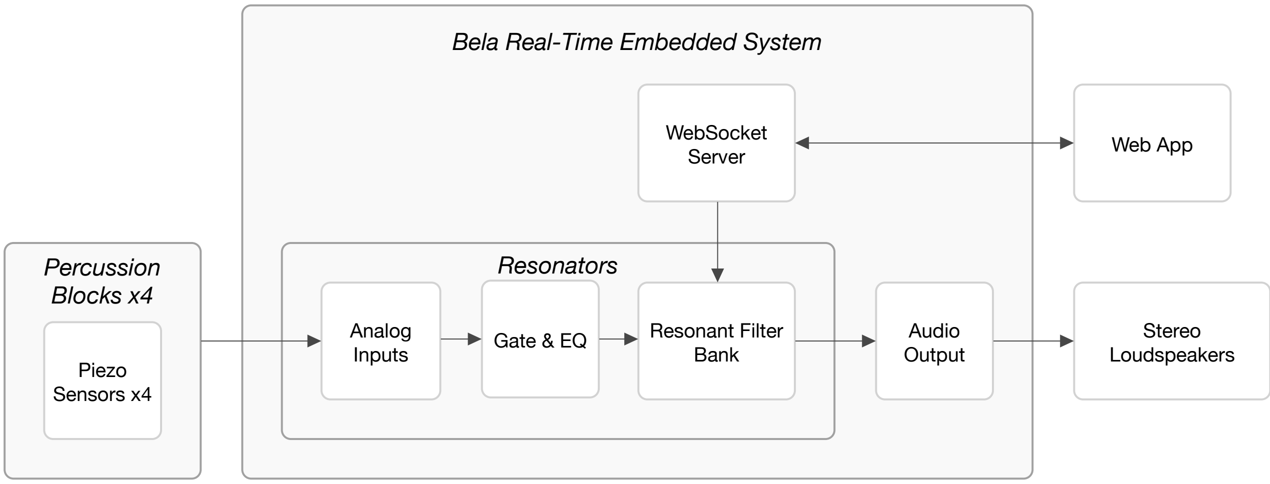


Figure 7.5: System architecture diagram detail for the tuned percussion instrument. Described in Section 7.3.

7.3.1 *Finished versus unfinished features*

In the previous two studies, the idea of presenting an "unfinished" instrument to participants was explored as a provocation for them to engage with the idea of what finished might mean to them in this context. However, on reflection those apparatus were unconstrained at the macro and meso scales, and relatively constrained at the micro scale, which appeared to divert responses away from refining details. In this study, the apparatus was designed to appear fixed and resolved at the macro and meso scales (despite a modest build quality), and invitingly open to interpretation at the micro scale.

Many design decisions were taken to constrain the macro scale identity and meso scale configuration of the instrument:

- The percussion was tuned so that a wide range of musical skills would be relevant, and to avoid experimental aesthetics associated with unpitched sounds (e.g. electroacoustic) that are more associated with macro and meso scale activity.
- Four pitched percussion blocks were selected with default pitches of C3, A3, G4 and D5 (where C4 denotes middle C), to reinforce a tonal base. Twelve blocks / one octave would have pushed musicality towards melodic rather than percussive playing, and would also have complicated the build process.
- In addition, the four pitched elements were similar to the previous study apparatus described in Chapters 5 and 6.
- The blocks were presented in a fixed horizontal row, such that participants would not consider rearranging them.

- The blocks were physically as identical as possible, to present them as heterarchical in relation to each other.
- The size of the blocks were approximately similar to a human palm, to constrain gestures towards tapping/hitting/scratching.
- Rather than offering an ulimited scope of resonance model generation, instead the participant is able only to select from four curated preset models and iterate or refine them.

Correspondingly, the apparatus' design features were also intended to encourage engagement and focus on micro scale details:

- Hand percussion was selected so that the participant would have an intimate tactile relationship with the digitally produced sound, enabling them to quickly build an embodied rapport with the instrument.
- The blocks being physically identical meant that comparisons could be made between resonance models using multiple blocks. For example, if block 1 had model A assigned to it, and block 2 had model B assigned, the participant could compare model A and B without the physical construction of the blocks contributing to the subtle differences between them.

7.3.2 *Percussion blocks build*

The percussion blocks were constructed as simply as possible, to signify a lack of preciousness to the participant, and constrain gestural interaction to the surface of the block (Figure 7.6). Each block consisted of five parts:

- A block of obeche (hard) wood, measured and cut with a bandsaw, with rough edges sanded down.
- A thin rectangular piece of wood glued to the underside of the block for mounting the piezo sensor to, with a width less than the circumference of the piezo sensor.
- A piezoelectric vibration sensor mounted flush on the quartz side, facing up against the small piece of wood, with the solder joints free in the gap between the two pieces of wood. This increased sensitivity compared to mounting on the flat underside.
- Double sided tape was used to mount the piezo sensor due to being thin yet highly adhesive, and thus having a low influence on vibration. It also allowed for easy replacement of the sensor if needed.
- Soft foam glued onto three sides of the underside of the block to mechanically isolate the blocks from each other when arranged in a row.

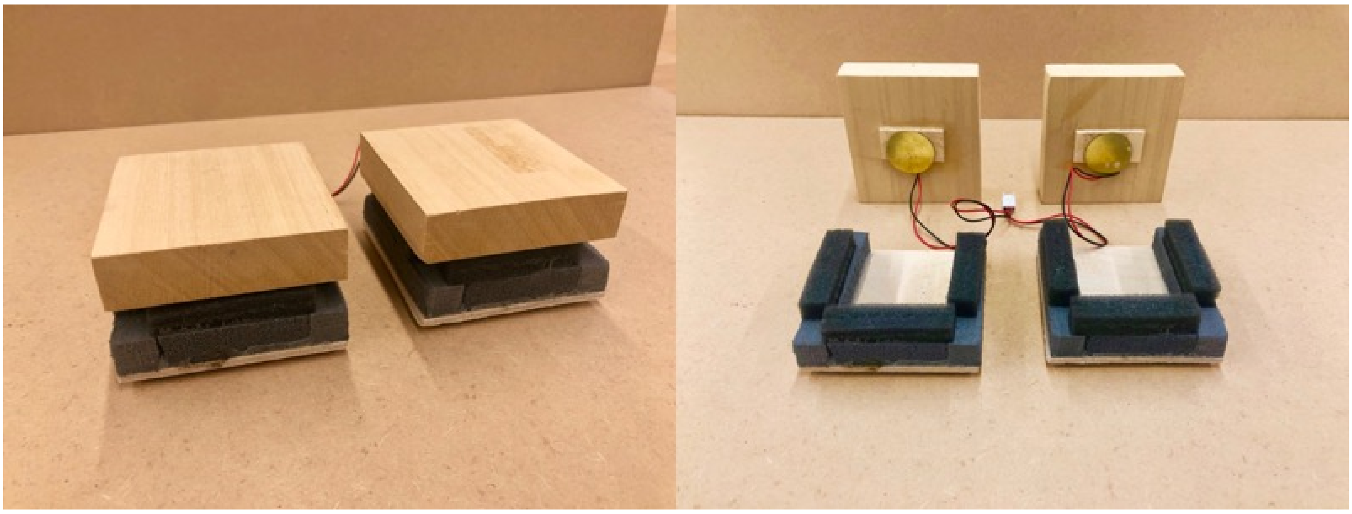


Figure 7.6: Photos of the tuned percussion.

7.3.3 *Digital signal processing*

The signal processing chain applied to the piezo vibration sensors is depicted in Figure 7.5. First, a gate was applied to the inputs to increase the mechanical isolation between the blocks. This signal was passed through two biquad filters to further emphasise the tactile intimacy of the blocks:

- High pass at 100Hz with Q = 0.1 and a gain of -24dB.
- High shelf boosting the signal at 2000Hz with Q = 0.5 and a gain of 3dB.

7.3.4 *Digital resonance models*

The digital resonance models used in this apparatus were based on the resonant filter bank implementation of CNMAT's `[resonators~]` object for Max/MSP and Pure Data[4] [129]. This implementation was ported to the Bela platform and the source code is available online[5]. Porting the object to Bela meant that tweaks could be made to enable real-time updating, and to decrease the interpolation and fidelity somewhat to enable larger models to be computed in real-time on the Bela. In addition, a JavaScript Object Notation (JSON) resonance model format was devised (Figure 7.7) to enable communication of models between Bela and the web application via WebSockets.

Percussion resonance models were used as presets for this apparatus based on Ali Momeni's aLib[6] [209]. Four presets were selected based on pilot studies with the apparatus, with three being taken from

4 `resonators~.c` accessed from https://github.com/CNMAT/CNMAT-Externs
5 `[resonators~]` for Bela, https://github.com/jarmitage/resonators
6 aLib resonance models, https://alimomeni.net/project/alib-resonance-models/

```json
{
  "metadata": {
    "name":        "marimba",
    "fundamental": 800,
    "resonators":  8
  },
  "resonators": [
    { "freq": 800,  "gain": 0.500000, "decay": 0.2 },
    { "freq": 1600, "gain": 0.033333, "decay": 0.4 },
    { "freq": 2400, "gain": 0.016666, "decay": 0.6 },
    { "freq": 3200, "gain": 0.006666, "decay": 0.7 },
    { "freq": 4000, "gain": 0.003333, "decay": 0.8 },
    { "freq": 4800, "gain": 0.001666, "decay": 0.9 },
    { "freq": 5400, "gain": 0.000666, "decay": 1.0 },
    { "freq": 6200, "gain": 0.000333, "decay": 1.0 }
  ]
}
```

Figure 7.7: JavaScript Object Notation (JSON) representation of a resonance model. Two child objects describe metadata and the array of resonators.

aLib: `Madal-1.m6`, `khol-5.m6` and `Mirdangam-4.m5`. To contrast these, a fourth model with a metallic, inharmonic sound was created via simple, random parameter generation. See Appendix E.2 for plots of these models. However, the names of the models are hidden from the participant, and they are instead represented by numbers 1-4. These selected models had similar loudness and an identifiable pitch, and were broad enough to demonstrate the versatility of the parameter space for imitating different materials, but similar enough to require active auditory discernment initially.

7.3.5 *Model synchronisation*

The instrument's resonance models were updated under a number of different circumstances via a WebSocket connection to the web application (Figure 7.5), such that it was always making sound as long as it was connected to the web application:

- When Bela first connected to the web application, a model was sent, either the first preset if the session was empty, or the last used model if a session was loaded or in progress. This behaviour also applied if the web page was refreshed or closed and reopened.
- When a new sculpt was added by the participant, the resulting mapped model would be immediately sent to the instrument to enable iterative sculpting and playing. The participant could however selectively "lock" individual percussion blocks to prevent automatic updating (see Section 7.6.1).

- When the participant navigated through the history of sculpts using the TUI/GUI interfaces, the corresponding model(s) on the instrument would update with every action.

Since there could be slightly varied delays between interactions taking place and synchronisations being completed, notification sounds were added to the Bela embedded system (Figure 7.4), providing simple auditory feedback as confirmation.

7.4 DIGITAL RESONANCE SCULPTING TOOL

For this section's glossary, see Appendix E.1.3.

This section describes the digital resonance sculpting tool, in terms of the major design decisions, use of sculpting clay, the sculpting surface, and the frequency response measurement process.

7.4.1 *Designing for micro scale crafting*

Resonance models consisting of resonant filters with frequency, gain and decay parameters were selected as the digital material for micro scale design for a number of reasons:

- Primarily, through this material it was possible to make modest qualitative changes which were directly comparable, with salient perceptual features lying in and around thresholds of noticeable difference.
- The quantity and range of these parameters offered a richness of timbral possibilities, which, while often reminiscent of physical materials, can also produce uncanny or alien resonances.
- Since the instrument, mapping algorithm and activity were to be otherwise tightly constrained, the above features would need to sustain the participant's interest throughout the activity.

The goal of the resonance sculpting tool was to facilitate handcrafting of micro scale details with minimal onboarding required. Where possible, the design of this apparatus followed the principles outlined by Kettley [153], and the outcomes from the interviews with violin luthiers described in Chapter 4. The tool itself involved close commingling of a variety of physical and digital processes, and aimed to open up a micro scale crafting domain of significant complexity and non-linearity comparable to a traditional handcraft. Crucially however, it also had to be repeatable, otherwise it would likely be perceived as completely arbitrary which would be demotivating.

Methodologically, while the tool needed to facilitate open and comparative crafting, it also had to feature discretisation of crafting steps to enable certain types of analytical and interpretive approaches. This constraint was met due to the pragmatic decision to use swept sine wave analysis for frequency response measurement (Section 7.4.4), which meant that terminology could be introduced to describe an

Figure 7.8: Top-down close-up photo view of the sculpting surface (Section 7.4).
Top-left: the sculpting surface (Section 7.4.3).
Top-right: the supplementary sculpting tools.
Bottom: the sculpting clay in its initial presentation (Section 7.4.2).

individual step as a sculpt, and a sequence of steps as a sculpture. While this meant that the interaction between the instrument and the tool would be non-real time, this conveyed certain advantages, for instance of delayed gratification. But this also meant that it would be unlikely for the sculpting process itself to turn into a performance, which would constitute a macro-scale change, and was felt to be a risk based on experience in previous studies.

7.4.2 *Sculpting clay and sculpting tools*

Commonly available modeling clay — plasticine — was used in a single grey colour for this apparatus. Its appearance was, like the craft materials used in previous studies, familiar, approachable, highly tactile, fun, low-cost, and non-precious. It was also easy to both add and subtract small amounts of material using simple tools. Due to its diverse use cases, it was an open-ended material which could be freely interpreted and used to represent both figurative and abstract ideas without much friction. In this study, this meant that participants could be expected to easily project their existing knowledge, skill and practices using this material.

Clay was also chosen in relation to the digital material of the apparatus, in particular the parametric digital resonance models described in Section 7.3.4. While discrete, precisely weighted materials made from for example brass could have been used, clay as a more flexible and analog choice suited the continuous domain of the timbre parameters, and encouraged free-form sculpting of the sound. The clay was prepared in the same way at the beginning of each session, and accompanied by a small selection of simple tools (Figure 7.8).

7.4.3 *Sculpting surface*

The design and build of the sculpting surface was extremely rudimentary, both for pragmatic and methodological reasons. Pragmatically, it did not make sense to invest the time to create a serious piece of acoustic equipment for this study. Using the frequency response measurement process (Section 7.4.4), it was possible to validate that two sequential measurements of the surface where alike enough that the sculpting process would be repeatable and thus engaging for the participants. Methodologically, the previous studies had focused on using approachable, everyday materials to make the apparatus seem approachable and non-precious, which helped participants to feel confident about interacting with the apparatus despite its lack of familiarity. Furthermore, in this study the participants had a range of backgrounds including in traditional handcrafts, and an overtly technologised aesthetic may have been off-putting, and perceived as inauthentic or incompatible with their practice.

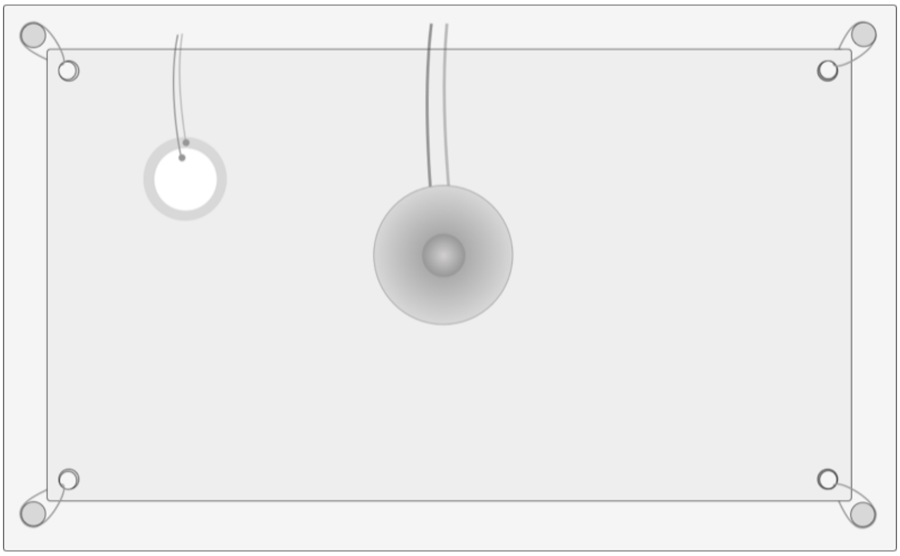


Figure 7.9: Detail illustration of the sculpting surface, see Section 7.4.3.

The sculpting surface consisted of a 3mm plywood sheet cut down to 18cm by 11cm, suspended at each corner via wooden dowels and crafting string above a hard wood (obeche) block. Beneath the surface, a Tectonic TEAX25C10-8/HS[7] vibration transducer and a piezoelectric vibration sensor were mounted via 3M double-sided adhesive tape. As Figure 7.9 illustrates, the transducer was mounted in the centre of the surface, and the sensor approximately half-way between the centre and the top-left corner. The sensor mounting position was selected based on trial and error of where the flattest frequency response curve could be found.

7.4.4 *Frequency response measurement*

Every time the participant wanted to update the instrument, they would use the *Add Sculpt* button on the TUI (Section 7.6.1), and the first thing they would notice after doing so would be a sine wave sweep coming from the sculpting surface. At this point, a frequency response measurement was being taken of the combined sculpting surface and sculpting clay. As Figure 7.4 indicates, this process involved the combination of multiple subsystems:

1. The *Add Sculpt* button triggered a MIDI note which was registered by Bela and forwarded to the web application via the embedded WebSocket server.

2. The web application then sent a request to the Jupyter kernel gateway server[8], which hosted the Python code for administering the frequency response measurement process, and the resonance model mapping algorithm (Section 7.5), for a new sculpt to be created.

7 https://www.tectonicaudiolabs.com/audio-components/audio-exciters/
8 https://jupyter-kernel-gateway.readthedocs.io/en/latest/

3. The server connected to a separate audio interface with high impedance inputs for the sculpting surface's piezo input, and simultaneously played a sine wave sweep through the vibration transducer, and recorded from the piezo sensor, both mounted underneath the sculpting surface.

4. The recorded signal was then processed by the commercial software FuzzMeasure[9], which was controlled by the Python server via an AppleScript[10], to produce a table of frequency response values.

5. The frequency response values could susbequently be used by the mapping algorithm (Section 7.5).

The sine wave sweep used was one second in duration, and spanned from 100Hz to 20000Hz (signals below 100Hz would visibly shake the sculpting surface). While an impulse could have been used instead of a sine sweep to reduce the roundtrip latency of sculpting, the sine wave sweep was preferred for its increased accuracy, given the rudimentary construction of the sculpting surface (Section 7.4.3).

When the participant created a new sculpture via the *New Sculpture* button, this would automatically trigger two frequency response measurements in sequence, and the results of these two measurements were visualised by the GUI (Section 7.6.1) for the researcher to visually confirm a successful setup. Ensuring that only a negligible difference between these two measurements existed validated that the sculpting surface was in a stable physical configuration, and that subsequent sculpts would be valid.

7.5 mapping frequency responses to resonance models

For this section's glossary, see Appendix E.1.4.

This section describes the process of mapping measured frequency responses to resonance models via an algorithm, in terms of its design goals, implementation details, and two specific, more advanced sculpting techniques that it facilitated.

7.5.1 *Mapping micro scale differences*

The main goal of the mapping process was to encourage participants to focus on making micro scale adjustments to the percussion instrument's resonance models, based on physical activity with the sculpting tool. Pragmatically, the mapping process needed to be simple and straightforward to implement, given the wide range of implementation tasks for this study. The mappings needed to be repeatable, such that repeating roughly the same sculpts would produce the same result. This was partly achieved by stabilising the build of the sculpting surface (Section 7.4.3), but it also meant that the mapping algorithm

9 https://www.rodetest.com/
10 https://en.wikipedia.org/wiki/AppleScript

had to have an element of linearity, rather than changing based on previous inputs. It was also felt that the mappings needed to demonstrate at least some intuitive correspondence between the types of physical changes being made and the sounds being heard.

Since the model parameters encoded frequency, gain and decay for each resonant filter (Section 7.3.4), and the sensing mechanism produced a profile of magnitudes across the audible frequency spectrum, the most obvious correspondence was between frequency response magnitudes and resonator gain parameters. The strategy for mapping frequency response onto decay parameters was less obvious, and eventually it was settled on that the peaks and troughs of the frequency response, as implied by its second-order derivative, would scale the decay parameters accordingly. Through trial and error and some pilot sessions, this simple approach was found to produce plenty of space for exploring different resonances, and so it was deemed unnecessarily complicated to map the model's frequency parameters.

As this study was focused on the scale of detail, the scaling of the mappings was important. If a large amount of physical change (relative to what was possible with the sculpting surface) was mapped to a low or barely perceptible amount of change in sound, participants would be unlikely to make small physical changes. If the opposite were true, the participants might be encouraged to focus not on small details but large changes in timbre. Thus, it was necessary, again through trial and error and pilot sessions, to establish appropriate scaling constants that felt correct based on sculpture-to-sound relationships.

7.5.2 *Mapping algorithm details*

The mapping algorithm had a single entry point, in the form of a function called `process()` which took three arguments:

- `model`: the selected preset model.
- `setup`: the frequency response of the setup measurement (the *Setup*).
- `sculpt`: the most recent frequency response measurement (the *Sculpt*).

This function returned a "mapped model", which was then sent to the tuned percussion instrument for the participant to play with and listen to (Section 7.3.5). The resonance models consisted of an array of resonant filters, where each resonator had three parameters for frequency (0-20000), gain (0-1) and decay (0-1) (Section 7.3.4). The mapping algorithm compared the current frequency response (`sculpt`) to the reference frequency response (`setup`), and updated the gain and decay parameters of the model, leaving the frequency parameters intact. The gain parameters were updated based on the difference in magnitude between the frequency responses. The decay parameters were updated based on the difference in second order gradient of magnitude between the frequency responses. These two mappings are depicted in Figure 7.10 with an example from a study session, which is described in more detail below.

First, the participant went through steps 1-2 of the sculpting workflow (Section 7.2.2) to create a new sculpture and select a preset base model. Next, in step 3 they set up the sculpting surface. In this case, the sculpting surface was setup with no additional material added. Next, the luthier added a small piece of clay, near the top left of the sculpting surface, and took a new frequency response measurement. When comparing these two frequency responses (Figure 7.10, top left plot), and interpolating them to retrieve frequency response values at the resonance model's frequencies, subtle differences are revealed.

Comparing the original base model with the mapped model (Figure 7.10, bottom left plot), it is possible to see what changes the algorithm made as a result of this sculpt. The most notable difference is that the 3$^{\text{rd}}$ resonator's gain has significantly decreased from around 0.7 to 0.45. Comparing this outcome with the frequency responses, it can be seen that the 3rd circle mark also decreases in the sculpt versus the setup measurement, and so this change was reflected in the mapped model.

To see how exactly this mapping took place, Figure 7.10 also provides two plots on the right, showing the state of the arrays of resonator parameters during each step taken by the algorithm, for the gain (top right) and decay (bottom right) parameters. The gain parameter mapping steps can be described in four steps:

1. Find the difference in magnitude, *DM*, between the setup and sculpt frequency responses.
2. Interpolate new *DM* values at the frequencies from the base model.
3. Scale the base model gain parameters by the *DM* (*Scaled* in the plot).
4. Scale *DM-1* (*Bias* in the plot) by a constant, 0.15, and add this to the updated gain parameters (*Biased* in the plot).

The decay parameter mapping steps can also be described in four steps:

1. Find the difference in the second-order gradient of the magnitude, *DGM*, between the setup and sculpt frequency responses.
2. Interpolate new *DGM* values at the frequencies of the base model.
3. Scale the base model decay parameters by *1/DGM* (*Scaled* in the plot).
4. Scale the *DGM-1 Bias* in the plot) by a constant, 0.2, and subtract this from the updated decay parameters *Biased* in the plot).

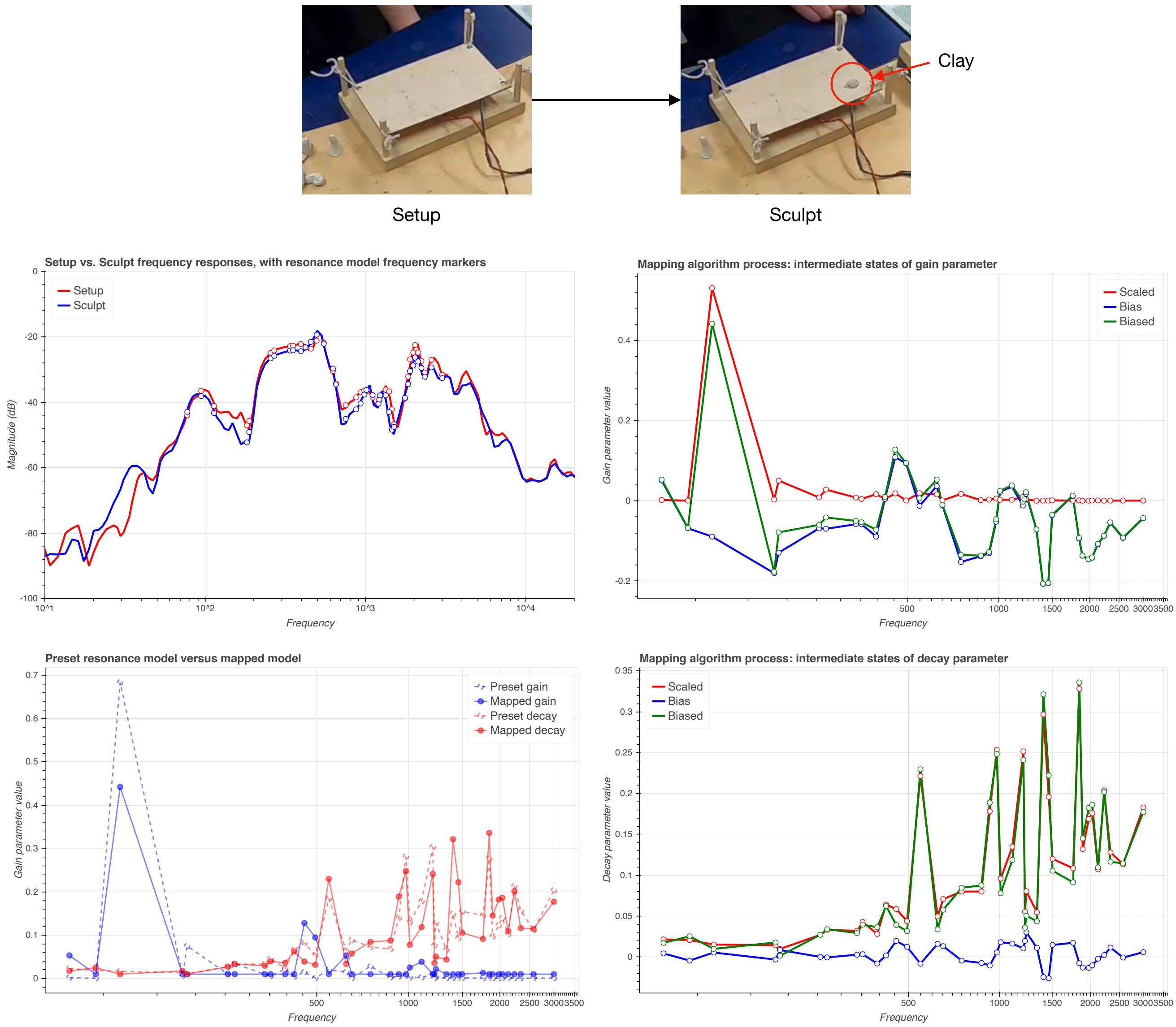


Figure 7.10: Plots illustrating details of how the mapping algorithm manipulates the resonance gain and decay parameters using an example sculpt from the outcomes.
Above: still images from the participant's session video illustrate the state of the sculpting surface before and after the sculpt, where a single, small piece of clay is placed in a corner of the surface.
Top left: the two frequency response measurements are compared.
Top right: the gain parameters are mapped based on difference in magnitude of the frequency response measurements.
Bottom right: the decay parameters are mapped based on the difference in the second order derivative of the magnitude of the frequency response measurements.
Bottom left: the original and mapped models are compared.
See Section 7.5.2.

7.5.3 *Additive versus subtractive sculpting*

The most obvious way to sculpt using the apparatus was to choose a preset, setup the surface, and then start adding material. However, given that the clay material was likely in most cases to dampen the sound rather than increase resonance, this led to a possible bias in the process towards dampening. To address this, the participants were also shown how to do 'subtractive sculpting'. This process was exactly the same as above, except they could configure material onto the surface before setting it up and calibrating it. This meant that subsequently removing the material would increase resonance compared to the starting sound, making the sound louder. By combining these 'additive' and 'subtractive' approaches to sculpting, participants could more readily increase as well as decrease resonance.

7.5.4 *Sculpts as Sculpture Presets*

One way in which the sculpting process was constrained towards micro scale details was by limiting the participant to creating sculptures based on only four 'preset' models (Section 7.3.4). There was an exception to this constraint, which was that it was also possible to use any existing resonance model created during the session as the preset (although the frequency parameters would remain the same). For example, if a participant first created a sculpture consisting of four individual sculpts, their next sculpture could be based on any of those four sculpts, as well as the four presets. The rationale for adding this feature was that it would permit participants to effectively 'zoom into' and refine further one of the sounds they had sculpted, and from a fresh starting point in terms of the sculpting clay. Sculptures created in this way were visually annotated as such in the GUI (Section 7.6.2 & Figure 7.11).

7.6 Session Navigation Interfaces and Workflow

This section describes how the sculpting workflow was displayed and navigated via the graphical (GUI) and tangible (TUI) user interfaces.

For this section's glossary, see Appendix E.1.5.

7.6.1 *Navigating micro scale details*

Since one of the main themes of this study was comparison between micro scale details, the apparatus needed to provide affordances for comparison. In particular, it was necessary to provide the ability to compare mapped resonance models or sculpts through selecting and auditioning them on the instrument. This meant that the sculpts had to be represented visually and made navigable physically, in a way that would not detract from the main focus of the activity which was sculpting with the sculpting tool, and playing with the tuned percussion instrument. These two tasks were split between two interfaces described subsequently, a GUI and a TUI, which together could be described as supporting case-based reasoning [177, 179].

The overall context of the participant's activity was based around a simple hierarchy of a *Session* made of *Sculptures* made of *Sculpts*, where each task that they performed during the activity corresponded to a *Session* (Section 8.1). Both the session, and transitioning between tasks, were administrated by the researcher. Session state was auto-saved by the web application after every navigation interaction by either the researcher or the participant (Section 8.1.5). In case the web browser crashed, or the window was closed or refreshed, the last open session would be restored again.

Participants created sculptures by following four steps illustrated on the TUI:

1. Start creating a new sculpture via the *New Sculpture* button.
2. Selecting a preset base model from four options (or from an existing sculpt if using the advanced sculpt-as-preset technique, Section 7.5.4).
3. Taking a frequency response measurement of the sculpting surface via the *Setup* button.
4. Using the *Add Sculpt* button to iteratively update the percussion instrument based on the sculpting surface's current state.

By default, after adding a sculpt, the percussion blocks would synchronise to the latest sculpt's resonance model unless "locked", to keep the process as hands-free as possible. If the participant wanted to keep a particular sound assigned to a percussion block while sculpting, they could use the lock icon in on the TUI to prevent it from automatically updating. This locking mechanism gave participants more control over the comparisons they could make. Finally, another comparison affordance was added in the form of a pitch toggling mechanism, whereby using the music icon button on the TUI would cycle the percussion block's pitch mappings through five different states:

- C3, A3, G4 and D5 (default) (Section 7.3.1).
- All set to C3.
- All set to A3.
- All set to G4.
- All set to D5.
- Back to default.

This feature meant that the participant could assign slightly different resonance models to multiple instrument blocks and audition them at the same pitch, meaning they could compare while playing or performing with the instrument rather than using the TUI to navigate. The locking and pitch toggling features were essential to facilitating the Matching Tasks described in Section 8.1.

7.6.2 *Graphical user interface*

The graphical user interface (Figure 7.11) displayed the state of the sculpting session only, meaning that there was no visualisation of frequency response measurement data, intermediate mapping algorithm steps, or mapped resonance model parameters. This was deliberate to focus participants on sculpting with their hands and playing and listening to the percussion instrument. Its design was simple and approachable, and mirrored in layout and colour scheme the percussion instrument and the TUI (Section 7.6.3). The interface displayed multiple simultaneous representations of the sculpting session to reduce unnecessary glancing: each percussion block's assigned resonance model could be seen both on the block itself in textual form in the *Instrument* panel, and in tabular form in the *Sculptures* panel. In the *Sculptures* panel, sculptures were displayed horizontally as tables of sculpts, which themselves also visually reflected the layout and colour scheme of the percussion blocks. Each sculpture was labelled numerically, and also with the resonance model it was based on. An additional *Session* panel allowed the researcher to manage the session and ensure that the Bela device (Section 7.3.5) and Jupyter kernel gateway server (Section 7.4.4) were both connected and synchronised.

7.6.3 *Tactile user interface*

The tangible user interface (TUI) was designed to enable rapid and simple navigation of both the sculpting workflow and the sculpts. The layout is described in Figure 7.12, and since it was based on the Sensel Morph's[11] custom overlay, it could be rapidly iterated through graphic designs printed on paper and tested straight away. The layout went through 12 iterations to ensure clarity and efficiency for the participants. Although it would have been spatially more efficient to have just one set of navigation arrows and a separate modifier key for selecting which percussion block to change, this would have made the interface modal and potentially two-handed. Having numerous navigation controls matched the instrument's layout and the GUI (Section 7.6.2), which in addition to being faster and simpler to use, also would reduce cognitive overhead of usage. Navigation options of left and right were also added, which corresponded to navigating

11 https://morph.sensel.com/

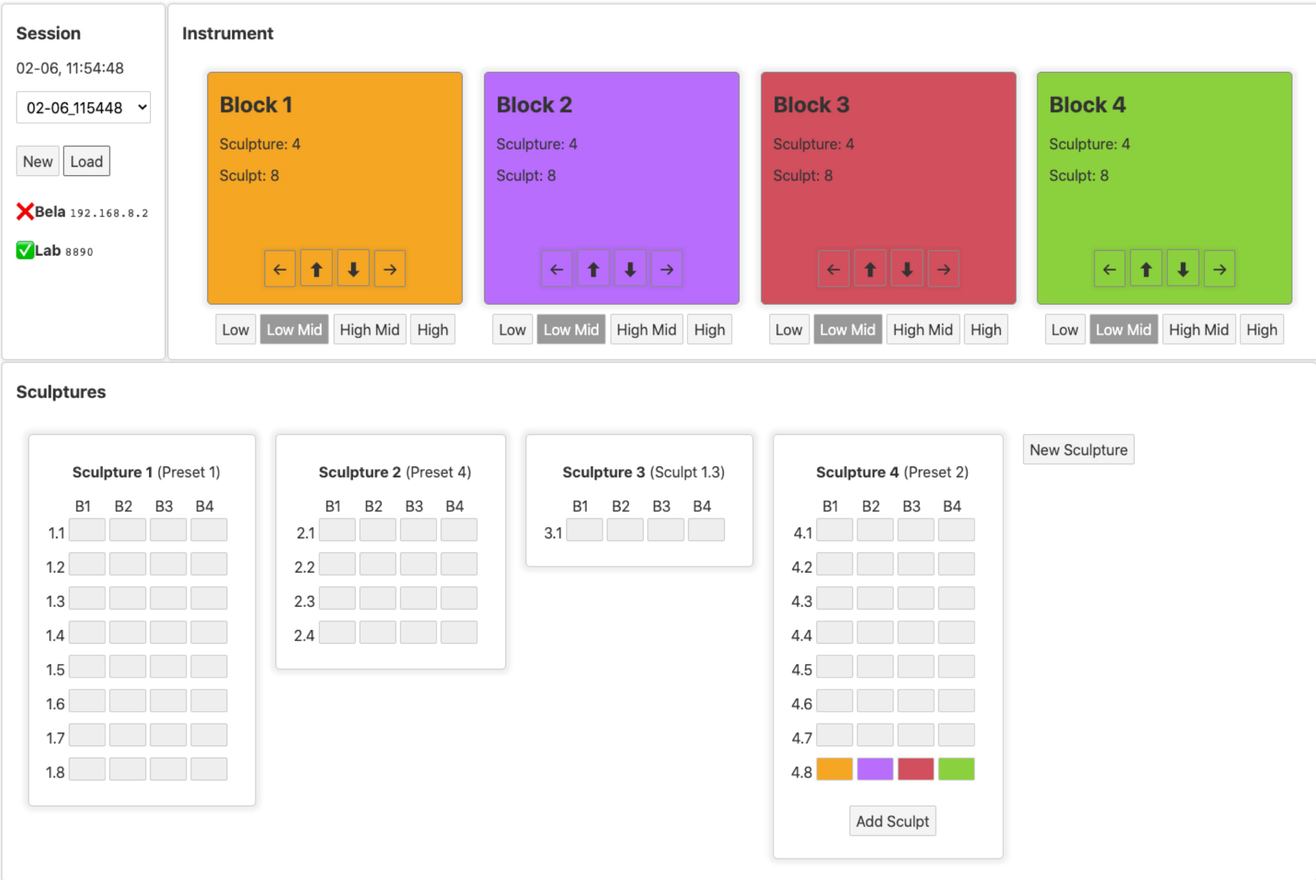


Figure 7.11: Graphical user interface (GUI) for the apparatus.
Top left: the *Session* panel displays the session timestamp and connection statuses, and allows loading of previous sessions and creation of new sessions.
Top middle: the *Instrument* panel displays the status of the instrument blocks: which sculpture and sculpt they are assigned to, and which pitch they are sounding.
Bottom: the *Sculptures* panel displays a table for each sculpture, with a row for each sculpt, and columns for each instrument block. Via the annotations for each Sculpture, it can be seen that Sculpture 3 was created based on Sculpture 1, Sculpt 3 using the sculpt-as-preset technique (Section 7.5.4).
See Section 7.6.2.

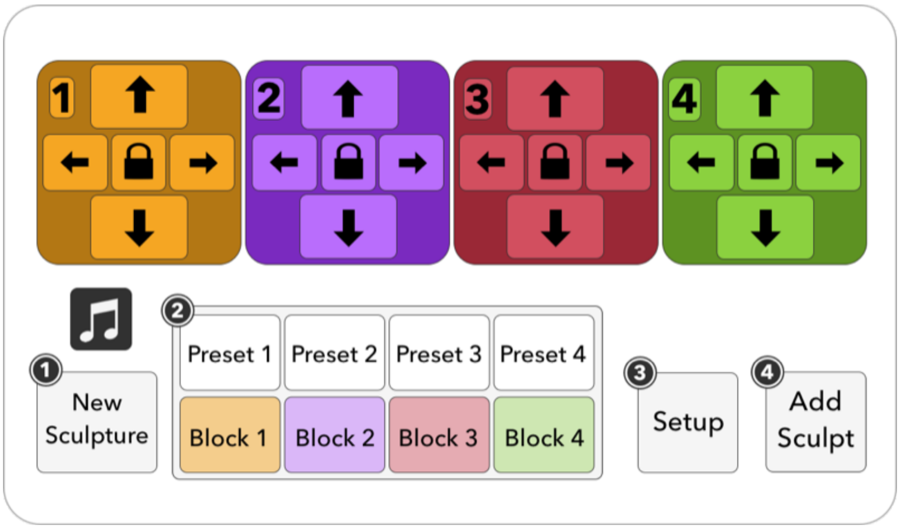


Figure 7.12: Tangible user interface (TUI) controls layout.
Top row: four blocks mirror the instrument's percussion blocks, providing individual sculpt navigation controls for each block.
Bottom row: the four workflow steps for creating and iterating sculptures are displayed and numbered from left to right.
See Section 7.6.3.

between sculptures rather than sculpts, which rapidly increased the speed of workflow. Since the sculpting workflow has four important steps that could only be completed sequentially, numbering was used to reinforce this, and again to alleviate the participant's need to remember this somewhat complicated process for themselves within a very short space of time. There was no tactile feedback on this device, so interactions were instead made audible via a simple sampler running on the Bela device.

7.7 SUMMARY

In this chapter we have described a set of DMI design probes, collectively referred to as a study apparatus, which attempted to synthesise the lessons learned from earlier studies about eliciting micro scale design activity. We have documented design decisions at every level that we believed would constrain macro and meso scale activity, while encouraging micro scale activity. We have also demonstrated how the resulting process combines digital affordances and traditional handcrafting to provide a hybrid crafting experience. The next chapter describes how this apparatus was put into action.

8 MICRO SCALE DMI DESIGN II: DESIGN AND EVALUATION OF A MACRO-MESO CONSTRAINED ACTIVITY

A random spatter of infinitely many points can never be described, and neither can a random curve. The only shapes we can talk about are those with a pattern, and it is the pattern itself – a finite set of words in a finite language – that defines the shape. Those shapes that do not have such a pattern (the vast majority, I'm afraid) can never be referred to, let alone measured, by any human beings, ever. The set of objects that we can think about and describe to others is limited from the start by our own humanity [...] Geometry, then, is not so much about shapes themselves as it is about the verbal patterns that define them.

— Paul Lockhart, *Measurement* [165]

This chapter describes the design and outcomes of a study designed to elicit micro scale DMI design activity. Where the studies in earlier chapters resulted in outcomes that leant more towards macro and meso scales of activity, this time a more sophisticated activity was created for individuals rather than groups. Rather than leaving aspects of the activity open-ended to facilitate discussion, the macro and meso scales of the activity were in this case tightly constrained. The one-hour activity involved a guided tutorial, followed by a five-minute technical task, a 15-minute creative task, and a repeated technical task, which was then followed by a 30-minute structured discussion (90 minutes in total). This activity also targeted participants from a wider variety of backgrounds including string instrument luthiers, digital luthiers, musicians and creatives with handcrafting experience. The research focused on the participants' motivation to focus on subtle details, and the influence of their backgrounds — their skills, practices, and sensibilities — on their responses. While some participants subverted the constraints, a majority sustained engagement with micro scale details throughout. Participants' use of the apparatus' sculpting clay (Chapter 7) led them through various metaphors and methods, resulting in indescribable shapes and intricate patterns. Violin luthiers' experience with minute vibrational phenomena advantaged their process over other participants, and musicians were surprisingly effective at following their musical intuition where their technical skills lacked. Most participants professed that their sound sculpting process had improved by the end of the activity, although they were not sure exactly how.

8.1 ACTIVITY DESIGN

This section describes the participants and recruitment process, the activity design and protocol, post-activity interview structure, and data capture and processing methods.

8.1.1 *Overview*

In the previous studies described in this thesis, the activity design had been deliberately left open-ended, first to facilitate discussion within a community, and second to not diverge too far from the first. In these cases, the activity brief was to consider "finishing" the instrument as it was presented, in whatever manner felt appropriate. In contrast, the activity in this study was highly constrained, but did not explicitly refer to the idea of finishing the instrument. Instead, a number of short tasks were devised to break up the one-hour activity into sections with specific goals in mind. While this meant that the time constraints for each task would be extremely tight, it also meant participants could be further directed away from any possible macro and meso responses to the apparatus.

8.1.2 *Participants*

Participants volunteered through a call posted on mailing lists related to digital media arts, and traditional musical instrument making, stating that participants would "be introduced to a set of digital hand-crafting tools and asked to use them to carry out a set of tasks" (see Appendix F.2.1) over a 60 minute activity, followed by a 30 minute discussion. Participants applied to join the study by submitting a survey in which they self-reported their experience levels in music, handcraft and instrument making (see Appendix F.2.2). 33 participant sessions were completed, with seven of those excluded from the final analysis leaving 26 total. The cohort of respondents is described in detail in Section 8.3.1. On arriving for their session, participants reviewed a proforma consent form, which contained a description of the activity ("this study presents a digital musical instrument along with some tools for modifying its sound characteristics", see Appendix F.2.3).

8.1.3 *Activity protocol*

The one-hour activity was composed of four tasks:

- Demo
- Matching Task 1
- Tuning Task

- Matching Task 2

A detailed timeline for the activity is given in Table 8.1. The overall arc of the activity was to rapidly enable the participant to administer the sculpting workflow and process by themselves, then to immerse them in specific contexts that would require them to work with the micro scale details of the apparatus. The Matching Task was a short, technical task, which was repeated to facilitate comparison of outcomes before and after a longer, creative task called the Tuning Task. In a brief introduction before the Demo began, the participant read and signed a pro-forma consent form with a study brief included, and the structure of the activity was described (Appendix F.1.1).

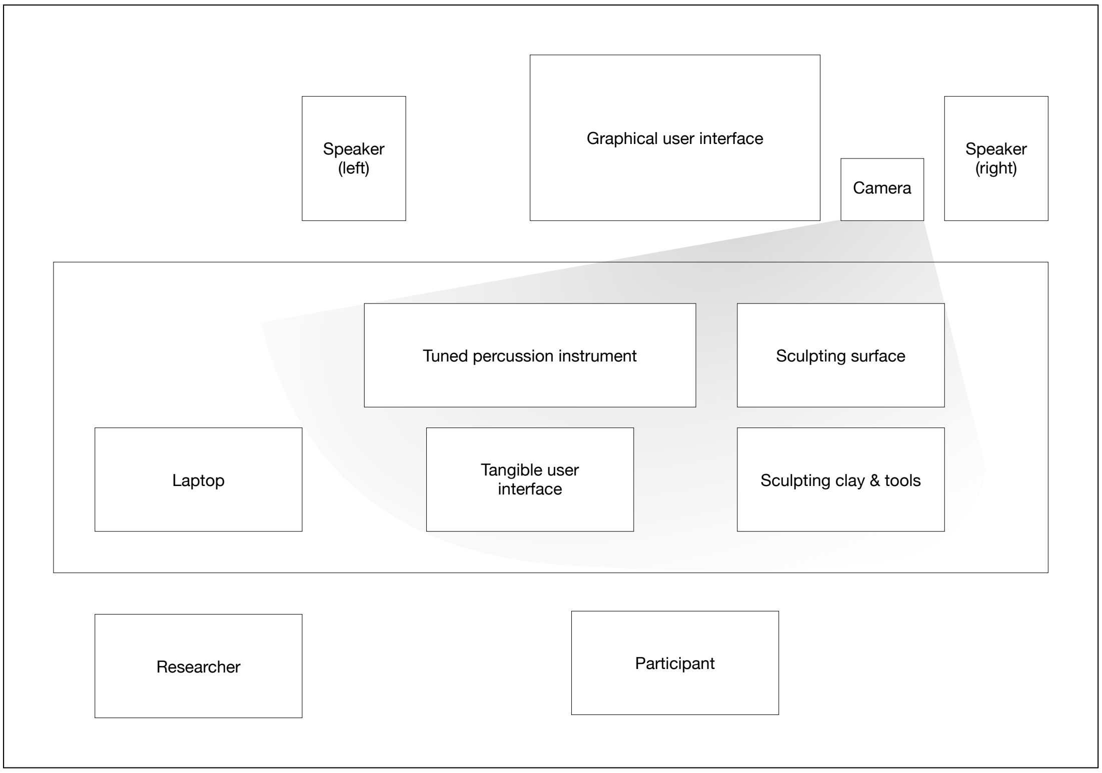


Figure 8.1: High-level, roughly proportioned diagram of the workshop environment. A participant sits at a desk facing a range of interfaces. A researcher sits alongside to guide the session. A camera captures audio and video of the desk.

Time (mins)	Duration (mins)	Activity	Summary of activity content	Reference
00:00	1-2	Introduction	Read brief and sign pro forma consent form	8.1.3
00:02	5	Demo 1: basics	The instrument and the sculpting tool	7.3, 7.4
			Setting up the sculpting process	7.2.2
			Adding sculpts	7.2.2
			Recap	
00:07	5	Free exploration	Adding new sculptures	7.2.2
			Free exploration	
00:12	5	Demo 2: advanced	Comparing and locking sculpts	7.6.1
			Subtractive sculpting method	7.5.3
			Creating a Sculpture based on an existing Sculpt	7.5.4
			Changing Block pitches	7.6.1
00:17	7-8	Matching Task 1	Sculpt Preset 2 to sound like Preset 4	8.1.3.3
00:25	25	Tuning Task	Prepare for a hypothetical concert	8.1.3.4
00:50	7-8	Matching Task 2	Sculpt Preset 4 to sound like Preset 2	8.1.3.5
00:58	25	Interview	Clarifications, reflections, survey follow-up	8.1.3.6

Table 8.1: Activity timeline. Scripts for each activity are reproduced in Appendix F.1.

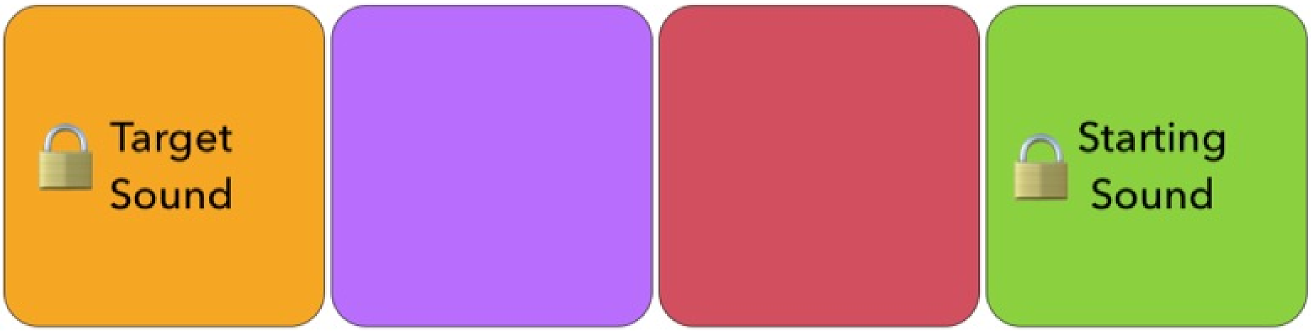


Figure 8.2: The Matching Task visualised for illustration purposes using the apparatus GUI (Section 7.6.2).
Percussion block one was locked to the target sound, and block four was locked to the starting sound, leaving the middle blocks to update automatically as the participant added sculpts. See Sections 8.1.3.3 & 8.1.3.5.

8.1.3.1 *Environment*

The activity environment is depicted in a high-level diagrammatic form in Figure 8.1. The activity took place in a recording studio, with the traditional recording equipment being replaced by a series of interfaces. The participant's main focus was the sculpting surface and the tuned percussion instrument, the latter being heard through stereo studio loudspeakers. Over the course of a one-hour session, participants learned how to use the sculpting surface to manipulate digital resonance models assigned to the tuned percussion blocks. A camera captured the session with a field of view restricted to the interfaces on the desk, and the participant's hands.

The role of the researcher was to directly instruct, support and encourage the participant's use of the apparatus, to go through the activity script with the participant (Appendix F.1), and to encourage think aloud responses and reflections from the participant throughout the activity. It was also critical to be present during the session to facilitate discussion about the contents of each session afterwards (Appendix F.1.6), which would not be possible without real-time observation. Undoubtedly, participants using the apparatus alone would produce different outcomes, and may be a preferable setting, but facilitating this was beyond the technical and methodological scope of this research, and is left as future work.

8.1.3.2 *Demo*

In the Demo activity, participants were shown how to use the tools and workflow progressively in a hands-on manner, through verbal instructions from the researcher which they then carry out. The demo was broken down into three segments: basic skills and know-how, free exploration, and advanced techniques. The full script can be reviewed in Appendix F.1.2. The precise ordering of this script was devised through pilot testing during the study development phase. This was necessary to devise an ordering of demo material which illustrated the key concepts and know-how in a fail-safe and efficient way. These tests showed that having the participant use their hands to do each step themselves, even before they fully understood what it meant, was key to them being able to do it themselves soon after. They also showed that the most efficient way to order the demo content was starting with the percussion instrument rather than the sculpting tool.

8.1.3.3 *Matching Task 1*

In this task, the participant was given a brief to sculpt a starting preset model to make it sound as similar as possible to another preset model, within a strict five-minute time limit (for the full script, see Appendix F.1.3). The context provided for this task was that they were given the role of a master sound sculptor, and that they are performing this task for a percussionist who has made the request for a quick adjustment to their instrument. These two sounds are chosen from the four available presets and were the same for all participants.

Figure 8.2 depicts how the percussion blocks were configured for this task. The starting and target sounds were locked to the first and last instrument blocks, and the block pitches were all set to the same pitch (Section 7.6.1), leaving the middle two blocks free to be sculpted and compared. At the end of the task, participants were asked how the task went, and whether any of the resulting sculpts they made were closer to the target sound or not.

Based on the data collected, it would be possible to quantitatively evaluate the outcomes of this task by comparing the mapped model's parameters to the target model's parameters. However, it was the participants' sculpting process and what they said about their experience which was the focus. In particular, the rationale for this task was to create a situation where refinement and attempted convergence towards a specific, non-negotiable goal was essentially the only possibility. This task was designed to ensure that, even if participants subverted the constraints by pursuing meso and macro scale responses during the Tuning Task, there would still be micro scale responses in each session. The task achieves this goal by removing the participant's creative autonomy and giving them a technical, relatively deterministic goal to focus on. The strict time limit was necessary given the overall activity's one-hour duration, however five minutes was chosen to elicit a quick response from the participant without them having any time to consider their actions. It was also necessary since it was anticipated that the participants would have a low motivation to complete this task compared to the Tuning Task, given their limited creative role.

8.1.3.4 *Tuning Task*

In this task, the participant is given a brief to prepare the instrument for a short, improvised performance they themselves will give at a (fictitious) concert scheduled for "tomorrow evening". They have 15 minutes to prepare the instrument, and they are free to sculpt it in any way they choose, and to use any of the techniques they have been introduced to or discovered. After this, a discussion takes place about the outcomes, and in some cases the participant was asked to refine one of the sounds in their instrument over a few extra minutes.

In contrast to the Matching Tasks, in this task the participant is given creative autonomy, and a more relaxed time constraint, to explore more freely but still with a clear goal in mind. It was expected that given this extra freedom, some participants might engage in activity that would no longer necessarily make sense to describe as micro scale. It was also expected that participants with different musical backgrounds and levels of musical experience would diverge in their approaches to this task, just as their practices themselves would.

8.1.3.5 *Matching Task 2*

In the final task, the Matching Task was repeated with the target and starting sound presets swapped (Appendix F.1.5). This task intended to facilitate comparison across the responses to both Matching Tasks, and to assess whether responses to the creative Tuning Task influenced participants' technical approaches. In addition, this being the final task of the activity, it was also intended to capture participants' best guess of how to use the apparatus most efficiently and effectively, by putting everything that they had learned together.

8.1.3.6 *Interview structure*

The interview topics and questions are described in full in Appendix F.1.6. As in previous studies, the interview was structured to facilitate coverage of appropriate subjects, but was carried out as a discussion, responsive to the participant's behaviour. The topics covered over 20-25 minutes were:

- Activity clarifications (3-5 mins)
- Activity reflections (3-5 mins)
- Participation survey follow up (3-5 mins)
- Comparing personal practices to activity (3-5 mins)
- Any other questions (3-5 mins)

8.1.4 *Micro, meso & macro scale responses*

In the context of the activity as described, perhaps it is helpful to delineate what we consider to be the boundaries between micro, meso and macro. In Section 2.3, we described the reality of observing these scales in practice would produce fuzzy borders between them. Nevertheless, there are some clear boundaries that can be set in this activity. A macro scale response to this activity would involve subverting or appropriating the activity in a way that reorganises its overall purpose, such as by pursuing a completely orthogonal goal, or by using the apparatus in a clearly unintended manner. A meso scale response would similarly involve some kind of reconfiguration, but without challenging the overall nature of the activity or the purpose of the apparatus, for example rearranging the percussion blocks or combining the sculpting and instrument materials. Any macro or meso scale interventions would fundamentally alter the nature of the micro scale details of the activity, in such a way as to prevent detailed comparison with other responses. Since macro scale responses are expected the least with this activity, the border between macro and meso scale activity is not of great concern, however the border between meso and micro scales is potentially less clear.

8.1.5 *Data*

This section describes data capture and annotation methods used in this study.

8.1.5.1 *Capture*

Data captured in this study included:

- Pre-activity survey.
- Audio and video of the activity (the camera was focused on the apparatus and the participants' hands, and the participant was informed that their face would not be captured).
- Logging of sculptures and sculpts during the activity:
  - Timestamp of when each sculpture/sculpt was created.
  - Unique session, sculpture and sculpt IDs.
  - Sculpting surface frequency response.
  - Mapping algorithm intermediate data.
  - Mapped resonance model.
- Logging of percussion blocks state changes during the activity:
  - Timestamp of any state change.

    - Sculpt ID for each block.
    - Pitch for each block.
    - Locked status for each block.

- Post-activity discussion audio recording.
- Additional photo/video documentation of sculpts as needed.

8.1.5.2 *Annotation*

Session transcripts were annotated solely by myself using Roam Research[1]. Themes were validated through presentation, discussion, reflection and iteration in weekly PhD supervision sessions with my supervisor. The preliminary tagging schema was derived based on responses in previous studies, the research sub-questions for this study, and expectations about apparatus usage:

- Sculpting activity:
    - Resonance models selected if given a choice and why.
    - Handcrafting materials selected and combinations thereof.
    - Handcrafting methods used and developed.
- Comparison activity:
    - Tactile and gestural interaction with the comparison blocks.
    - Methods of singular or combined use of blocks.
    - Presence and detail level of verbal comparison.
- Design activity:
    - Presence or absence of intention setting at the beginning of each sculpt.
    - Reflections and decision making criteria used to guide subsequent sculpts.
    - Case-based reasoning behaviour such as refering to previous sculpts and personal experiences.
    - Sequences of sculpts that are part of the same iteration.
    - The extent to which sculpts and iterations become more, less or similarly detailed over time.

This schema evolved iteratively in a thematic analysis manner, through multiple passes of reading and tagging followed by reflection and thematising. The final tagging schema was as follows:

- Apparatus issues (Section 8.3.2)
    - Frustrations: issues participants had with the apparatus that broke their creative engagement.

1 `https://roamresearch.com`

  - Liveness: issues reported based on the workflow speed and level of interactivity.
  - Memory: issues with remembering previous physical sculpts.
  - Hidden state: issues relating to information withheld from being displayed.

- Activity (8.3.3)
  - Tasks: referring to or reflecting on the tasks.
  - Time: referring to time constraints.
  - MT1 (Matching Task 1): refering to this specific task.
  - TT (Tuning Task): refering to this specific task.
  - MT2 (Matching Task 2): refering to this specific task.

- Intentions (8.3.4)

- Assumptions about the sculpting surface and corresponding motifs (8.3.5)
  - Graphical: motifs based on assuming 2D representations (8.3.5.1)
  - Geometric: assuming 3D or otherwise geometric representations (8.3.5.2)
  - Physical: assuming physical acoustic properties governed sculpting response (8.3.5.3)
  - Progressions of motifs: how motifs progressed over time (8.3.5.4)

- Sculpting methods (8.3.6)
  - Trial and error: referring to deliberate iterative experimentation (8.3.6.1)
  - Limit-finding: referring to seeking the extremes of the sculpting response (8.3.6.2)
  - Order and patterns: referring to systematic methods of sculpting (8.3.6.3)
  - Intuition: referals to intuition as a guiding influence (8.3.6.4)
  - MT2: how particpants self-evaluated their final task performance (8.3.6.5)
  - Future: what participants would do given extra time (8.3.6.6)
  - Progressions of methods: how methods progressed over time (8.3.6.7)

- Scale of detail according to our ontology
  - Micro: discussing or reflecting on micro scale details (8.3.7)
  - Meso: discussing or reflecting on meso scale elements (8.3.8)
  - Macro: discussing or reflecting on the macro scale (8.3.9)

Further thematic analysis was conducted about comparative methods in relation to the third research question (see next, Section 8.2). This produced three themes which have been moved into a standalone subsequent chapter, Chapter 9.

8.2 RESEARCH QUESTIONS AND EXPECTATIONS

This study addresses Research Question 5 along with its three sub-questions:

What methods and processes emerge when instrument makers encounter a subtle and detailed design space?

a. What motivates instrument makers and creatives to focus on subtle and detailed design or not in a one hour activity?

b. How do instrument makers and creatives from different domains approach subtle and detailed design?

c. What kinds of comparative activity are present when subtle and detailed design is taking place?

To support the reader to understand why these questions were being asked, the following sections elaborate on them in terms of the expectations we had going into the study.

8.2.1 *Motivation to focus on subtle details*

Outcomes from the previous studies cautioned against assuming that a given study apparatus and activity would motivate all participants equally towards consistently designing at the micro scale. In this study the apparatus and activity was much more deliberately and tightly constrained, and participation was in an individual rather than group setting. It was expected that these two factors would greatly increase the chances that the majority of each participants' session would focus on micro scale details.

Regarding the apparatus, the tactility and familiarity of the hands-on clay sculpting, and the intimacy and variety of the digital tuned percussion instrument, were anticipated as being motivational enough to sustain engagement for the full hour. On the other hand, it was expected that the non-real time aspect of the sculpting process, and the mapping algorithm's hidden complexities, would potentially cause some frustration and be demotivating. Experienced violin luthiers were expected to find the apparatus to be physically rudimentary compared to their practices, and it was not clear how this would affect their motivation. It was anticipated that participants with little or no acoustics or handcrafting experience would struggle technically with the sculpting process, and that this might be a demotivating factor for them. Although the Matching Task was expected to be less motivating than the Tuning Task, overall the time constrained tasks were expected to keep the activity focused and progressing, where some participants may otherwise have lost interest inside an hour if there was a completely open brief.

8.2.2 *Influence of participants' backgrounds*

The cohort had backgrounds that combined music, instrument making in both acoustic and digital domains, handcraft and other creative and technical practices, in different ways and to varying degrees (Section 8.3.1). Due to the level of diversity in both breadth and depth of the cohort's background practices compared to previous studies, expectations were not overly specific, however a few assumptions were made. It was expected that acoustic instrument makers and people with handcrafting skills would have distinct advantages in this activity compared to digital instrument makers and musicians. They were expected to have more applicable experiences and skills, leading to more applicable intuitions, and this was expected to result in more controlled use of the apparatus by the end of the activity. Although the study cohort's depth of experience across different practices was informally self-reported, it was expected different depths of experience would also be noticeable from observing responses to the apparatus. For example, experienced craftspeople might be expected to focus on their fluency and speed with the sculpting workflow early on, to reduce the bottleneck on how many ideas they could try.

8.2.3 *Comparative activity during detailed design*

This study sought to produce significant quantitative data about comparisons made by participants between physical sculpts and digital sounds, because it was expected that patterns of comparison would emerge which would have the potential to illustrate approaches to micro scale design. In particular, it was expected that participants would make comparisons quickly and often, developing fluency in a variety of comparison methods and combining them ad-hoc to gain insight into the sculpting process. In aid of this goal, comparative affordances were added to the apparatus that were inherently discrete, namely in the TUI/GUI interfaces (Section 7.6). It was expected that these affordances would be learnable within a short demo activity (Section 8.1.3.2), and that the affordances provided would be useful for comparing sculpts.

8.3 OUTCOMES

This section describes responses to the apparatus and outcomes of the activity. First, the participant cohort of 26 is reviewed in terms of their experience levels and backgrounds. Following this, a brief description is given of the influence of the different aspects of the apparatus and activity design on the participants' responses. In summary, while the task briefs appeared to have some impact, the responses were more diverse and interesting where sculpting processes and outcomes were concerned. Issues with the GUI/TUI were encountered, which we felt should preclude them from comparative interpretation across participants.

With the focus mainly but not exclusively on responses to the sculpting data, the next four parts of this section proceed as an approximately chronological account of the participants' micro scale design activity. The four sections describe the participants' assumptions about the apparatus and resulting sculpting motifs, intentions and methodologies that emerged without any explicit prompt, sculpting methods and patterns, and participants' final sense of progress. In each of these sections, sculpting data is supported with activity transcripts and interview quotes, and plots based on the apparatus logs.

The outcomes are elaborated on further from micro, meso and macro scale perspectives. Based on post-activity interviews, the scale of sculpting seen during the activity is related to the role of micro scale details in participants' personal practices. Included are accounts of meso and macro scale responses to the activity which emerged despite the rigid constraints.

Finally, this section ends by reviewing these various outcomes from the perspective of the original research questions. The reader may wish to start with these sections to get a sense of the outcomes, and refer back to these summaries as jumping off points.

An additional note to the reader is also due. This section of the chapter features many full-page figures displaying participants' sculpting outcomes. In terms of the sequencing of pages, these figures have been clustered together in order to facilitate visual comparison across neighbouring pages, and to allow the text to flow unbroken. Due to this trade off, in some cases there are figures whose textual reference is some number of pages away. The recommended reading setup for this section would be to have two views of the document available, such that one can read the text and browse the figures independently. To further facilitate this style of parallel reading, the figures are provided in a separate standalone document accompanying this thesis.

8.3.1 *Participant cohort*

The cohort size was 33, of which seven were excluded from the task analyses due either to issues with the apparatus or activity protocol. However, some interview material has been retained from those seven. This left 26 participant sessions for consideration and interpretation. The cohort displayed a varied mix of background experience, ranging across instrument making and music making, and also including other artistic and technical backgrounds such as architecture. The backgrounds and experience levels of the cohort are summarised in Figure 8.3. The participants were assigned luthier IDs (**L1-L33**) roughly in order of experience level with instrument making, handcraft, and musicianship, although this is only approximate due to the high level nature of the self-report survey.

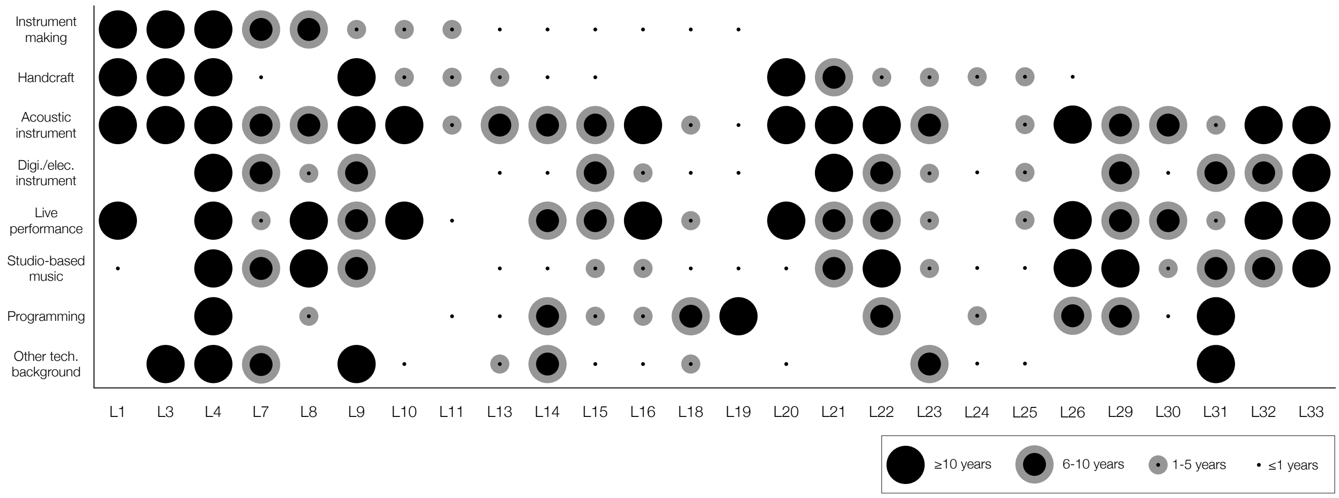


Figure 8.3: Experience levels of the participant cohort across eight questions, sorted approximately row by row.

8.3.2 *Apparatus influence*

The apparatus was designed to encourage open-ended sculpting of micro scale design details using the clay and tools, in doing so encouraging participants to explore correspondences between audio and tactile domains, with the visual domain deliberately excluded. While the participants appeared to for the most part enjoy the emphasis on tactility, some did comment that the approach they would ideally take with the apparatus would be predicated on technical visualisation of the frequency response data, mapping algorithm and resonance models:

L4: *"I think what I'd really need for this sort of thing is an actual picture of what it looked like, rather than just cursoring back through the sounds."*

L19: *"I'm having to do it all by ear because I don't have any graphic, I don't have any spectrum analysis or anything."*

While many of the apparatus constraints were purposefully designed, some were more the result of technical trade offs and development time constraints. Of these, the two that were repeatedly mentioned by participants were the non-real time or non-continuous aspects of sculpting (the delay between adding a new sculpt to hearing the result was around three seconds), and the lack of photographic sculpting memory in the session visualisation:

L4: *"I use little joysticks a lot, I can assign a couple of unrelated parameters, and I find I remember where the good bits are, you can move between them [...]*

you've got a sort of biofeedback [...] the snapshots mean I'm forgetting what I've changed. I know that I can cursor back and go, oh, that one's more like it, but I can't remember what [clay] I had here".

L7: *"Because of the time you have to take to update the sculpt, if the changes are subtle, it makes you sort of forget"*

L10: *"It tells you that your fifth attempt sounds like that. It doesn't tell you that it was loads of material spread evenly or anything like that."*

L20: *"I couldn't relate what was on there [GUI] to what was on here [sculpting surface], and therefore going back to there wouldn't actually help. So if each of those slots had a photograph of where the things [clay] were, then you could look at it and think, right, well, that was the sound I wanted, but not loud enough, and it's changed from what it was, to where I've got to now".*

Participants who had less familiarity with digital interfaces, or who used computers generally on a far less frequent basis, required more technical support or simply interacted much less with the GUI/TUI interfaces:

L10: *"The first five to 10 minutes for me was 'press which button to do what?' I don't use computers a lot in my life in general [...] so yeah, I found it harder to spot patterns in it, throughout the whole process, even after an hour".*

L30: *"I think having lots of different input methods overwhelmed me a little bit in within a short space of time"*

These difficulties experienced by participants make it difficult to regard the TUI interaction data as being uniformly representative of how much value participants got from its affordances of navigating and auditioning previous sculpts, given that some participants may have wanted to use it more than they did. As such, comparisons will not be made across participants using this data, and instead it may be used to clarify actions taken during specific design episodes of interest.

Participants who had greater musical experience gave more attention to the percussion instrument than those whose practice was more squarely focused in building, designing or making, exploring in greater detail its musicality and gestural potential. However, overall participants' main focus of attention was as hoped on the sculpting surface, clay and tools, and on their correspondence with the digital resonance models. Accordingly, much of the reportage in this section focuses on cropped video stills of the sculpting surface itself, arranged into sequences and collages.

8.3.3 *Activity influence*

Experiences in previous studies (Chapters 5 & 6), which had much less constrained activities, indicated that a lack of activity constraints would result in highly divergent behaviour and questioning of the main assumptions made by the apparatus. The activity structure and tasks did influence the participants to maintain their focus on micro scale details, in the sense that the vast majority of tasks were met in a task-positive way and completed according to their briefs. The exceptions to this are described in later sections where meso (Section 8.3.8) and macro (Section 8.3.9) scale responses occurred, however these episodes were part of a small minority.

Visually contrasting participants' sculpting responses across the tasks, however, demonstrates clearly a continuity of motifs, methods and processes. Within tasks, the end of one sculpture and the beginning of the next would often show continuity, and this was also true with tasks. Sections 8.3.5.4 and 8.3.6.7 respectively describe these progressions of sculpting motifs and methods across the tasks.

Indeed, as the post-activity interviews tell, the participants had already started forming ideas about their goals and what motifs, methods and processes they wanted to try, seemingly from the moment they entered the room or when they were first guided through the Demo. The next section describes their early intentions towards the apparatus and activity.

8.3.4 *Participants' self-reported intentions*

In the post-activity interview, the participants were asked to describe what happened for them during the first few minutes of the demo. Although they were not prompted to do so, it appears that the participants had immediately become curious and set their intentions towards understanding how the apparatus worked:

L1: *"I'm just trying to find a logic, desperately trying to find a logic."*

L15: *"I was very much trying to, like I guess, work out the mapping, like from my actions into how that influences the sound."*

L16: *"I was just trying to work out how the sound like got affected really. I was listening out for things like pitch, if it filtered it at all, or the kind of resonance of things and the length, you know, of envelopes, how long the decay and stuff was, those kinds of things."*

L18: *"I was thinking in a very technical way [...] I was trying to imagine how this thing was going to work, and I could picture vibration or weight, so I tried to figure out like by moving it [the clay] in what spot of the board."*

L19: *"I guess my brain was trying to grasp for how making a change was a function that changed the initial sound, looking for principles."*

L22: *"I was trying to work out, what is it measuring, with all the clay stuff and so on? How closely is it aligned to what I understand about sound and music?"*

L29: *"It was a bit chaotic and I was just wanting to try like, what does this mean? What are the rules?"*

L32: *"I kind of tried to find like a pattern of like, you know, where things resonated and how to like, kind of change the pitch of resonance."*

8.3.5 *Apparatus assumptions and sculpting motifs*

Each sculpt image features a unique ID in the top left corner, e.g. ***L19S3S04S05****:*

L19*: the participant's ID.*

S3*: task 3, where 0 = Demo, 1 = Matching Task 1, 2 = Tuning Task, & 3 = Matching Task 2.*

S04*: Sculpture index 4 (zero-indexed).*

S05*: Sculpt index 5 (zero-indexed).*

Once the participants were guided to the stage of the Demo where they could take more control over the sculpting, they quickly diverged in their use of the available clay, representing a variety of forms or motifs early in the session, and often trialling new motifs throughout. Underlying these motifs were assumptions the participants made about how the apparatus worked, which appeared to be based on their own backgrounds and first impressions of the experimental context and apparatus. As will be described in this section, participants with predominantly digital media-focused backgrounds interpreted the sculpting surface in either a graphical way (assuming orthogonal axes of XY or XYZ) or a geometric way (assuming some mechanism of high-level shape recognition). Participants with acoustic instrument making backgrounds were more likely to assume that the sculpting surface was a rough approximation of a 2D acoustic plane, and operated under principles of vibration.

Different assumptions could give rise to visually similar motifs. To demonstrate this, the figures accompanying this section visually group motifs into five categories with detailed captions: 2D primitives (Figure 8.4), 3D forms (8.5), symmetry (8.6), physically-inspired (8.7) and material distribution (8.8). The assumptions, which were sometimes revealed by the participants during their activity, but mostly after during the interview, are described below and reference specific motifs in the figures above where appropriate.

8.3.5.1 *Graphical*

A common assumption about the apparatus among participants with some aspect of digital media practice in their backgrounds was that it mapped orthogonal geometric axes — referencing "XY" or "XYZ" axes, or describing the surface as "spatial" or a "graph" — and audio parameters such as gain and decay. This was a fair assumption for these participants, as they were after all doing the activity in an audio production studio, surrounded by interfaces designed exactly in this way.

L4: *"I was trying to see if there's a relationship between the XY position on this surface and the change in sound"*

L8: *"I wasn't sure at first whether it might work like a kind of frequency spread from low to high in that direction as an XY thing, whether covering up all at one side might do something noticeable."*

L14: *"I think at least location on the X-axis is one parameter. I think it increases the vibrato towards that end."*

L15: *"I'm getting a bit more understanding about the vertical axis. So now I'm thinking this axis is attack, and decay on this axis. So I'm expecting like I guess a curve now."*

L26: *"I can kind of see it's like an EQ, in a sense. I'm trying to figure out the frequencies they want to block, I think that's what's going on."*

Participants with graphical assumptions appeared to be inclined to manifest and explore them using precise shapes and symmetry (Figures 8.4 & 8.6). This would again make sense in relation to how normalised graphical sound representations are in music and audio production software products.

8.3.5.2 *Geometric*

Other participants projected even higher levels of sophistication onto the apparatus, supposing that there might be some form of object or shape recognition occurring. **L7**, a musician, producer and DIY electronics maker, spoke during the session of a reference they engaged with: "It makes me think of Reactable, because that was a sort of a combination of geometric shapes that you would create sort of relationships with them to create oscillators, and then you know, put the filters and effects" (Figure 8.4, top row). In the interview, they further described what drew them towards shapes: "I think the material because of the specific tools and stuff, it just feels like shapes would be something to do, but also because of the Reactable, it's just that memory was a bit influential I think." **L11**, a violin making student with three years experience, described a related thought process without the same reference point: "I was wondering whether [the sculpting apparatus] isn't just weight [sensitive], whether it was something to do with surface area and whether the circles or squares would produce different sounds" (Figure 8.4, second row).

It could have been that the research context and environment for the activity influenced some participants towards expecting a high-technology prototype rather than the quite rudimentary one which was presented. Below are further examples of assumptions about the apparatus having a higher level of sensing and semantic recognition than it did:

L4: *"I'm thinking you're using the camera to look at this [sculpting surface] [...] that's why I was messing around with the height of things."*

L31: *"I was trying to figure out what different shapes and the position on the plate did to sound."*

L33: *"In the beginning I was just trying to figure out if you make something which looks like a sawtooth, you will get something closer to sawtooth or something, I guess. Or if you make something round, you will get to something closer to a sine wave."* (Figure 8.4, bottom row)

8.3.5.3 *Physical*

While geometric motifs emerged on the one hand due to assumptions that it would be semantically or symbolically syntactical, geometric motifs also manifested out of assumptions which instead were inspired by physics or acoustics. Combining geometry and physics, **L23** and **L19** referenced architectural forms, while **L25** referenced mathematical theories of resonance.

L23 is a trained architect and trained in violin and piano, and manages cultural projects at the intersection of architecture and sound. They found material connections to their practice early in their session: "I want to see that [the clay] as you know, like building cladding. Because this looks pretty much what like what cladding is, like a surface which is insulating and then the house or face" (Figure 8.5, bottom right). Reflecting on this in the interview, they used the apparatus to think about their practice: "I could associate [the apparatus] with things that I know that I would like to potentially see it merged with, for example, like musical buildings [...] maybe if you had a room where you could modify the acoustics by like, just sculpting something, that would be really cool."

L19 is a professional software engineer with some electronic music and maker electronics experience. They stacked pieces vertically early in their session, and decided to take this idea further: "I could really go crazy with the clay. I just realised I've been a bit tame actually." This led to a bridge-like form: "I'm thinking something really wobbly would be quite interesting, because we didn't really cover if I had something slightly unstable on top" (Figure 8.5, third row). Although it wasn't made explicit, it seemed that their proposition was that structural instability might increase resonance during the measurement process, in effect introducing further non-linearities to the mapping. **L19** later made a series of sculpts inspired by the geometry of Chladni plates: "Yeah, I don't know what is it called a Chladni plate? I'm thinking of that. There's a guy called Nigel Stanford in New Zealand who did that video with the cymatics" (Figure 8.7, second row).

L25, a professional chef with a background in physics, referred to their mathematical understanding of resonance, and further referenced cymbals and gongs:

L25: *I was thinking about a maths module [studied at university], is it like Legendre polynomials where you solve the resonances of different shapes? And I was thinking, it sounds like that sort of spherical-based objects in here [the vibration transducer], and I've got a sort of square one [sculpting surface]. So can I make a transformation between like square world and sphere world? Because I also had an idea from like cymbals and gongs, that if a cymbal has many bands, many thin rings that are joined together, the lowest notes that come from the longest rings, because they're just like wide resonators, and the highest come from the smallest [...] I was just trying to think, is there a way that I can pinch the smaller symmetries and allow the bigger symmetries to* *sing, in order to like favour the bass notes? And that's why I was trying to like put dampening there [in a thin rectangle border].* (Figure 8.7, bottom left)

Participants with backgrounds in acoustic instrument making, made an even more direct assumption that the sculpting surface could be treated as a soundboard. **L3** "started designing and building guitars as a schoolboy, and qualified formally as an early-fretted instrument (lutes, early guitars) designer/maker in 1980's". They narrated as they sculpted:

L3: *"At the moment, I've just been editing a paper on soundboard construction in lutes. And the inside of a soundboard has transverse bars of wood to stiffen the surface of the wood. So I'm just kind of approximating that situation [...] Obviously here, I'm doing it fairly quickly. I'm not really yet measuring or calculating, I'm just sort of guessing really."* (Figure 8.7, top row)

They continued with this reference in mind as they played and listened to the resulting sounds:

L3: *"There's too many overtones and I prefer something a bit deeper, there's a sort of high frequency for some reason. Probably take some of these off actually see what happens. I freed a part of the panel so it can vibrate more freely, although constraining some of the added mass. [They try this idea out.] Okay, too much constraint. It looks like the freedom of the plate has been constrained by the weight close to the pivots on the edge here. So probably a mass in the center gives the deeper sound that I like. I'm just going to try that. I've seen this on, especially on Indian drums, they tend to load the center of the membrane with an added mass."*

Although far less experienced in instrument making than **L3**, **L20**, a highly experienced lute player and model maker with some elementary lute building experience, declared after some initial experiments with symmetry (Figure 8.6, third row):

L20: *"Okay, so we've got an asymmetrical soundboard, haven't we [...] there's obviously a diagonal effect on what's happening, because if I take two corners off, it goes one way, if I take two corners off it doesn't go the same way. And by just reversing the same piece, I can compare and contrast the two. So I mean on balance, it seems that the other way is producing a, what I might call a sweeter sound."*

8.3.5.4 *Progressions of assumptions and motifs*

Even when motifs employed by the participants began as loose, visual references to their experiences, the ideas embedded within them became an active set of assumptions which were interacted with and evaluated as hypotheses. Where some participants appeared to maintain their initial assumptions throughout, others progressed through different assumptions as they gained more experience. **L32**, a musician, noted: "At first, I kind of thought it was more spatial, but after a while, I kind of maybe it's also like the weights, yeah, it definitely is because it doesn't resonate as much if you put a lot of things" (Figure 8.8, second row). **L7**, who had initially referenced the Reactable, explained that they rejected this reference after evaluating numerous related assumptions and references, landing at a graphical assumption:

> **L7:** *"I was thinking of photography, like, you know, if, if this was light based, then I would have a difference between light and shadow, and then it's just variations of negative and positive and the shading of the length of exposure. But in this case, we only had a binary light [one colour of clay], or shape. I didn't know if it was pressure sensitive, and then you would, you know, get the pressure of the outline of the triangle. And then I moved away from it, because I saw I was getting nowhere with the results of the sounds with my triangles. And then I thought, 'No, it's got the plate, it's got an axis. Probably the analogy will actually be with graphs.' And, you know, that kind of instrument where it's an X, Y, and Z".*

To demonstrate patterns of motif progressions, four figures are provided displaying sculpts across tasks for four participants (**L11**, **L14**, **L8** and **L13** — see Figures 8.9, 8.10, 8.11, & 8.12). **L11** and **L14** (Figures 8.9 & 8.10) demonstrate, in the earlier tasks, relatively formal and precise graphical and geometric motifs (Sections 8.3.5.1 & 8.3.5.2), whereas in the final task their sculpting is much less formal and precise. **L8** and **L13** (Figures 8.11 & 8.12) demonstrate different approaches based on the task: in the Matching Tasks they converge towards simpler sculpts, whereas in the Tuning Task their motifs become more creative and sophisticated. These progressions are discussed further, later in Section 8.3.6.7.

8.3.5.5 *Summary*

In this chapter section, various motifs and their underlying assumptions made by the participants have been described, and related to participants' backgrounds. With little explanation given as to the hidden aspects of the apparatus, the participants were free to associate what they were encountering with a large variety of references, and manifest and test out ideas that those references inspired. Once the participants had made some initial evaluations of their initial assumptions, and in some cases iterated through a range of assumptions, they were immediately plunged into the three structured tasks, the first of which was deliberately technical beyond their level of experience.

This and the subsequent tasks forced the participants to devise methods and methodologies to constrain and guide their sculpting decisions, which are described in the next section. The methods and methodologies used by the participants were, like the assumptions and motifs they were drawn to, informed by participants' backgrounds and practices, and extrapolated and operationalised the motifs to progress their sculpting within the activity constraints. As with the motifs, the next section will describe how methods were fixated on and refined by some participants, where others cycled through many approaches in succession.

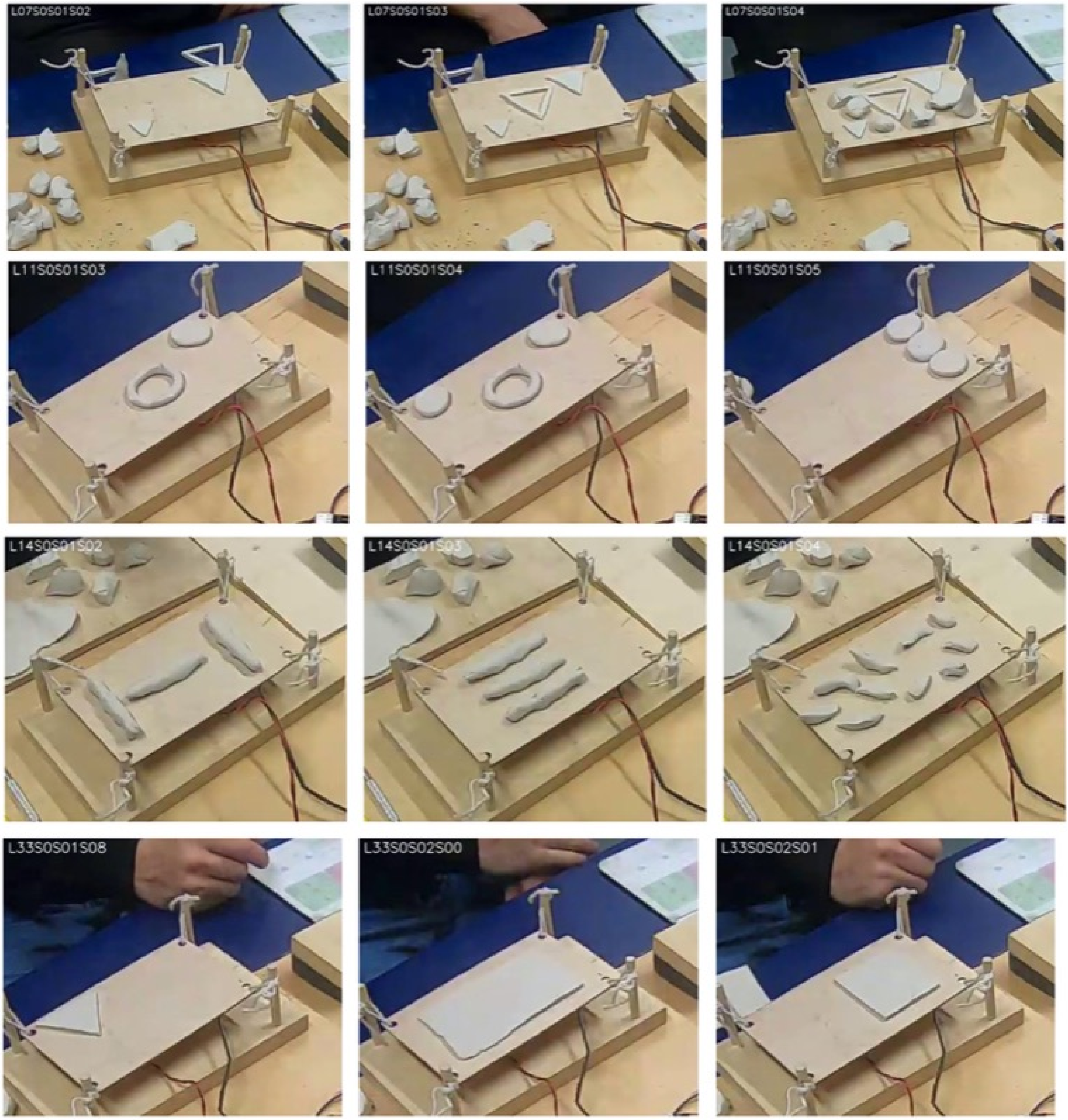


Figure 8.4: Two dimensional primitive forms used as sculpting motifs. Each row features a sequence of three sculpts from four participants.
L7 created equilateral triangles of different sizes, including some with the centres removed leaving just a perimeter.
L11 similarly created circles and torus shapes, of roughly the same size, and arranged these at the centre, corners and sides of the sculpting surface.
L14 created straight line-like pieces of similar length and arranged these in perpendicular and parallel formations, before breaking them into smaller pieces and arranging them in wavy patterns.
L33 also created equilateral triangles, along with rectangles which were divided into squares.
See Section 8.3.5.1.

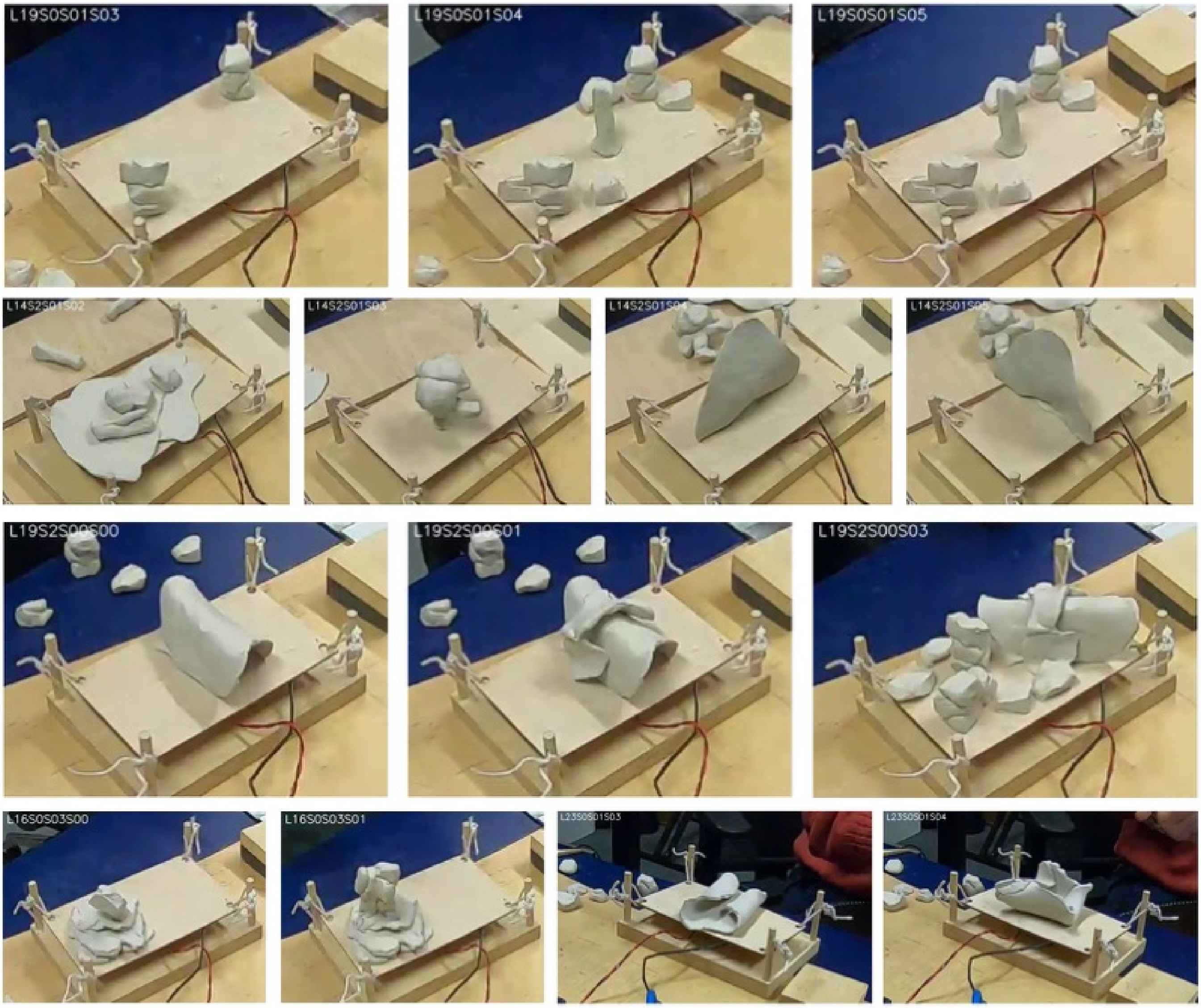


Figure 8.5: Sculpting motifs exhibiting complex three dimensional forms.
L19 demonstrates an interest in stacking smaller pieces vertically and piling them in opposing corners, and standing a longer piece upright in the centre.
L14 balances a large sphere on top of smaller pieces, and subsequently stands up a flat piece vertically, then rotating the same piece 90 degrees.
L19 created a bridge-like structure with two points of contact with the surface, with further pieces then balanced on top and leaning on the side.
In the left of the bottom row, **L16** was piling up flat, thin layers and then adding more material on top.
In the right of the bottom row, **L23** created curved, almost bowl-like shapes from large flat pieces.
See Section 8.3.5.

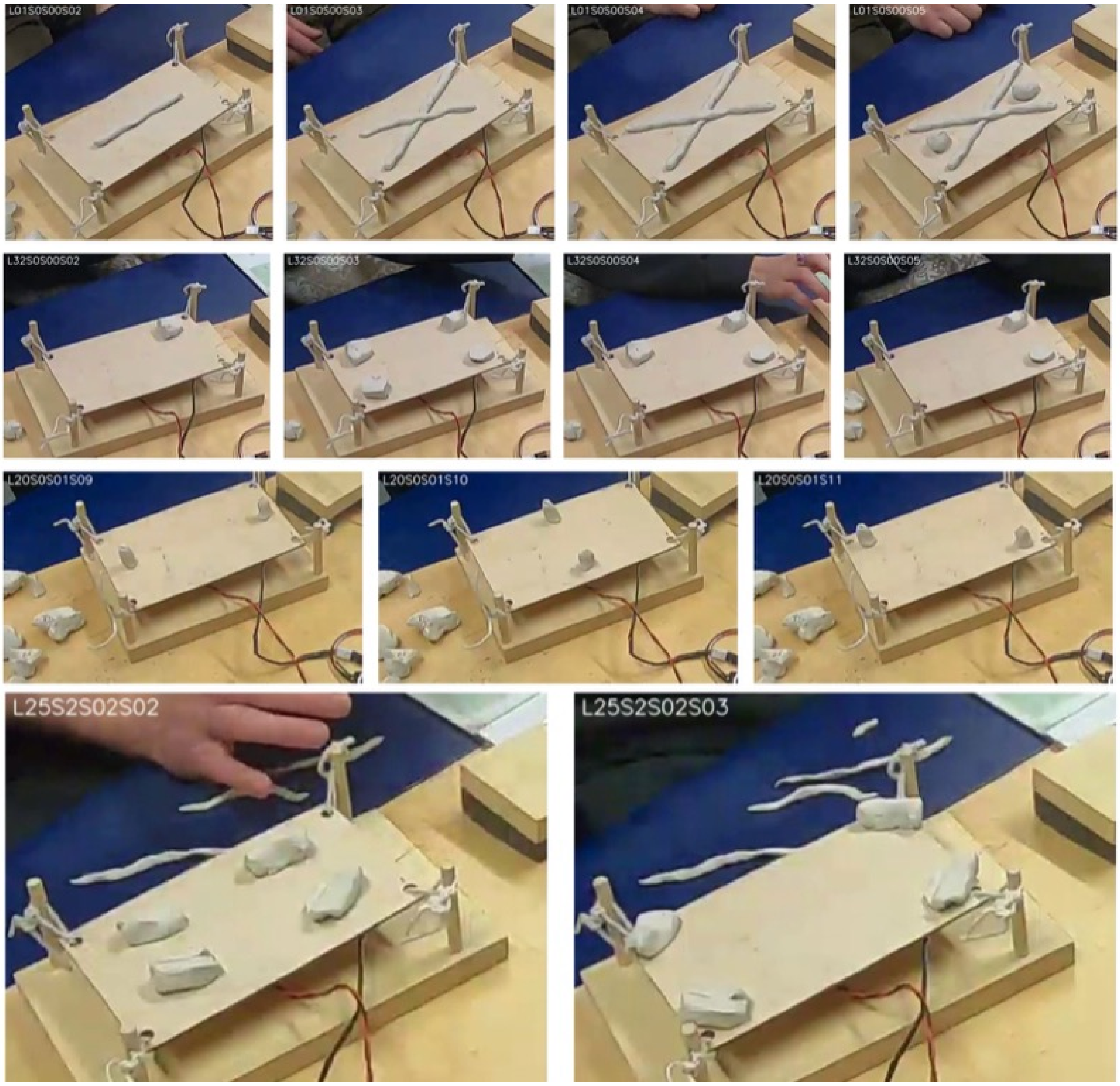


Figure 8.6: Sculpting motifs making use of one or two dimensions of symmetry, and spatialising material with respect to the corners and sides of the sculpting surface.
L1 started their session first with a line in the centre pointing towards the sides, which was then duplicated and criss-crossed pointing towards the corners, and subsequently the negative space was filled with small spherical pieces.
L32, in a sequence that was representative of a number of others, took small similar sized, roundish pieces and sequentially added them to different corners and sides.
L20 worked with two small pieces, moving them together to trial different symmetries and reflections.
L25 varied the distances of four pieces between the corners and the centre, maintaning a radial symmetry.
See Section 8.3.5.2.

Figure 8.7: Sculpting motifs inspired by physical principles.
L3 imitated a violin soundboard in clay on the surface and gradually removed material in place.
L19 imitated modal vibration patterns seen on a membrane, referencing the work of Ernst Chladni.
L1 added a sphere to the centre and gradually removed weight while keeping the position constant.
L25 in the bottom left laid out thin rectangular borders of different areas, roughly centred. **L25** in the bottom right also damped the edges of the sculpting surface by pinching clay directly onto the edge rather than fixing it on top, with differing lengths of clay.
See Section 8.3.5.3.

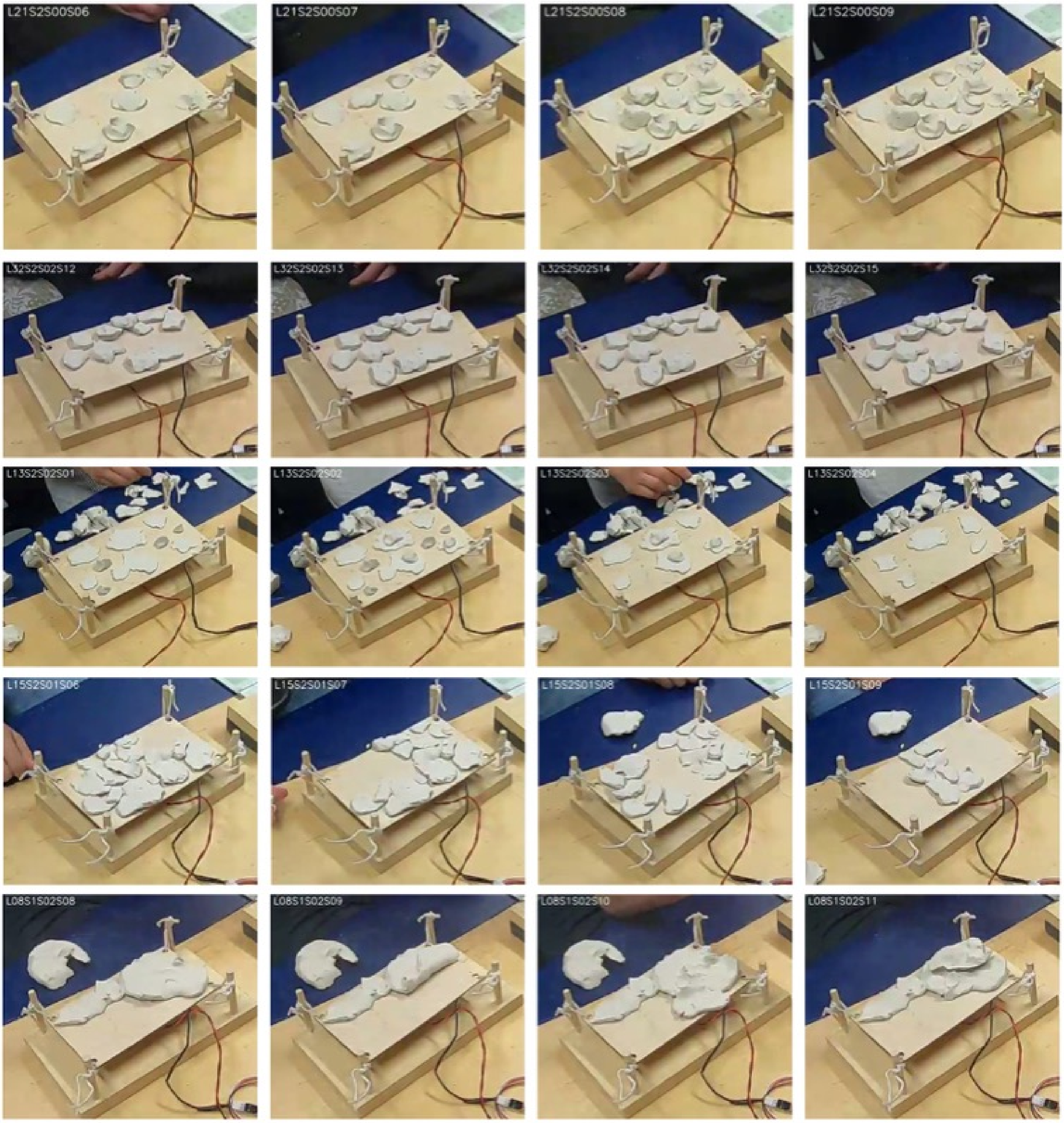


Figure 8.8: Sculpting motifs that indicate to varying degrees an interest in the distribution of the raw material rather than any specific form.
L21 shows finger marks in the clay where the pieces have been forcefully squashed down in place.
L32 arranged the pieces in such a way as to leave an off-centred gap.
L13 used flattened pieces, some of which were been stood up on their sides and squashed down on the surface or on top of the flat pieces.
All of these sequences demonstrate stepwise additions or subtractions of one or a few pieces, apart from in the final row where **L15** made larger rearrangements of material in each sculpt.
See Section 8.3.5.3.

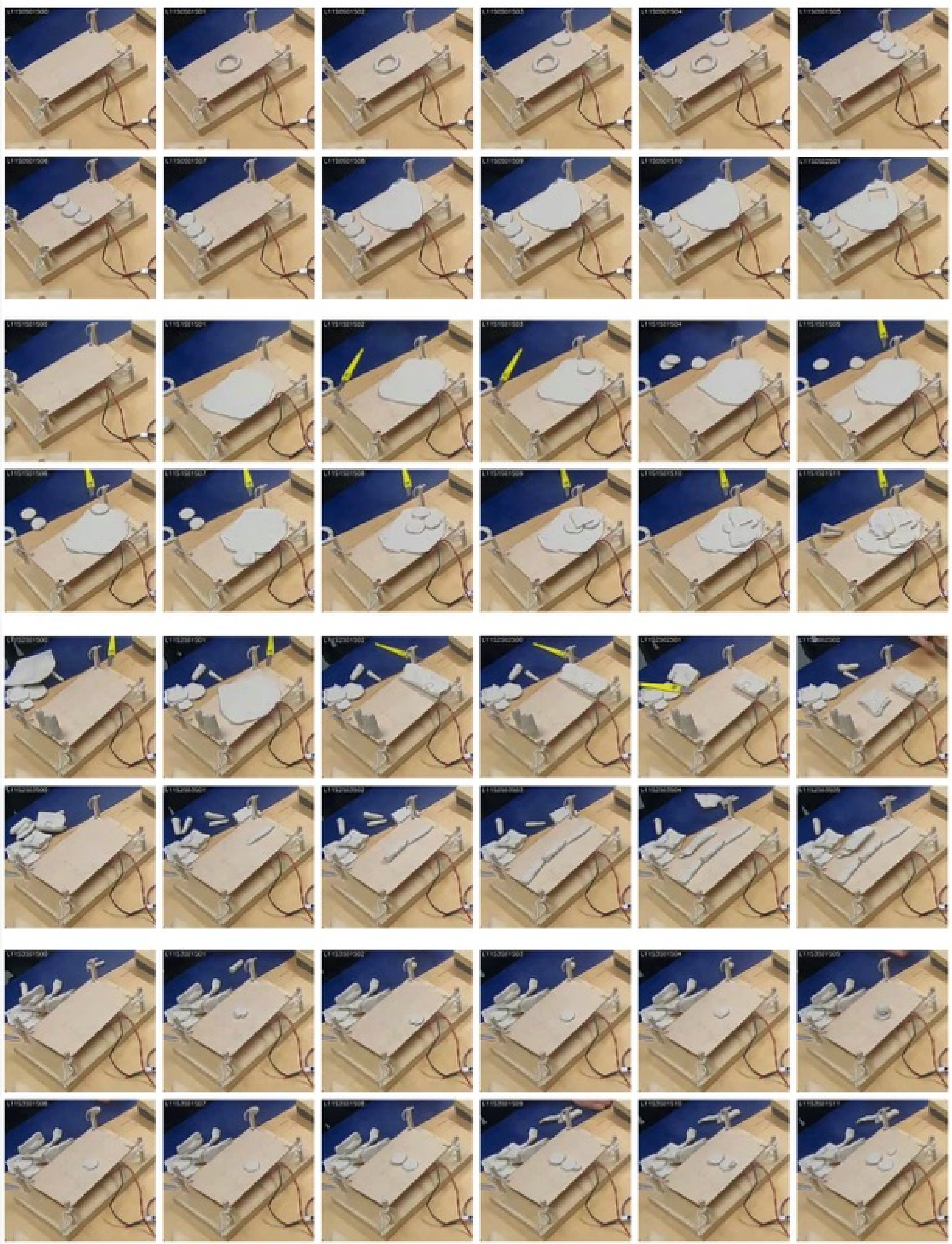


Figure 8.9: Comparison of sculpts across tasks for **L11** (for further discussion, see Sections 8.3.5.4 and 8.3.6.7).
Demo (top 6x2 block): precise geometric motifs (see Section 8.3.5.2).
Matching Task 1 (2nd): combination of large flat piece and circles.
Tuning Task (3rd): pillars arranged vertically and horizontally, exploring sides and symmetry.
Matching Task 2 (4th): simplified approach with less material.

Figure 8.10: Comparison of sculpts across tasks for **L14** (for further discussion, see Sections 8.3.5.4 and 8.3.6.7).
Demo (top 6x2 block): lines or cyllinders arranged symmetrically then stood upright.
Matching Task 1 (2nd): more lines, then using more material.
Tuning Task (3rd): elaboration and combination of previous ideas.
Matching Task 2 (4th): simplified approach moving one large piece around.

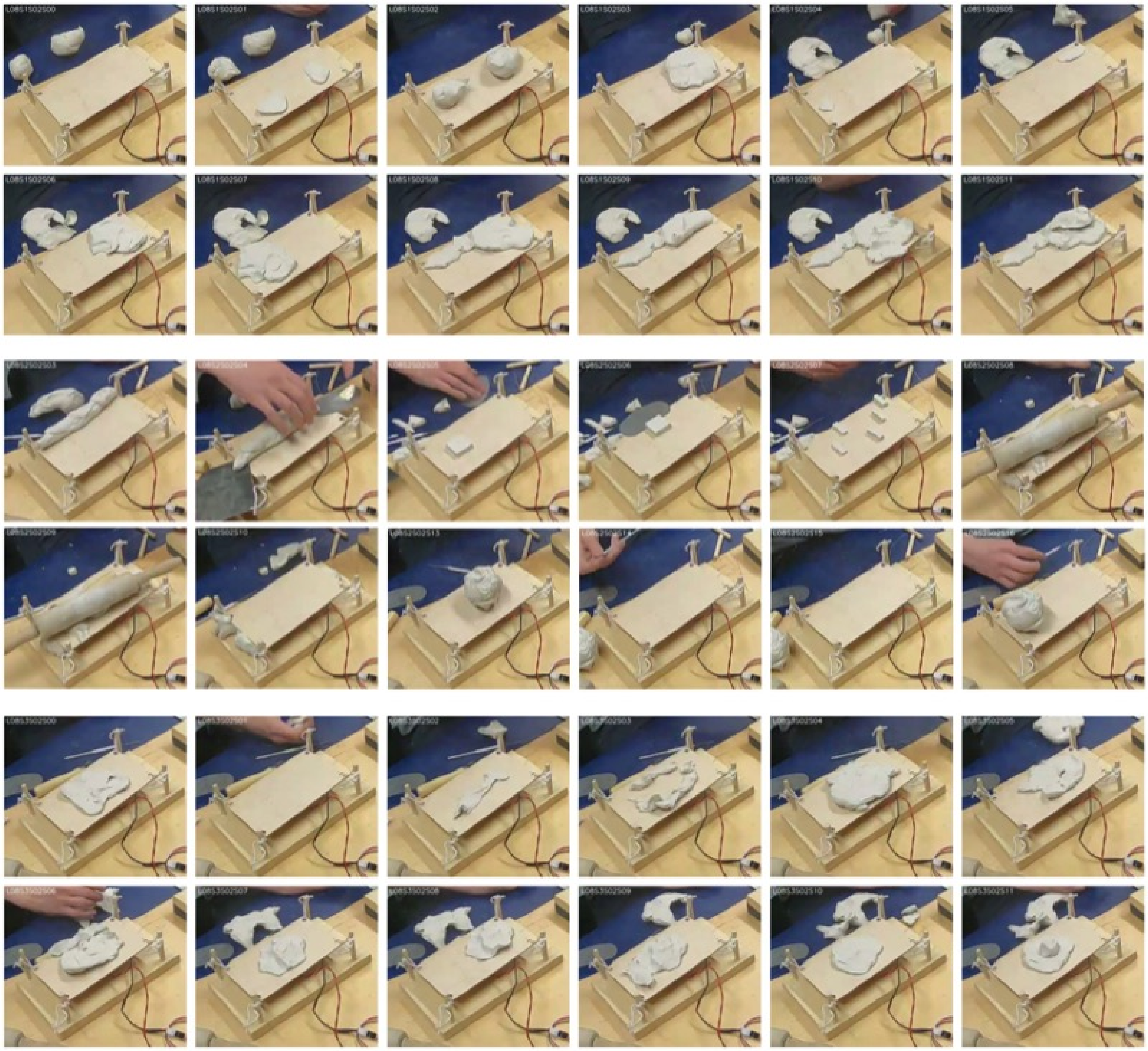


Figure 8.11: Comparison of sculpts across tasks for **L8** (for further discussion, see Sections 8.3.5.4 and 8.3.6.7).
Matching Task 1 (top 6x2 block): simple forms, contrast between large and small changes.
Tuning Task (middle): sequential exploration of very different ideas, use of tools as materials.
Matching Task 2 (bottom): simplified approach again with more focus on the centre.

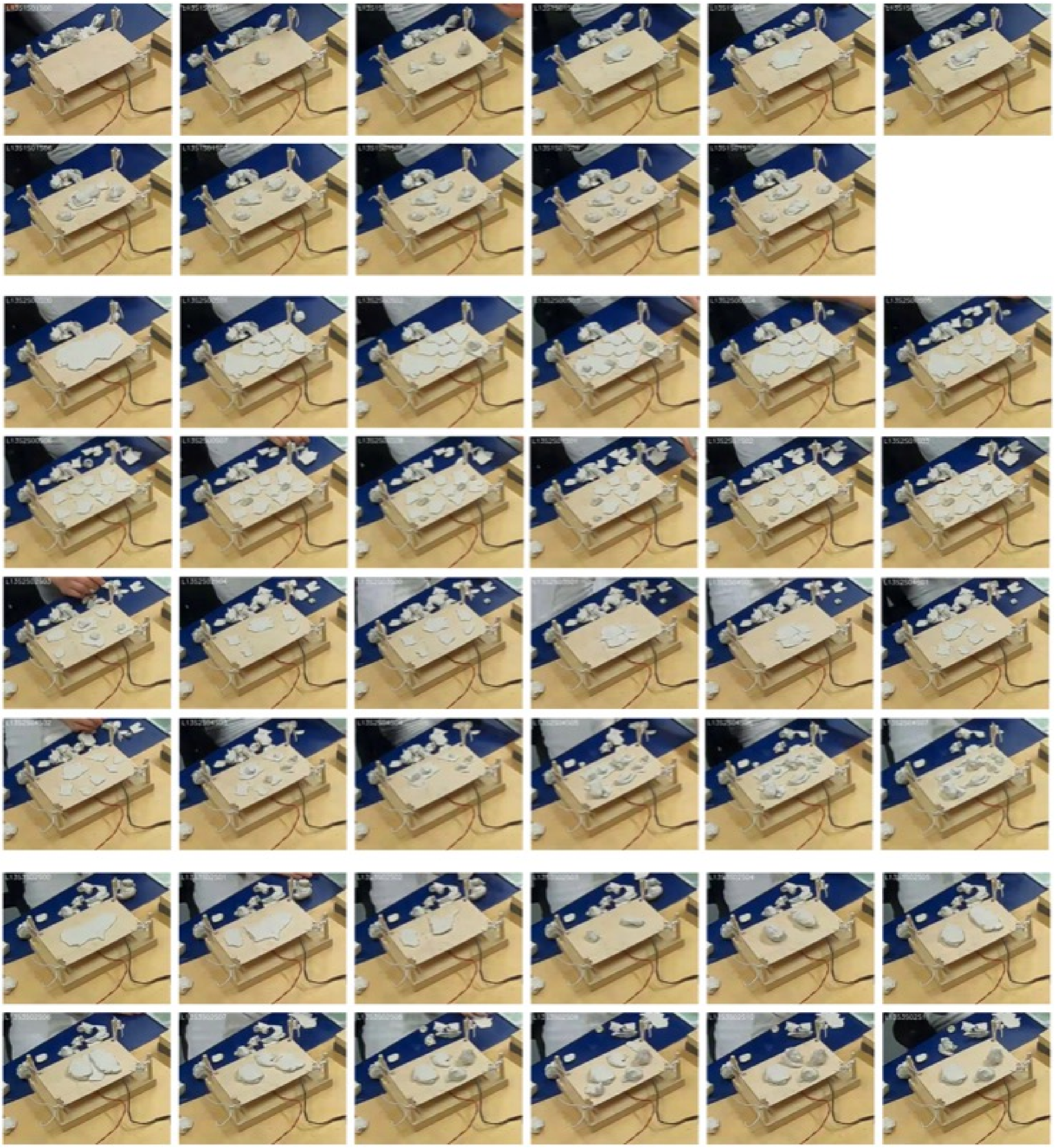


Figure 8.12: Comparison of sculpts across tasks for **L13** (for further discussion, see Sections 8.3.5.4 and 8.3.6.7).
Matching Task 1 (top 6x2 block): simple arrangement of small pieces, sometimes stacked vertically.
Tuning Task (middle): elaboration of previous motifs into complex patterned arrangements.
Matching Task 2 (bottom): simplified approach with larger pieces.

8.3.6 *Sculpting strategies and methods*

Participants trialled and developed a variety of sculpting techniques, which are described across four themes in this section. The first theme describes how trial and error approaches were adopted by some participants, after their early attempts to find discernible correlations between sculpts and resonance models returned unsatisfactory results. The second theme describes responses and episodes where participants were searching for the limits and dynamic range of the sound models via sculpting. The third theme describes how participants used patterns of sculpting motifs and extrapolated them over time in different ways, in an attempt to give their process some order and consistency. The final theme describes different ways in which intuition was felt to be driving sculpting methods; some participants avoided assumptions and patterns from the beginning as part of their methodology, whereas others arrived at intuition-led approaches later on. Finally, the evolution of participants' methods across the tasks are considered, and high-level trends in methods across participants during the final task, Matching Task 2, are described.

8.3.6.1 *Trial and error*

Regardless of the participants' backgrounds or what assumptions and motifs they initially explored, the sculpting process was both unfamiliar and the results complex to interpret, which meant that any method or strategy for sculpting would feature an element of trial and error. In many cases it appeared that both the 'trials', attempts or guesses made by the participants, and the outcomes, were felt by participants to tend towards randomness or arbitrariness. **L7** and **L16** explicitly referenced trial and error in this manner:

L7: *"I was navigating literally, trial and error basis [...] I also feel like do you know when it gets to a point that you're randomly just pushing buttons and that's sort of what digital things do to you? By pushing the same things expecting different results or pushing random different things expecting to magically achieve what you wish."*

L16: *"I still felt clueless though, I have to admit that. I think I probably must have had more of a sense of what's going on [by the end]. And I think it's slightly closer, the last one [sculpt], but that was random the whole time [...] I think just as I went through it, it wasn't changing any particularly obvious way [...] So it was kind of like trial and error, very much trial and error."*

In contrast to the general sense of an intention towards understanding or figuring out the sculpting process (see Section 8.3.4), and perhaps as a result of being misled by initial assumptions (see Section 8.3.5), **L10**, **L22** and **L33** all felt their trial and error approach was not yielding intelligible results. **L33** in particular mentions switching mindset to evaluating outcomes based on preference for different sounds, in absence of workable sculpting outcomes:

L10: *"It was interesting and motivating. There was definitely a point where I found it a little bit frustrating. It kind of it didn't seem to matter what I did, I wasn't heading in the right direction."*

L22: *"I started with small pieces, but even then putting on small things, you know, maybe it's just a small thing here, and then it went wildly different. I went, Oh, yeah, this doesn't work how I think it does."*

L33: *"I didn't really understand the changes. I mean, when I do something, I don't really understand what it does. It was a bit random, and I was just looking for sounds that I like."*

While the apparently chaotic nature of the sculpting process was described as "confusing" (**L13**) and mysterious (**L21**), they also described it as "nice [...] like an exchange" (**L29**), "fun" (**L13**), and "intriguing" (**L21**), suggesting that whether the experience was enjoyable or not was partly down to the participants' creative perspective:

L13: *"It's really confusing, like, after that point, I was doing what I was doing earlier, which is splitting the material into smaller parts and it [the sound] just gets further and further away, and I couldn't find a way back, and it kind of just feels coincidental that I got the right sound [...] But also, it's fun, it's just I definitely feel out of control. I feel a bit uncomfortable, like a bit slow."*

L21: *"There's definitely a mystery element to it [..] you start to think, well, this means that and that means that, and then when it's not, it's kind of more intriguing. And so that difference between playing a really easy game, or more difficult game, actually the more difficult one is in a way more interesting."*

L29: *"It's nice, like it's just really like an exchange. We can just say, you don't know what's going to happen, but you like it."*

L18 reflected on and compared the value of unexpected versus totally random results:

L18: *"The unexpected value or sound would like open up things that maybe you wouldn't have done if you merely purely knew the machine, whereas also I feel like, you know, if you were completely random, then it wouldn't really be an instrument. You also do want to know what's happening [...] This was I guess 60-40: 60% deterministic and 40%I sorta went with the flow, I wouldn't be able to explain it."*

While **L4** and **L30** embraced deliberate randomness:

L4: *"If I was picking up a synth [...] what I usually do is I just go through every preset to find something and then change it and quite often end up with something completely different anyway, but it's like having a starting point. So when I was putting quite a few lumps on it, that was the equivalent of some different random starting point."*

L30: *"There was times when I was just like, I'm just gonna make this up and see what happens. I literally blanked, not even gonna think about coding, like problem solving."*

When trials appeared to produce pleasing or less random results, **L14** and **L18** described cautiously directing their trials in the direction they preferred:

L14: *"If I observed one kind of specific characteristic of a sound that is enhanced with a certain structure. If I liked that characteristic, I would try to make it even more obvious. By you know, being slightly logical [with the clay]."*

L18: *"You know, like, Okay, this is making a nicer sound, Oh, look, I removed that, and it sounds, really high pitched, so let's put it back and remove another piece, without trying to think too much of, about theory. Cos also doing by doing that I was getting better sounds."*

8.3.6.2 *Timbre limit finding*

The Demo activity was scripted such that the first few sculpts made by the participants involved placing a single small piece of clay on the sculpting surface and moving it around. This was not only designed to introduce them to the workflow one step at a time, but also to highlight that such sculpts would result in both subtle and complex resonance model changes, and that simply moving a single piece around would not reveal how to sculpt the sound in an intelligible manner. The natural response for some participants was to gravitate towards the inverse of these subtle changes, and seek extremes. This was inherently very difficult, as the obvious spatial mappings of clay on the surface did not always correspond directly to timbral extremes. It was possible to create a large change with a small amount of clay and vice versa, as **L1**, a highly experienced instrument maker, encountered:

L1: *"Well, I was hoping that it would make a huge effect if I would sculpt away, but I probably would have if I would have placed it in a different place. But since I started in the middle, it didn't really do anything, so I kind of gave up that really quickly. And then I also thought that I'm going to try to find out the logic by putting extremes, to bring mass into the extremes."*
(Figure 8.13, top row)

L1 in this excerpt reveals that their hope was that extremes in the input space (sculpting) would produce much more obvious effects in the output space (resonance models) compared to the initial smaller changes. However, both the physical complexity of the sculpting surface, and the subtlety of the mapping algorithm, made this true in some instances and not others. Explaining further why they were searching for these extremes, **L1** referenced how they would employ a similar top-down methodology in the crucial early stages of troubleshooting in instrument repair:

L1: *"That's also what I'm used to in troubleshooting, quite typically, in a lot of my work. An example would be let's say like in guitar repair, there was a quick analysis, if there's a fret buzz which you can't get away with, but everything seems physically okay so the shapes are fine. But there might be a buzz, and* *it's very likely that it's the frequency of the neck. So you just put a clamp on the end of the headstock, so then the bass changes. So, like in the violins and cellos, there's a wolf note, and then you move the mass and then move the wolf notes. So it's about finding where it is, and then figuring out if you want to deal with it. And if so, then how."*

During their session, **L1** created and used small balls of clay, and this was in fact a technique directly borrowed from their own practice, to adjust instrument playability:

L1: *"I do that with ball making as well, there we just put mass not dissimilar to this. That's more working with playability and feel, it has a marginal effect on sound, but it will affect on the sound through the player. So just adding mass in different parts is a huge, huge distance, so we just put it somewhere."*

L10, an instrument maker who specialises in repair, like **L1** also contrasted different amounts of material in the centre of the sculpting surface, referencing a drum membrane:

L10: *"If you think of a drum, it's all held around the edges, and then the middle is the freest bit. I was trying to see what the difference would be between putting it all in the middle, and, you know, a little ball on the bottom and a bigger ball on top. So it's all focused on a point or if it's all right around the edges. Because I was struggling to see the patterns, I was trying to do the extremes."* (Figure 8.13, second row)

Similarly to **L1** and **L10**, **L8** was also drawn to seeking out the "extremes" as a means to getting the apparatus to reveal more about itself:

L8: *"I guess, going into extremes to see if that would help me to work out what was doing what I suppose, because the range isn't that great anyway. It's not like you can totally obliterate the sound whatsoever, it sort of feels like it's very subtle, some of the changes. So you would need to kind of try extremes in order to be able to see what direction you're going in for different things."*

Where **L1** used the metaphor of searching the sonic space by physical means, to "find" where specific sonic characteristics could be physically manipulated, **L8** used a metaphor of navigation, describing how they wanted to be able to see in different directions. In addition to searching for the greatest changes, **L8** was also motivated by the sculpting tools to explore and find the smallest changes:

L8: *"I quite quickly went from initially thinking, I guess because of the tools there, I always wondered how subtle it would be able to detect. I was thinking maybe even that sort of lines cut into things might make a difference. So I've tried later on, trying to do a really neat square to see what that would do, and again, that was a case of thinking of trying different extremes. So going from using really big or medium sized pieces to then tiny bits."* (Figure 8.13, third row)

L19 and **23** also pursued the limit finding strategy:

L19: *"I'm trying to get something that's a little bit more dramatically different in terms of the next change [...] so I've covered the whole spectrum."*

L23: *"I went on to make like larger shapes right afterwards to get like, bigger variation effects that I felt like I could understand, like a larger range of the possibilities."* (Figure 8.13, bottom row)

8.3.6.3 *Order and patterns*

The apparatus did not provide any facility to visually recall sculpts (see Section 8.3.2), yet despite this limitation, participants created sequences of Sculpts with distinctive patterns. These patterns can be revealed post hoc by creating matrices of video stills for each session. The sculpting motifs (see Section 8.3.5) in these episodes became pattern components, repeated and varied spatially across the sculpting surface (Figure 8.14). These patterns themselves were then iterated over time, sometimes with clear order and consistency, over a relatively large number of sculpts (8.15). These patterns, invisibly unfolding over time, seemed to be following unspoken rules, and even where they were less visually distinctive, logical connections between sculpts could still be traced (Figures 8.16 and 8.17).

L20 demonstrated a regimented approach to sculpting, highlighted by their sculpture of 38 steps, the longest in the dataset (Figure 8.15). This sequence when appreciated visually appears almost like the frames of a stop motion animation, or snapshots of a choreographed dance. Breaking the pattern down, a singular motif can be identified: a mound, about fingertip diameter at the base, and pointed at the top. As the base component of the pattern, this mound motif is replicated and varied in base diameter, height and mass throughout the sculpts.

A secondary component of a thin ridge with sloping ends is introduced (third row, third column) by elongating the mound component. These two components are then composed together by way of spatial motifs relating to diagonals, symmetry, proximity to each other, proximity to the centre of the sculpting surface, and parallel versus perpendicular arrangements. The overall sequence can be broken down into overlapping subsequences, where the combinatoric spaces of pattern components and spatial motifs is explored. For example, in the subsequence from sculpts 2-10, two similarly proportioned mounds are iterated through diagonal arrangements with varying proximities between them. This is followed by the subsequence from sculpts 11-14 combining the two mounds with a ridge, which reappears again from sculpt 18 onwards, and so on. As the sequence continues, an additional pattern layer of mass variation is added, while the same spatial patterns of diagonal arrangements are iterated over.

L20 assumed that the sculpting surface was an "asymmetrical soundboard" with "a diagonal effect" (Section 8.3.5.3), but they were frustrated by the lack of visual memory in the GUI, lamenting "I've gone

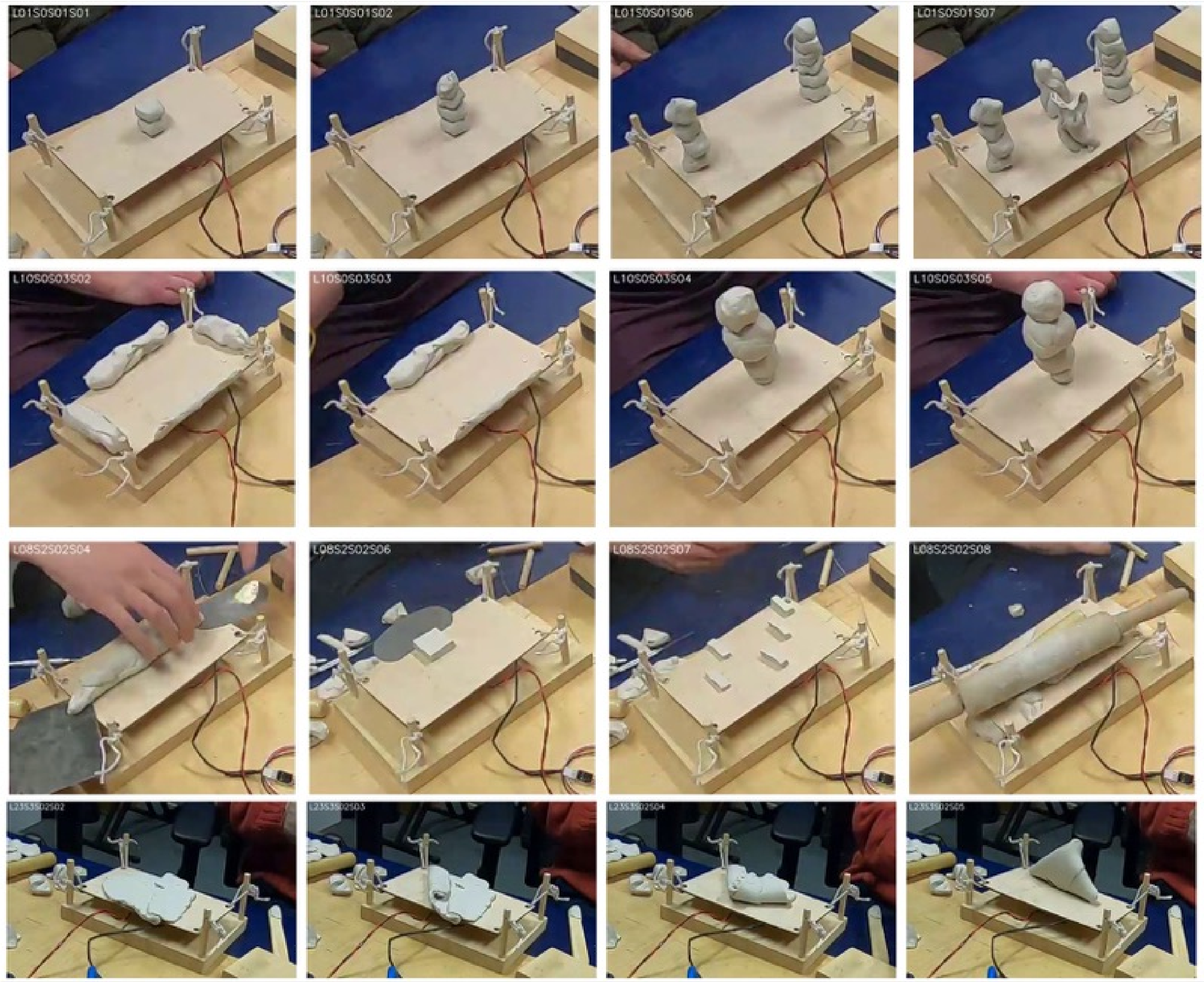


Figure 8.13: Attempts at timbre limit finding via "extreme" sculpting.
L1 gradually added more and more mass.
L10 focused stacked mass onto a fine point.
L8 explored multiple kinds of extremes.
L23 manipulated one large piece of clay.
See Section 8.3.6.2.

through a series of sequences, I've not remembered which one was which" (see Section 8.3.2). They remarked further on their use of symmetrical spatial motifs:

L20: *"And also, although realising it's not symmetrical, I've been playing around using symmetrically placed pieces, because that seemed to be in what in some ways, it's easier to manipulate and think about what you're doing, rather than just put one at one end, or one at the other [...] So the approach was logical, but because I hadn't got all the material or all of the information there were gaps in the logic."*

Other participants also commented on ordered or systematic approaches, either in reference to what they actually did during the session, or what they would do if they had more time:

L3: *"I think if I needed to do things more accurately, I'd have to experiment more with the plate itself. I've only just become aware of its characteristics. If I was doing this in a formal way, I'd try a systematic application of mass and location to see what results came out of them."*

L7: *"In my experience with handmade electronics, sometimes you already prepare three different values of things so that you can just switch, plug and play, and just see the difference. For example, values of resistors [...] When you are comparing things, and results of materials, you have to create something that is variable and something that's constant. So for example the triangle [of clay] would be the constant, but then vary the shape or the feeling, like an empty one or a solid one."* (see Figure 8.4, top row)

L13: *"I think if I would be able to sit down and actually have a method of doing it, I would probably start with the number of items. And then the area, basically test really scientifically on each parameter, like I have a compare group of having one constant variable and then compare all of them."*

L18: *"When I put three of them [pieces of clay], it was kind of like so I could see it. But if I had put like six or more, and then it would have been hard to like detect it. But with three it's kind of keeping it simple, so I can hear a clear difference, and I don't have too many combinations of all the on/off."*

While **L25** did not exhibit distinctive patterns visually in their sculpting, they relied heavily on their physics background and scientific mindset to develop organising principles for their process, and readily described how they felt their ability to test their theories and models was improving:

L25: *"I felt like even though I basically had started to assemble a still somewhat misty model of what I could be playing with and the parameters and how it would affect it - and I don't feel like I got any better, and objectively, I probably didn't - I at least had a model, which maybe after five more tests I would have totally thrown away. I still felt like I was taking baby steps, and just being like, no that theory doesn't matter. You've got such few data points that there's so many different curves that can fit those data points in terms of like finding an underlying theory for how to affect the sound. I mean, I felt sort of more, more comfortable in that process. I felt more confident, because I* *felt like even though I didn't have much faith in my model, I felt like I was getting to a slightly more advanced stage of being able to test the model. There comes a point where actually you just have to accept floundering is probably better."*

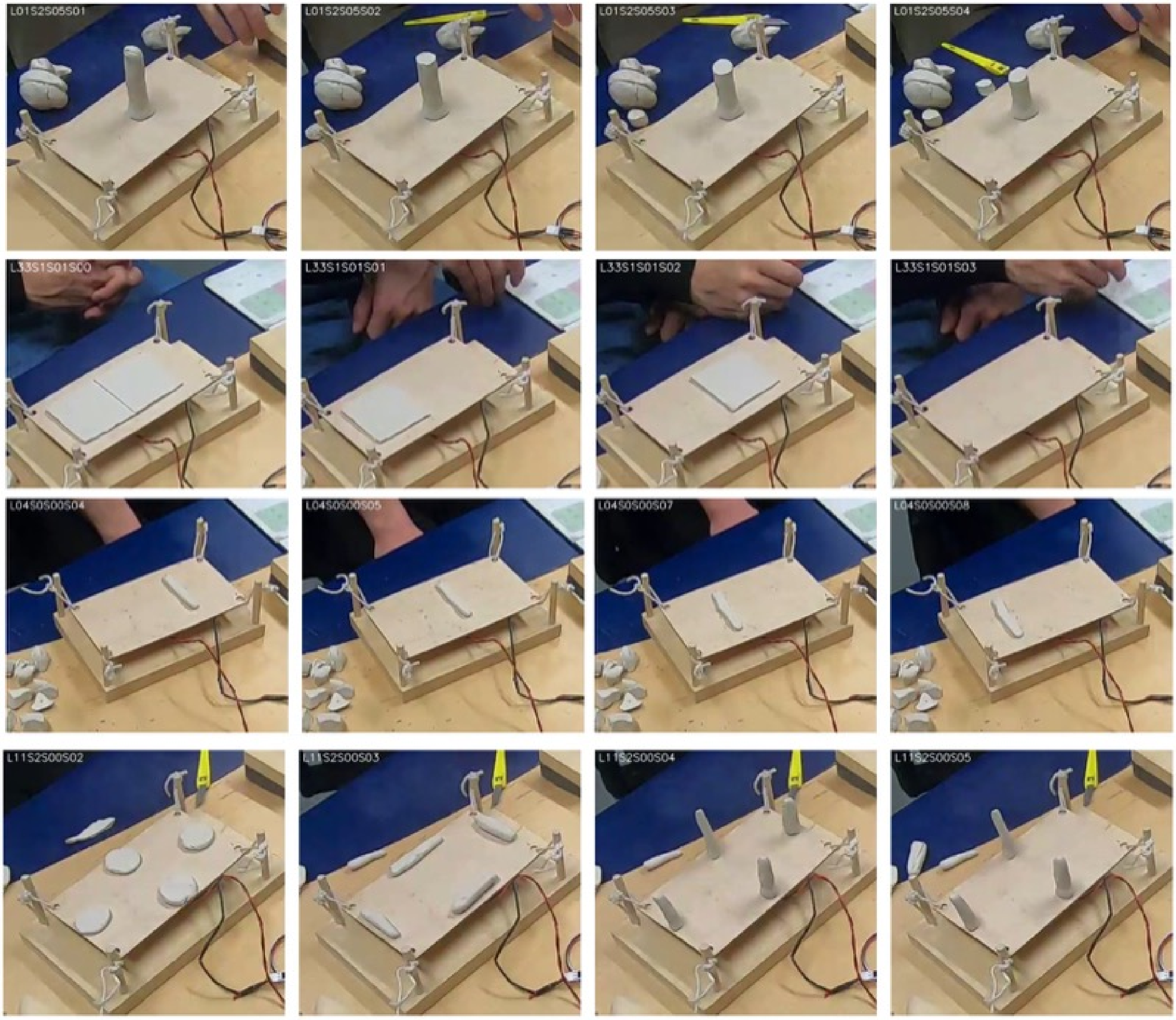


Figure 8.14: Four examples of patterned sculpting.
L1 took progressive slices away from a vertical cylinder.
L33 sequenced the combinations of a binary pair.
L4 moved a line across the length of the surface.
L11 placed four pieces in the centre of each side and replaced them with different shapes.
See Section 8.3.6.3.

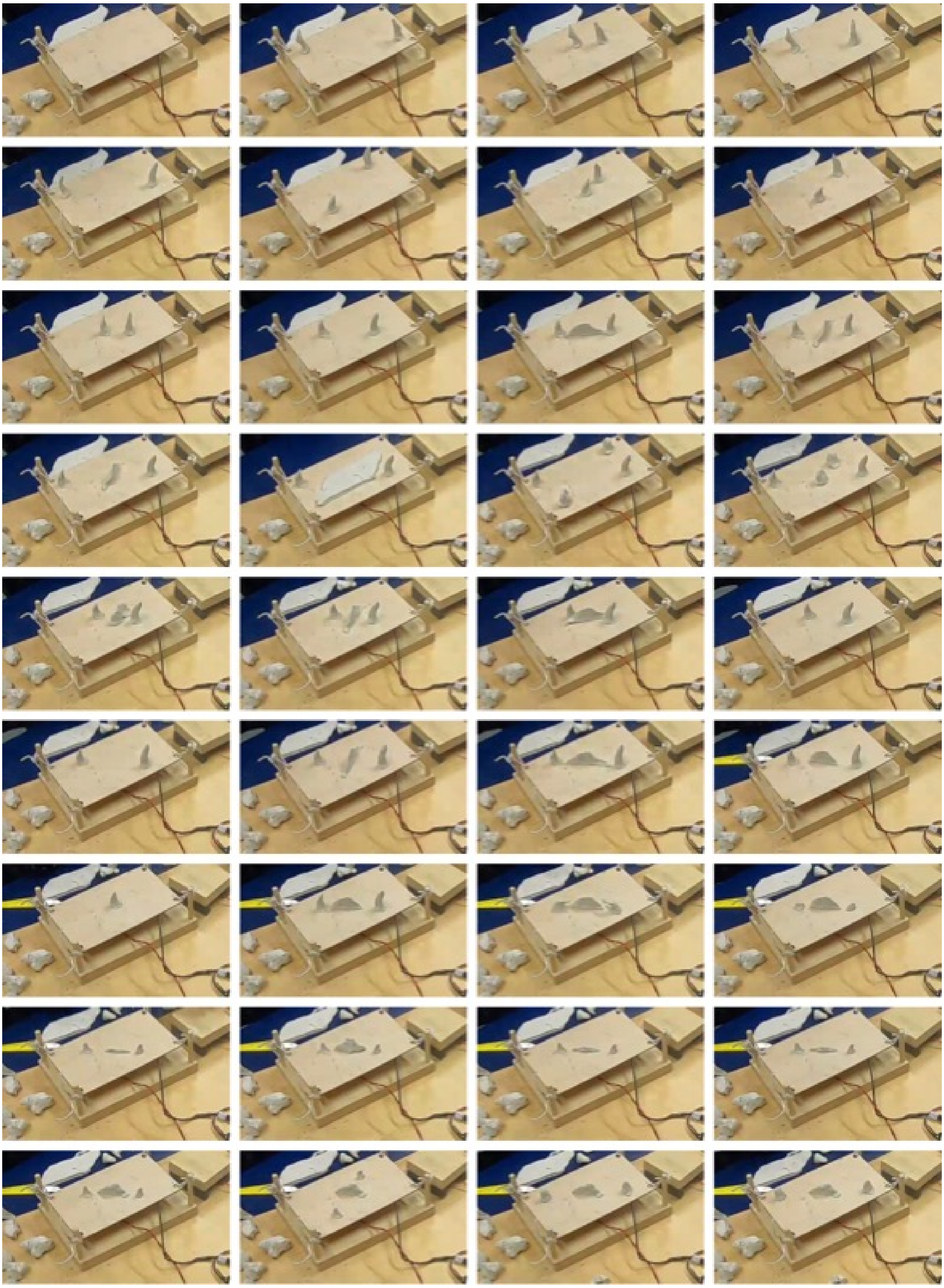


Figure 8.15: **L20** embarked on the longest sculpture in the dataset (38 sculpts, final two not shown), demonstrating procedural iteration of sculpting patterns based on specific motifs, and under the assumption that the sculpting surface could be considered as an "asymetrical soundboard". The pattern starts with two small stalagmite-like pieces marking out diagonal lines of varying lengths across the sculpting surface, and increases in complexity over time.
See Section 8.3.6.3.

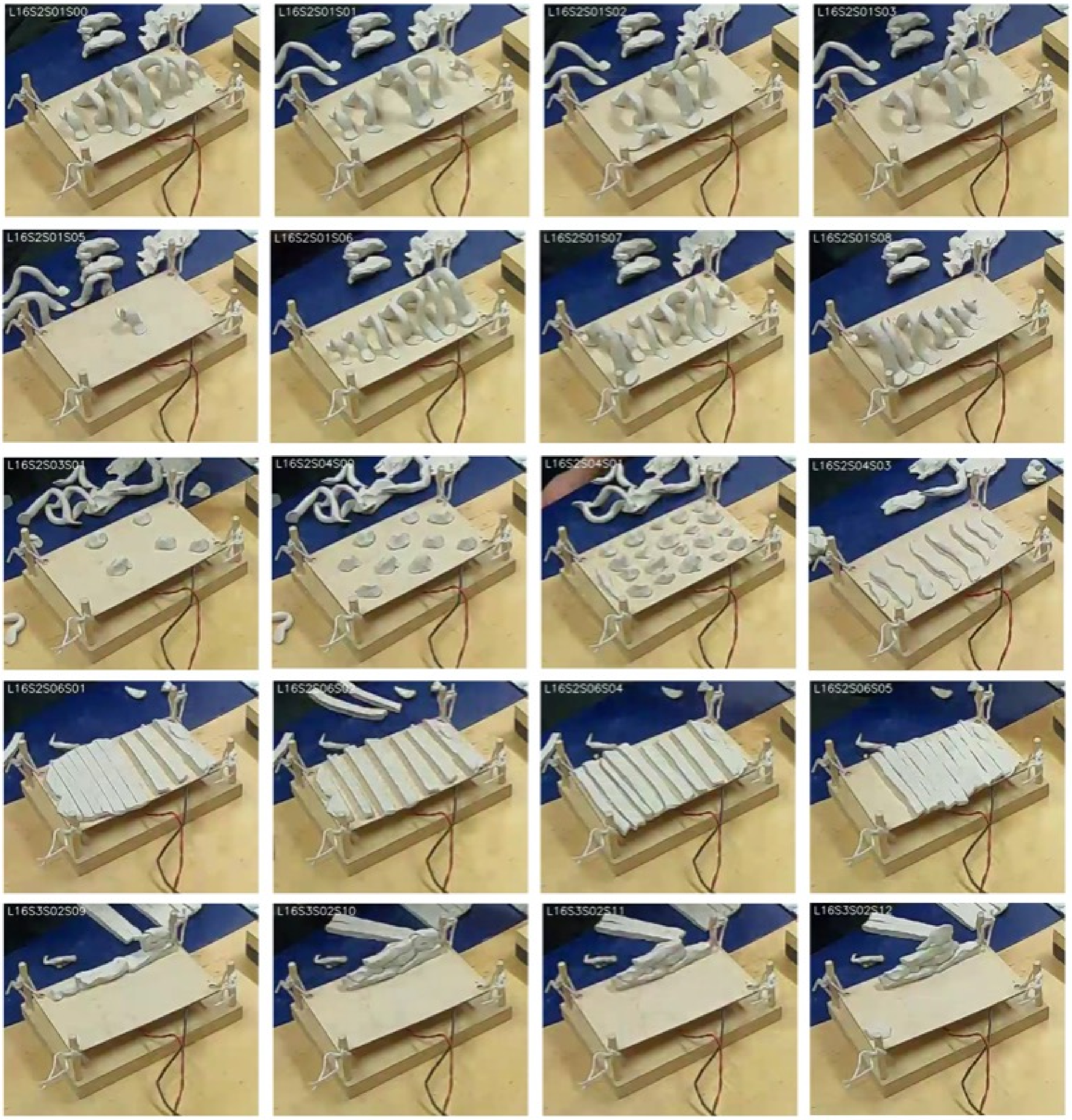


Figure 8.16: Abridged examples of sculpting patterns from **L16**.
Top two rows: a group of clay bridges of different lengths are laid out parallel to each other, in different combinations, and sorted in different ways.
Third row: small roundish pieces are arranged with increasing density before being replaced with bridges which have been flattened into lines and distributed in parallel again.
Fourth row: a large, surface-covering piece of clay has been cut into thin bands, some of which are then removed, and subsequently the negative space between them is varied.
Bottom row: the bands from the previous sculpts are being stacked along one side of the surface, like bricks in a wall.
See Section 8.3.6.3.

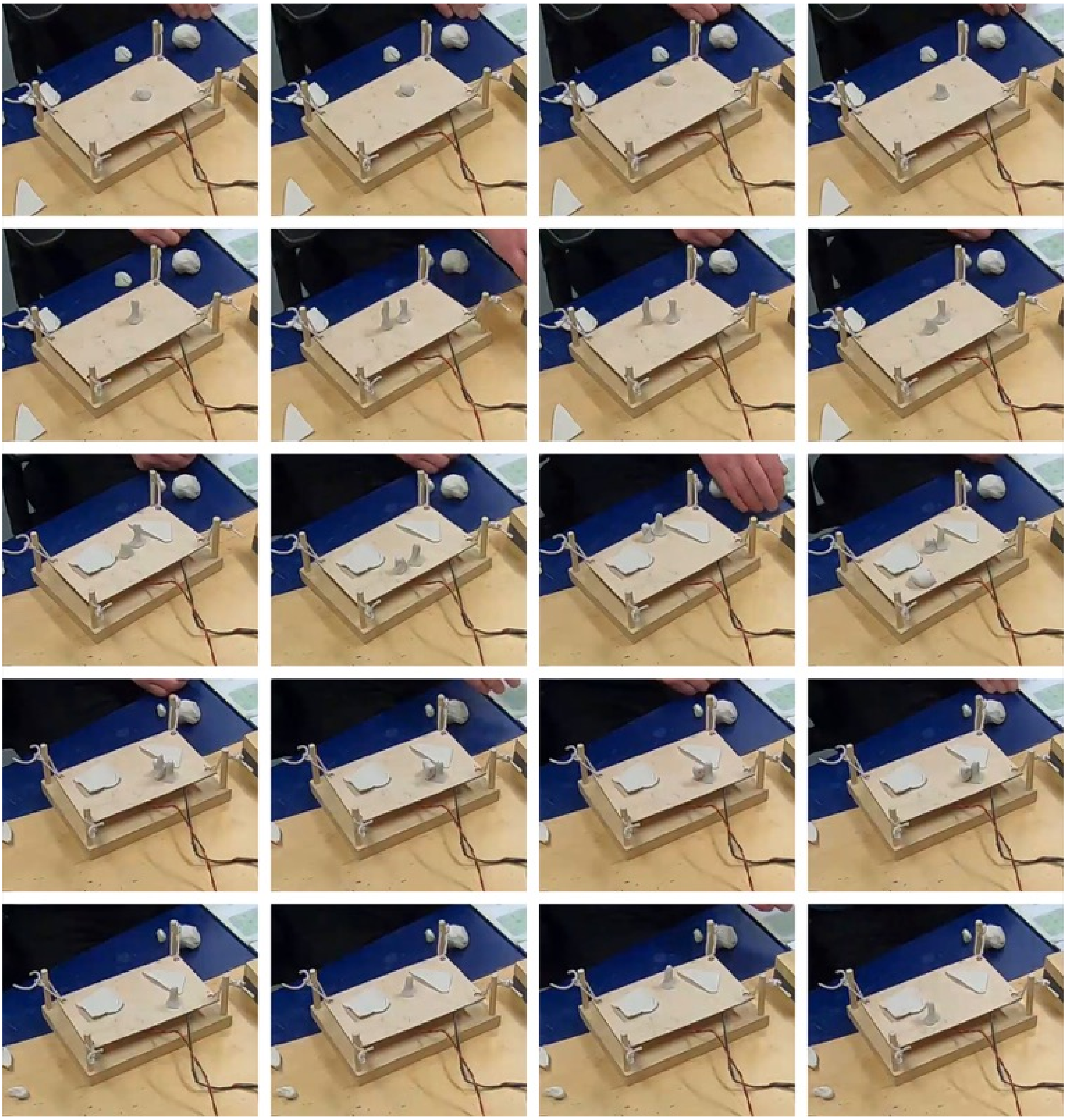


Figure 8.17: This sculpting sequence from **L4** demonstrates continuous morphing between different pattern motifs, and overlapping/combination of multiple patterns simultaneously. See Section 8.3.6.3.

8.3.6.4 *Intuition*

While Section 8.3.4 highlighted participants' initial curiosity towards understanding the apparatus, subsequent attempts at understanding or controlling the sculpting process were met with confusion (Section 8.3.6.1), subversion of expectations (8.3.6.2) and difficulty in establishing systematicity (8.3.6.3). Once it became clear to participants' that rigorous experimentation was sure to exceed the activity's time constraints, some turned to intuition to guide their sculpting. Descriptions of the role(s) of intuition reveal variations regarding what kinds of intuition were being used and why, and how intuition influenced the sculpting process.

Participants possessed intuitions about different disciplines, to different depths, depending on their practices and experience levels (Section 8.3.1). They evaluated the validity of their background knowledge through various assumptions made about the sculpting surface in the form of motifs (Section 8.3.5). These efforts could be described as trying to gain a technical intuition for how the sculpting affected the sound. During the more open-ended and creatively focused Tuning Task however, participants discovered that their musical intuition was now more valid, since they were deciding for themselves which sounds would play well together in a hypothetical relaxed concert setting. In this case, musical intuition could supersede and obviate the need for technical intuition, because this was not necessary to evaluate whether a particular resonance model pleased them, as opposed to understanding how it was created. **L32** compared this to their electronic music production practice:

L32: *"I really like it, because I'm very instinctive [...] it's kind of my relationship to some synths I use. Sometimes I don't really know the controls when I start, but I like trusting my ears and twisting stuff and seeing what it does. So it's kind of the same thing, I like it. But it's not that I don't understand it in a way, because it's more fun that way, I think. Especially to create because when you said you have to replicate [Matching Tasks], then it gets like way more difficult to do it instinctively. But obviously, like creating a song, it's like, it's kind of fun to do it that way [...] I have no idea [how instinct works], I think it's just like trying out stuff."*

L13 similarly described a musical goal of wanting a large variety of sounds to choose from, and sculpting intuitively towards that:

L13: *"I think at some point, when I realised what I was doing, I was selecting the texture from the preset and then I can tweak it from how I want my lows to sound, how I want the highs and mids. And then once I did that I started figuring out, okay, I have a really vague idea of how I want it to sound, and then the sculpting, a lot of it is just intuition, I don't always know what I was doing. But then I wanted to at least try a few different things so I have a large variety, a spectrum to go between when I can listen and then choose. I mean at least in hindsight that's what I think I was doing."*

L13: *"I don't think that there's like a defined a set of qualities I can associate the quality of clay to the quality of sound. So at the end, I just went with my intuition and see if I could develop an association at the back of my head, which is not necessarily not like a conscious kind of process [...] When I start a new sculpture, what's happening at the back of my head is I'm testing these across a spectrum of many different small pieces and one big piece, to go across the spectrum to use that as a way of measuring."*

Treating the problem space of the apparatus as a technical one meant working within a very small number of possible solutions, based on how the apparatus was implemented, which was deliberately complex. Whereas if the problem space was approached as a musical or aesthetic one, it had a much greater (or infinite) number of possible solutions, which could be navigated via a felt sense. **L14**, **L15** and **L18** all describe letting go of pursuing technical assumptions, in order to achieve greater freedom in creative process, effectively reducing the amount of "error" in their trial and error (Section 8.3.6.1):

L14: *"After spending some time with it, I started thinking that I actually enjoy it this way better, that I don't know the mapping, which gives me more freedom when sculpting objects which, essentially, I think helps with the creative process."*

L15: *"I think if I still played it for longer, I'd still be trying to work out my mapping, just my own set of rules [...] Whereas the way it's built, there's no inherent mapping, which I think is very against your standard instrument. You just kind of let go and be more intuitive or not necessarily be as close minded. Don't be limited to mappings [...] I guess I learned the intuition to the instrument. I found more like, I can navigate it, even if I can't say exactly what the outcomes will be."*

L18: *"I was thinking in a very technical way which is something I do, so I was thinking trying to like, imagine how this thing was going to work. And I could picture vibration or weight so I tried to figure out like by moving it in what spot of the board [...] What I expected didn't match what happened and that kind of threw out my theory. So towards the end, I guess I was trying more to go with it [...] Cos also doing by doing that I was getting better sounds. Like, for instance, I was trying at the beginning, to work out fat long sounds, and then I ended up finding it [later], just because by moving something it worked."*

In contrast, participants with backgrounds in acoustic instrument making, particularly **L1** and **L3**, both highly experienced makers, found their technical intuitions to be valid:

L1: *"From my toolbox so to say, I think all of them [were relevant], I wouldn't know what to think if I was without them. I've been doing this for a long time, but I would imagine that I would have not tried to solve any problems [without them]."*

L3: *"I work from intuition, my own personal experience of sound. I don't have a technical, you know, strictly technical approach, although I do use it sometimes*

[...] My intuition was I want to get the frequency response down on the existing panel. The center of the board is vibrating at high frequency, I want to slow it down. I want to keep it vibrating, but I want to slow it down. So the points of freedom where it's swinging, if I had mass there it would slow the actual motion overall, even though the panels still resonate itself, so it seemed to work in this case."

L1 reflected further by comparing this activity to their own practice in terms of experience, knowledge and intuition:

L1: *"In all fairness, I think it's not dissimilar to musical instruments, which are totally, in the knowledge it's empirical. So it's only logical because we have worked with them for generations, so we can kind of inherit knowledge. It's such a complex system that anyone who tries to figure out that 'I know the key', they're usually wrong because they're trying to solve something which isn't solvable. So I think the best restorers and makers out there, they base their knowledge on their own experiences and previous generations and colleagues. And solutions are usually very kind of, intuitive is the wrong word, holistic, or esoteric in some ways. First of all, sound is so abstract that to describe it, it's already a problem. And then if you try to nail that, like, Oh, yeah, it's such a good sound, and you've kind of already gone on a path which might lead nowhere."*

Researcher: *"How well does this system approximate some of that?"*

L1: *"As a beginner to this system? Hugely, because it's a totally weird thing when you start. And you think every time you approach it, oh now I know, and then the more you do it, the less you know, but the more you have experiences, and then you can start to kind of build up on those experiences."*

However, there were clearly aspects of the mapping algorithm (Section 7.5), particularly how the decay parameters were affected, that did not align with physical intuitions, as **L10**, an instrument maker and repairer/restorer, described:

L1: *"I felt like I started to understand some sort of relationship between height and volume. I still don't know where upper frequencies are, I can't take them out. I was desperately trying to take some high frequencies out and then put, like mid low frequencies in, I don't know where they are."*

L4: *"I made what I thought was a small change and sounded like quite a different sound to me. There's, you know, some higher harmonics coming in. And I added some more pieces in thinking that was going to dampen it. And instead, I got these higher harmonics. So that's surprised me slightly."*

L10: *"I found it harder to spot patterns in it, throughout the whole process, even after an hour of playing. I think maybe very slightly at the end, but it didn't seem very intuitive to me, or as intuitive as I thought. And maybe that's because the differences in the sound are quite subtle. I had an idea of how an instrument would work, doing this sort of thing to it. Mainly, I think I was picturing a stringed instrument, a violin or a guitar or something: so you've got a hollow body, and adding stuff to it is gonna dampen it, it's gonna stop it. So I kind of spread it [the clay] out, I thought maybe more of it would dampen it, and if you put it in one point, then it would have less of an overall effect on it, but it didn't quite seem to entirely do that."*

8.3.6.5 *Self-evaluation after Matching Task 2*

After Matching Task 2, participants were asked if they felt their sculpting had evolved or not over the course of the activity. While the majority felt that their level of direct control over the sound had not improved — they were not technically able to replicate a target sound during Matching Task 2 — they nonetheless felt they had made progress, even if it was hard to define what that meant:

L7: *"I don't think the results really improved. But I think my approach I would say that even though I didn't change achieve the sound, I was more conscious of what I was looking for and engaged more actively."*

L15: *"I think it's much the same as last time where we try and find a rough and then scope in. But I felt more confident where I was placing the plasticine. Whereas last time I was much more trying lots of things."*

L16: *"I still didn't have much of a clue, I think I was less panicked, though. I was doing it a bit more methodically. [In Matching Task 1] I was like, blimey, those two sound really similar. And any move I've made seems to make it go further away. But actually, when I did it the second time around, I could tell that there was, I could tell the difference. I knew the differences I needed to reach [...] there's multiple pitches in each one [resonance model]."*

L18: *"The second task of the drummer [Matching Task 2] went much better than than the first one [...] I was more confident with the instrument. I made much more sounds, like now we made like, 12, and the previous one we made maybe five?"*

L23: *"I feel like I understood a bit more how my sculpting was affecting sounds. It doesn't mean that I did better."*

L25: *"In terms of the actual output of the sound, there wasn't a huge amount of difference in terms of kind of like the absolute surface level, are you making improvements or not? But just in terms of like, the hidden variables language, just the variables which you're trying to uncover, I felt like more confident."*

The progress they had made was in some cases clear to them, for example some participants noted their fluency with the apparatus was noticeably improved:

L1: *"I'd say the difference is that I get used to the thing, so I can try a lot more. I have more speed, so therefore, I could do more trials, and maybe I felt like I was approaching something."*

L14: *"It was slightly easier, since I'm more used to this stuff and some creative things, but it was still not very linear, neither straightforward to find the desired sound."*

L19: *"So I mean, I was trying to do more iterations this time."*

In an attempt to corroborate participants' comments, and our observations, we calculated the speed and size of each sculpt across the four tasks. The speed of sculpting could indicate the proficiency of the

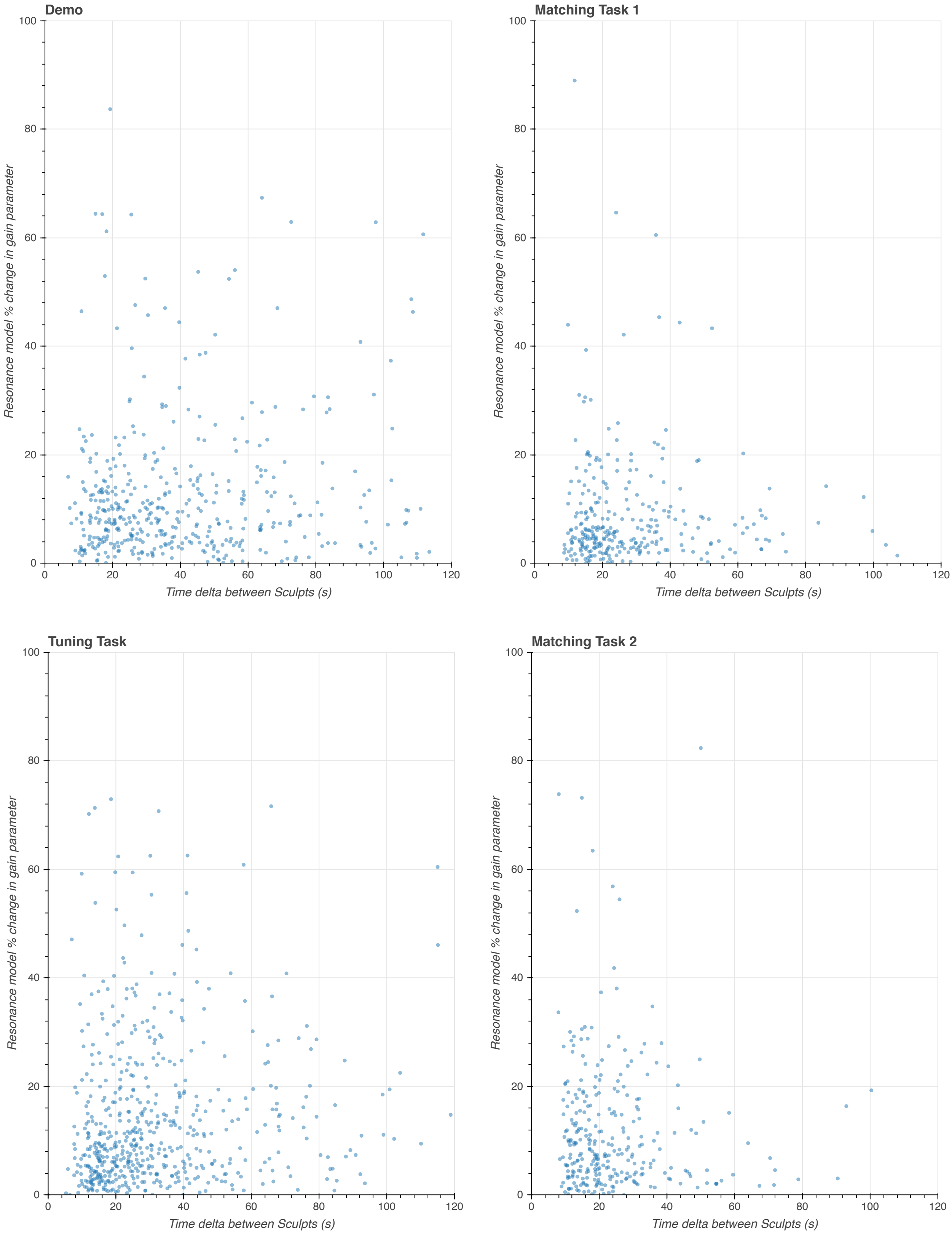


Figure 8.18: One scatter plot for each task (Demo, Matching Task 1, Tuning Task, Matching Task 2) of sculpts from all participants, arranged by time elapsed since previous sculpt (X) and size of change (Y). The time delta between sculpts is counted as the time between use of the *Add Sculpt* button on the TUI (see Section 7.6). The size of change of sculpt is measured in terms of comparing the sculpt's mapped resonance model to that of the previous sculpt, represented as the percentage difference between them, relative to the largest possible change (setting all parameters to their maximum value). See Section 8.3.6.7.

participant, and their level of creative flow, whereas the size of each sculpt could indicate what level of detail they were currently exploring. Figure 8.18 compares, for all participants, the speed versus the size of sculpt for each of the four tasks (Demo, Matching Task 1, Tuning Task and Matching Task 2, see Section 8.1). These plots reveal a similarity in speed and size of sculpting between the Demo and Tuning Task, which were more open-ended and longer in duration, and the two Matching Tasks, which were shorted and more constrained. However, there is a slight trend for sculpting in Matching Task 2 to be both faster and larger when compared to Matching Task 1. This correlates with participants' reports of achieving greater fluency, awareness and confidence with the apparatus by the end of the session. **L18**'s description of their approach to Matching Task 2 also seems to fit this interpretation:

L18: *"In fact, it really helped at the end to just go back and see what I did. So I felt like I was like kind of going around a problem, and maybe going further. And so like, once I had done all the routes, just going back and trying to find the closest point. And that's what we did when we went back to [sculpt ID] 3.5. That was like, you know, just stay experimenting and trying to get closer. Maybe you get further away, maybe you get closer, but then eventually there's the minimum one, the closest distance."*

In terms of the sense of randomness of the process described in Section 8.3.6.1, participants felt their sculpting was quite deliberate, whereas for others it remained as guesswork:

L11: *"So I was not just randomly trying to throw stuff on and see what happens. I like started by just like adding, because I knew I wanted to save the tone."*

L21: *"I had just been putting stuff on there completely at random and just hearing how it sounds, whereas now I was thinking, what are the differences between putting things at the edge and in the middle, or on the bottom? I still haven't quite worked it out, but clearly, there's some patterns emerging."*

L24: *"I just randomly tried everything so I cannot say it's better, but sounds better."*

L31: *"It was definitely easier, but I find it very hard to just affect one parameter at a time. And they got lost because after some change both the volume and the pitch change. And then I had to go back and forth, frankly, to find out which one was affected."*

And although there was a thread of intending to understand how the apparatus worked, running from first impressions (Section 8.3.4) and conscious assumptions (8.3.5) through to later intuition-led approaches (8.3.6.4), the majority of participants felt that by the end they had not gained much insight or control compared to their expectations:

L8: *"I guess I'm still sort of thinking about what's changing what? I'm still not sure. So still, I feel like I'm still testing things out, but not sure. I don't know, nothing closer [to the target sound]. I feel like there's something I'm not getting that's missing."*

L10: *"It's harder than I thought, I really thought I'd be able to spot more patterns, you know if you're adding stuff here that you're getting closer or further away. And it sort of seemed different, but I couldn't find the qualities I was after."*

L13: *"I think there is not much difference maybe slightly improved. Maybe it's because I don't really have the knowledge of like, the quality of sound like I don't know, what are these terms of like how you refine the instrument, like it's really hard for me to match what exactly I was doing to like the outcome."*

L14: *"I didn't expect to have this kind of sound as a result of this shape. So I couldn't figure out how it functions, or the mapping."*

L19: *"It was a bit better, but I know there must be something to do to move in a certain way, but because it's my first time my brain is having troubles you know, making the connection."*

L32: *"It's kind of difficult for me because I don't really understand what it does in terms of concretely to the sound."*

Both **L10** and **L20** had realisations about their techniques after finishing their sessions. **L10** regularly used large amounts of clay in each sculpt, and realised they did not explore using smaller amounts of clay. **L20** realised they did not explore the subtractive sculpting technique (Section 7.5.3), whereas **L31** had done to good effect:

L10: *"I thought I was putting stuff on and taking [small] bits away. But having had the conversation that we had, I'd do some stuff with smaller bits [...] It sort of clicked right at the end that no, you've not actually done the systematic thing that you were hoping that you would do."*

L20: *"If you set it up with more on in the first place, then your baseline will be different. So you then have more scope for increasing the volume or reducing the overall amount of stuff on it. And I think I hadn't quite worked that out when I started this one."*

L31: *"So, because that felt louder to me, I started the setup with a lot of stuff in it so that I could make it closer by removing the thing [clay]."*

8.3.6.6 *Hypothetical future sculpting*

As part of the post-activity interview, participants were suggested the hypothetical scenario of being given the apparatus for an extended amount of time to use as they wish, and asked what they would do. The participants' background practices appeared to be the primary influencing factor. Participants with predominantly musical backgrounds described how they would integrate the apparatus into their music making, more technically oriented participants emphasized, and the violin luthiers described possible practical use cases in their making.

For responses describing musical contexts, there were two main groups. The first group, typified by the responses of **L8**, **L14** and **L21**, would perform with the tuned percussion instrument:

L8: *"I'd replace this [sculpting surface] with like a cymbal or something, and have springs on it and stuff [...] and just, I guess, get a bit more extreme with it. As an instrument, I would be using it alongside other stuff, and potentially with some effects as well, just because of the way that I use sound, recorded to tape."*

L14: *"I will [use it] with my composition [...] I think, apart from creating my new album, I would use it as a tool for meditation. At least me, when my hands are on something, when I'm busy with something with my hands I worry less about work [...] I think this is something that reminds me of my childhood."*

L21: *"I'd probably get the most fun out of it by just loading loads of different presets [models] into it, I imagine [...] And just using it as a little sampler, because I quite like the idea of using little bits of wood as a sample, and I'd probably get some things to hit them with as well [...] some sticks or some brushes or something, fiddle around, make little drum kits [...] It'd be primarily a musical thing, I think, just because of the context of how I would use it."*

The other musical group, which included **L31**, **L32** and **L33**, would record samples of the instrument for use in their own separate music composition or production process:

L31: *"I'd try to come up with some system that will allow me to do as little work, as when I find a trick that I like, I tend to obsess about it and just to use it [...] I wouldn't necessarily perform this, because it's it's very percussion oriented, the UI interface. But I'd definitely stick them in a sampler, and then just reuse the sounds."*

L32: *"I would definitely try to make samples [...] try to make one track with just this."*

L33: *"I think I would sample it, because it kind of works with low, low-medium, medium and high [the four percussion blocks], but it seems really difficult to have an exact pitch, so I think I would choose one pitch and just sample it."*

L33 continued that they could imagine integrating the sculpting apparatus and process into their digital audio workstation workflow:

L33: *"It would be cool to have like this kind of option inside a plugin, and if you just want to change the type of sound you're using, then you control all the other parameters with a plugin, and you just use this one [sculpting surface] to add a bit of awareness and reality to it [...] It wouldn't be a problem to have this really difficult thing to control, if you just control the timbre."*

Despite focusing on sampling and music production, **L32** and **L33** would still continue to try to understand the process better, whether through conscious or subconscious means:

L32: *"I would definitely try to modify the sounds and try to understand the machine I guess, at some point. I think you have to go to the logical anyway, instinctively, at some point, you start to understand the logic. Even if you don't see, it might be like, oh, yeah, if I do this, that happens."*

L33: *"I think at the beginning, I would try to understand more how it reacts to what I do. Every time I got a new synth or something, I just spend a lot of time understanding it. So maybe it's a few first nights, I would just do this, and then I would just create my own presets."*

L29 and **L31** both were interested in changing the resonance model's excitation signal away from the piezo, but for different reasons; **L29** as a means to further understanding, and **L31** for musical aesthetic reasons:

L29: *"Just put, like maybe other samples [instead of piezo inputs] to understand how everything works [...] Like percussive but also like vocals."*

L31: *"I'd also do something rhythmic [as the model excitation input], I'd find dishwashers and washing machines, because they have a cadence, it's like a sequencer but you don't have to do anything."*

In contrast, **L4**, **L15** and **L22** all described technical approaches they would take in order to approach a more fundamental or systematic understanding of the apparatus, which was itself the apparent goal:

L4: *"The first thing I'd do is have a look at what the sensors were picking up."*

L15: *"I'd probably experiment with the plasticine for a bit and then, especially if I worked out density, and if that's how the system worked, and look at incorporating different mediums on it. Putting a sponge on it, just like household objects, pencils or something. And I'd probably spend too long trying to work out how it works, so I understand it all."*

L22: *"I'd draw a grid, enough to make 12 or 16 different squares. And then just go, I know if I stick something roughly in B2, this tends to do this kind of thing. And then try and think about the rules of weight, and see what happens when you put twice as heavy objects on B2, just to learn about the kind the parameters with which you push, and then maybe experiment with the shape as well."*

L23 seemed to combine ideas of the above, describing how they would aim to "master" the TUI/GUI and percussion instrument first, but then explore the sculpting process openly and creatively rather than systematically, using found materials:

L23: *"There's like some simple things where I would probably try and master the technical skills, because that [GUI] looks quite technical in a way. That's also quite technical [percussion instrument], because it's the way that you play it. So it's like, have you got a good rhythm? Can you actually hit it quite precisely? I feel like if you've got this figured out, you can maybe take advantage of this better as well. This just to get like a good basis, a good technique, and then move on with the more alien thing [sculpting]. Then I would take the time to, even like draw, or use found objects and just put them on here [sculpting surface] as a texture, so literally make a leaf sound or [use] some trash."*

L11, a violin maker, imagined how the apparatus could be experimentally integrated into their practice:

L11: *"If I was gonna do it again, I just would have been a bit more strategic. I would have done a circle and replaced it with the same weight, but with a square. I'd like to control something like the weight, and then change the shapes [...] Shape effects things in violin making, I've tried to do things in a quantitative way [...] if you're going to change and adjust the sound, you do it one thing at a time."*

L11: *"I think I would change the board, I'd be interested in that, to maple spruce, and then I might do adding weights, and making it rigid in certain places [...] I'd also be super interested to do it with like a violin top and see whether you can tell anything about the violin top, like the way the sounds come out of it, and see how that could aid you in your making. Because at the moment, there isn't a way other than tapping it and hearing it to actually simulate in the final thing."*

L20, a professional lute player and amateur maker, in contrast described possible approaches for using the cheap plywood board to verify assumptions about actual soundboards:

L20: *"If I was experimenting further, I would actually probably add more, and then take more away in the future, because I think adding little bits isn't working [...] I think I'm learning a method, and I think if I spent longer on it, I would actually probably be able to manipulate the sounds more in in terms of what I'm trying to do. I would have a systematic approach to mapping position of individual pieces at diagonal points and transverse points, but I'd want to write them down. I think the general principle is if I do that, regardless of the size, that will produce a certain change. If I was an instrument maker, and I spent a longer thinking about the the changes I was making and the effects that was having and noting them down, I might be able over time to think... Well, we tend to follow traditional patterns of barring, so I might be able to say well, okay, I think if I altered this bar, and this bar it would have that effect. And then you'd have to make a soundboard and then see if it did have that effect, [but] soundboards aren't cheap, so there's a limit to how much you could do with it. Plywood doesn't make a very good soundboard, but you could actually use sheets of ply and try different barrings on them, to see what the effects are, as a rough guide and see whether you thought, actually that has made a difference in the right direction. I wonder if that would work on an actual soundboard."*

8.3.6.7 *Progressions of methods across tasks*

In Section 8.3.5.4, the progressions of assumptions and motifs were considered as participants navigated different ideas of what and how to sculpt over the course of their session. This section considers progressions of methods across the four activity tasks, relating the strategies and methods described thus far, beginning with another look at the sessions of **L11**, **L14**, **L8** and **L13**, as depicted in Figures 8.9, 8.10, 8.11, & 8.12.

L11 and **L14** (Figures 8.9 & 8.10) both started with formal and precise sculpts, and trended towards less formal and imprecise sculpts over the course of their sessions. **L14** used a combination of graphical and physical assumptions and motifs in their session (see Sections 8.3.5.1 & 8.3.5.3), but at some point let go of trying to understand the mapping to gain "more freedom when sculpting" (see Section 8.3.6.4). **L11** reflected on their initial versus eventual approaches, similarly describing a more care-free attitude taking over:

> **L11:** *"At first, I was very tempted to just make it look pretty, which is definitely a thing from while I'm making, where it's as much about the aesthetic as anything else. Because if it doesn't look how a violin is supposed to look, people won't buy them and won't play them, even if it sounds good [...] Towards the end I wasn't doing that. I was experimenting with splitting stuff down in difference places and didn't care too much about how it looked."*

L8 and **L13** (Figures 8.11 & 8.12) both exhibited creative divergence and variation during the Tuning Task and convergence towards simplicity during the Matching Tasks. **L8** described "going into extremes [...] in order to be able to see what direction you're going in" and "going from using really big or medium-sized pieces to then tiny bits" (Section 8.3.6.2), however in their Matching Task sculpts (Figure 8.11) they clearly preferred using large pieces of sculpting clay. **L13** found the results of their sculpting "confusing" (Section 8.3.6.1) and wanted ideally to "test really scientifically each parameter" (Section 8.3.6.3), but in the end explained "I just went with my intuition and see if I could just develop an association at the back of my head" (Section 8.3.6.4). Comparing their sculpts across the tasks (Figure 8.12), it seems clear that, similarly to **L8**, their more methodical ideas were trialed during the Tuning Task rather than the Matching Task. The most obvious activity-based factors contributing to these differences in methods were the different time constraints (five versus 15 or more minutes) and the briefs (technical and constrained versus creative and more open-ended). An alternative approach to **L8** and **L13** was taken by **L16**, as seen in Figure 8.16 between rows four and five, which occurred in the penultimate and final tasks, respectively. In this scenario, rather than reverting to their approach in Matching Task 1, **L16** repurposed the clay shapes they had made at the end of the Tuning Task as the basis of their sculpts for Matching Task 2.

An interesting comparison can be made between the participants' descriptions of trial and error approaches and encountering apparent randomness (Section 8.3.6.1), and the self-evaluations given after Matching Task 2 (Section 8.1.3.5). Some participants felt they had moved beyond random trial and error (**L11**: "I was not just randomly trying to throw stuff on and see what happens [by the end]", **L21**: "I had just been putting stuff on there completely at random [...] whereas now I was thinking, what are the differences between putting things at the edge and in the middle?"). Whereas other participants mentioned that even though they still felt "clueless" about the sculpting outcomes, they were more fluent with the process and better able to direct and navigate the resonance models (**L15**: "I found more like, I can navigate it, even if I can't say exactly what the outcomes will be"). Indeed, Figure 8.18, discussed in Section 8.3.6.5, corroborated this by showing that the final task featured both increased average sculpting frequency, and increased average sculpting size. In this figure, the subplot for the open-ended Tuning Task shares similarity in distribution with the Demo except for including smaller change sizes. The two Matching Task subplots are also similar, except in the second version, the sculpting was faster with on average larger changes being made.

The more systematic approaches were described in terms of seeking out the limits of the instrument's timbre range (Section 8.3.6.2), and seeking order and control of sculpted sounds through regularised sculpting patterns (Section 8.3.6.3). In a number of cases, and perhaps due in large part to the tight time constraints, participants reported transitioning towards more free-form, intuition-led approaches (Section 8.3.6.4). **L18** reported that "What I expected didn't match what happened, and that kind of threw out my theory. So towards the end, I guess I was trying more to go with it", and similarly **L15** said "You just kind of let go and be more intuitive [...] Don't be limited to mappings". Section 8.3.6.4 also described the emergent role of musical intuition, which made the sculpting approach less dependent on technique and more open to creative interpretation. **L32** followed their musical instincts to the extent that for them, it didn't exactly make sense to talk about the progression of their sculpting methods:

> **L32:** *"I guess I tried to a bit more things, but I still don't do it logically, so I don't think there's a real progression. You know what I mean? But yeah, I tried more combinations maybe?"*

8.3.7 *Micro scale activity*

One of the main aims of this study was to observe micro scale design activity to see how it could be broken down further and potentially characterised, and compared with meso and macro scale activity. The previous sections have described the outcomes from the perspective of how participants responded to the apparatus and activity. In this and the following sections, additional review of the outcomes is given in terms of micro, meso and macro scale activity.

This section first describes quantitative data of the relative size of each sculpt in terms of resonance model parameter changes, highlighting specific participant episodes and patterns of change size, which are related to the previously described sculpting methods (Section 8.3.6). Subsequently, post-activity interview excerpts are reviewed where participants discussed the role (or lack thereof) of micro scale details in their own practice, and how it felt for them to be encouraged towards micro scale focus by this apparatus and activity.

8.3.7.1 *Levels of detail within the micro*

Whereas the micro scale has been defined in this thesis with respect to the meso and macro scales, the responses to this apparatus and activity enable its characterisation from within itself. This section approaches the micro scale in practice as a domain of continuous detail, ranging from the fuzzy micro-meso boundary, down to the impercitible or subperceptual. Using the same metric as Figure 8.18, this section describes the varying traces left by participants through this domain, in terms of the size of change between sculpts relative to the largest possible change (setting all model parameters to their maximum value). These episodes are related to the sculpting strategies and methods described in Section 8.3.6.

Section 8.3.6.2 described attempts by participants to find timbral extremes, as a means of orientation within the space of possible resonance models. Two exemplars of this approach were **L8** and **L19**, and Figure 8.19 contrasts the size of their sculpting changes. **L8** found it difficult to grasp how to access these extremes, no doubt in part due to the counterintuitive relationship between the scale of physical changes made with clay, versus the scale of perceived difference in sound (Section 8.3.2). However, **L19** was similarly inclined towards larger changes, but was more successful in achieving them than **L8**, due to their use of the subtractive sculpting technique (Section 7.5.3), where clay is added before sculpting surface calibration, and can be subsequently removed in order to decrease dampening. Both of these participants were attempting to navigating away from the micro scale detail that the apparatus was constrained towards. Though not quite achieving meso scale changes, as perhaps was desired, their sculpting could be described as operating within a fuzzy boundary level between micro and meso scales. Their changes were 'large' relative to average usage of the apparatus, however they didn't ultimately transform the nature of the process or the instrument at a higher level, as will be described in Sections 8.3.8 and 8.3.9.

L20's rigorously patterned sculpture of 38 sculpts was described in detail in Section 8.3.6.3 as being the longest in the dataset, and when comparing the amount of changes being made per sculpt, it was also the "most micro" in scale. Figure 8.19 shows the changes in this sequence deviated little from a range of 1-5%. As well as clearly having the self-motivation to explore the apparatus in this way, **L20** presumably possessed fine enough listening skills coming into the session that they could operate close to the lower limits of the apparatus' range. **L20** reflected on their use of smaller pieces of clay:

> **L20:** *"I've shown that the small pieces actually have quite a big effect, but then if you add a big slab on, then the small pieces have very little effect, because their relative mass is insignificant compared with the main slab."*

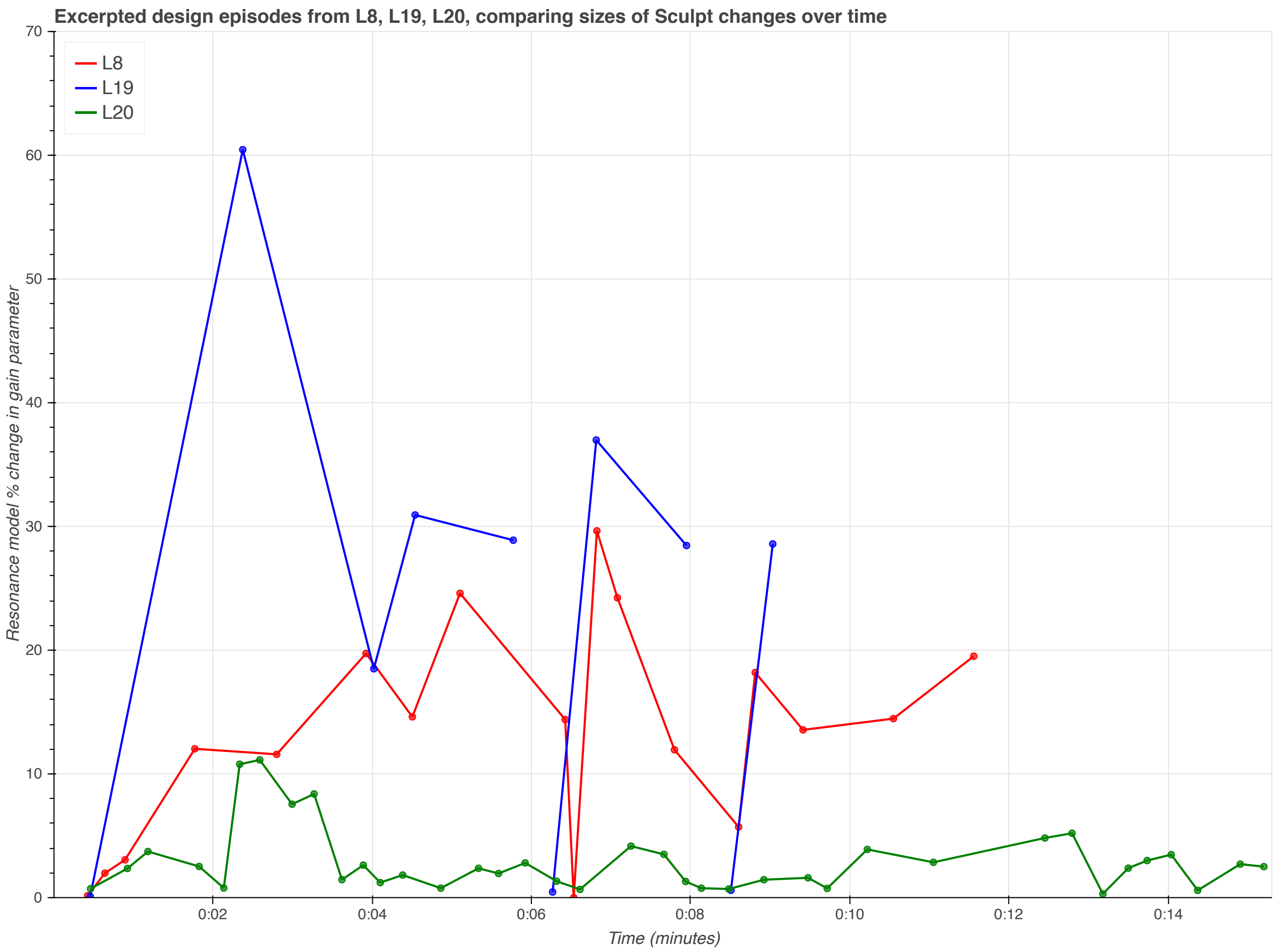


Figure 8.19: Comparison between **L8**, **L19** and **L20**'s sculpt change sizes during the Tuning Task, where **L8** and **L19** were attempting to find timbral limits (Section 8.3.6.2), whereas **L20** was creating ordered patterns (Section 8.3.6.3). Each line represents a Sculpture, and each point represents a Sculpt.
Despite **L8**'s diverse and rapidly evolving approach to sculpting (for images, see Figure 8.11), they only once managed to reach a change size close to 30%.
In contrast, **L19** used the subtractive sculpting technique (Section 7.5.3) and was repeatedly able to create changes near or above 30%.
Sculpt change sizes during **L20**'s Sculpture of 38 Sculpts stayed consistently well below 10% (for images, see Figure 8.15).
See Section 8.3.7.1.

L20: *"By going down to small pieces, I got an increase in volume, but then I lost tone, and I was struggling to get the tone back, and I also had a different set of harmonics so it sounded a bit more tinny, and I couldn't work out quickly how to get that back."*

L20: *"I've tended to stick to the same size pieces and move them, but when I've adjusted the size, it hasn't made as much difference as expected."*

8.3.7.2 *Micro scale in participants' practices*

The responses to the activity were complex and diverse in their approach to crafting and tinkering with micro scale details, and equally the participants described their own creative practices as having varied and complex relationships with detail. Examples of ideas or experiences underlying participants' motivation to work at fine levels of detail in their own practice (or not) included pleasure, emotion, focus, aesthetics, dramatisation, cultural memory, and perfectionism, and was also not fixed but evolving over time and responsive to context. While the complexity of participants' relationships with detail is not diluted, reduced or explained by their responses, it does become easier to appreciate in its sophistication, situatedness and dynamism.

L14 described which details mattered to them during their time as a professional session bass player. This is neatly contrasted with **L10**'s description of how instruments of varying quality can appear superficially similar, but as in **L14**'s description of their instrument, in reality there are categorical differences:

L14: *"I mean, everything right? The type of string, type of wood, even the type of tree, but also the tree itself is important, the age and whatever. And also when I was playing [more often], the length of my nails, that's really important for me. If it's longer than a certain extent my timbre would sound really trebly, which I didn't appreciate at all."*

L10: *"When I was trying to get this drum to sound like [the Matching Task target sound], it did pop into my mind at one point that sometimes you get the person that's got a £200 instrument and wonders why it doesn't play as well as their cousins £2000 instrument, and why they don't have the same tone quality. And it's because it's fundamentally not the same instrument. And it doesn't actually matter what you do to it, you can't get it to sound the same."*

As an experimental musician and performance artist, **L9** explained the very practical dramatic role that working with detail can assume during a piece. **L16** similarly related the idea of performing with the tuned percussion instrument in terms of focusing attention inwards towards the inherent detail of the sounds:

L9: *"Sometimes you don't need to detail because you're making a range of sounds. And if it's going more in detail, then it is about exploring maybe one object or one instrument and only one particular part of it for longer time, so that the listener would get more detailed information from it. [It's about] concentrating the audience, or getting myself on the vibe without distraction [...] [Attention* *to detail] is naturally like a cause of [concentration] because there's only one thing, and nobody wants to get bored. So everybody will listen to the small changes, which will make them concentrated, including the one who does it [the performer], and tune everybody on one thing. And if then sometimes, after a while a change comes, everybody's cheerful."*

L16: *"I'm an advocate of working with a small palette. I think that was really good with the improvisation thing [Tuning Task]. I was trying to pick sounds that could last a long time. If I'd have seen some piece with this, I'd want to see something where you really get involved in each of the sounds [...] There's a kind of infinite amount of sound in that cymbal right here [playing instrument block], and this, say one of these [playing another sound], it's like, there's loads of different sound in it. But you have to keep listening to it."*

L32 and **L33** are both songwriters and electronic music producers. **L32** explained their approach to detail was in a phase of progressive deepening, whereas **L33** was clear about the crucial relationship for them between detail, and enjoyment and emotion:

L32: *"I used to think the whole is interesting, the whole idea and, whatever, we don't need to bother about details. But now I think sometimes the ensemble is way better when you've actually spent so much time on each little thing, especially in terms of mixing."*

L33: *"I spend hours on every sound basically [...] just finding a sound I really like, really enjoy the most [...] I'm a pretty logical person in the end but it's a bit more about magic. Magic stuff. So yeah, just if it makes me feel something."*

L3, an experienced string-instrument maker and conservator, wrote a fairly detailed response to the activity, which is provided in Appendix F.3. **L10** and **L11**, both involved in acoustic instrument making, described their work as simultaneously always striving for perfection, yet working with an infinite amount of detail:

L10: *"We always aim for perfection. Sometimes that's more achievable than others and sometimes the customer has different expectations. Some people come in and they just want the basic repair doing, they just want it to be able to play because they want to spend as little money as possible. Other people want it to play as well as possible no matter how much it costs, and they're kind of different goalposts."*

L11: *"I'll never get bored, because it's just an endless amount [of detail], you could spend 10 years just learning about [violin] scrolls or something. There are all sorts of aspects of it that are just like, an endless problem, but in an interesting way."*

L25, a professional chef, compared the micro scale details in their world to violin making, and described that much of their practical knowledge is similarly too complex to be worth trying to quantify:

L25: *"Every time I do it, like really going to development [of a new dish], I'm quite humbled by the actual technical complexity, as in I'm pressing these buttons and actually, the result is wildly different. And the complexity of the interplay between the elements is, I imagine, quite similar to a violin."*

L25: *"I feel a lot of gratitude to chefs that [...] actually hit upon this stuff with their mouths, and because of the complexity of what you're working with, the science actually doesn't really matter. Baking is so complicated that this one weird tweak creates the end product, and that's all you want to be dealing with unless you've got serious resources behind you, which just isn't very present in the space."*

L11 and **L25** gave relatable descriptions of the experience of learning how to perceive and manipulate micro scale details, highlighting the importance of repetition and controlled variation:

L11: *"I felt like the trying to figure it out part of this was part of the fun of why I liked it, which is the same with violin making, that you have a certain number of steps that you have to go through. But to an extent, you are also just trying to figure it out and trialing stuff until you've sort of developed. Because there's also this gap between when you know what you're trying to do, and actually being able to do it, physically having the knife skills and the tools to be able to make something flat or whatever. And so you just do it over and over again. And I think that's not necessarily something that would be daunting to instrument makers, having to do it over and over and over again, that's just that what we do every day."*

L25: *"It's walking the path through the steps of the process, many times, that allows your brain to start probing the different moments of the path, and thinking of different theories. And I guess you're gathering data, it's like as you step through each step in the process, you learn a bit about the causal chain. And then that gives you that data to start experimenting, and to think for a given result, where you need to focus your energy."*

And while **L11** and **L25**'s accounts above make the process seem wonderfully straightforward, **L14**, **L15** and **L30** all conveyed that conflict, struggle and contradiction were also part of the psychological and emotional experience of working with fine details:

L14: *"The thing is, the more you think about the details, the less peace you will have in your soul. Especially when it comes to instruments, because for instance, bass strings particularly, they get old really fast. So if I didn't care about it, I would be more peaceful. But then again, it wouldn't be the sound that I want. So I'm not sure thinking about more details is essentially making me happier, more peaceful, but it's kind of inherent."*

L15: *"I was talking to a friend the other day and I was saying like, how I hate studio work, just because I hate like the feeling that your hearing can never sound right. And you're just there at the computer for hours tweaking things. I don't care for that. But I will spend hours on a Max/MSP patch just trying to get like two triangle waves sounding good. Just getting a sound sounding good rather than a track."*

L30: *"I can't focus myself to do it, as much as I want to do what might be like an idealistic thing. I have like a perfectionist attitude in ways, I know exactly what I want in an idea. I don't always feel like I have the skills to get there, or I'm not patient enough for myself, to be able to reach them. So then we could say procrastination is one of them [issues], or being just easily distracted by something else that's gonna appear easy to me in that moment."*

In another interesting instance of contradiction, **L11** and **L13** appeared to display completely opposing relationships to precision achieved through handcraft versus digital fabrication:

L11: *"We've got a couple of people from software engineering backgrounds who have joined the class to learn to become violin makers. And they're [saying], why wouldn't you just do this with a computer, why wouldn't you get a CNC machine to cut it out? And it was just like, because that's not the point. The point is the enjoyment of producing the thing, and enjoying the detail, and spending all day staring at this one piece of wood."*

L13: *"Before I went into architecture, I studied math and philosophy, and I think it's always just been a thing for me that I think really precisely. I have this obsession with doing things very exactly, and digital tools allow you to not be messy. Whatever command that you give, that's it. It's not like, say I want a cube from the clay, you're not going to get a cube [by hand]."*

L7 highlighted that the micro scale details of the apparatus presented in the activity did not possess any "cultural memory" of its own when compared with the guitar as an example, and insightfully pointed out that part of the difficulty of engaging with this activity was due to the lack of context through which to find meaning in the detail. For them this meant that the time investment into detail would potentially be wasted, a sentiment shared by **L18** when discussing dependencies between macro and micro scale details in their design process:

L7: *"If you have a guitar, you don't have any instructions, but you have a lot of cultural memory of it. And when you have an instrument that has no cultural memory of it, then I would benefit from a little bit more information. Because what happens was, I was browsing so many things that I didn't really understand entirely the difference. So it feels a little bit wasted time, having so many options to navigate the parameters that I didn't understand. But also, I understand that once I knew how to actually use it, there would be a point where I would need exactly every single function."*

L18: *"I'm somewhat of a perfectionist. I would just go into detail really early in the project, which I figured is not necessarily good, especially then if you make a major change, and all the effort that you put into that tiny detail is wasted [...] In my practice, I am trying to go for steps that get more and more into depth, first one is the skeleton sort of, and then if I like the skeleton, let's go one level in and try to make that more detailed. But then eventually, yes, I want the thing to be the exact way I want it to be, so I would go into detail."*

Of course, there were participants for whom this apparatus lacked appeal due to its overt focus on micro scale details, which conflicted with their own aesthetic interests. **L8**, who was particularly driven towards finding timbral limits (see Sections 8.3.6.2 & 8.3.7.1), and **L26**, both indicated preferences towards engaging with higher-level changes in their practices:

L8: *"This seemed much more nuanced than I would normally go [...] The way that I work is to allow quite a lot of mistakes [...] I just generally record to stereo and then make edits from that [...] So I'm not that sort of person, you hear about electronic producers who spent a week getting the perfect snare drum sound in a track."*

L26: *"I feel like many times when I look for small differences, they don't matter too much. And I look at them instead of looking at things that are more drastic, usually. So it doesn't matter if it's doing performance or production or whatever. Like you use something, try to fiddle with a small thing and then you realise that, that could have been a drastic move that you could take that is much more important for the piece [...] It's my personal taste of how I want to make music [...] More drastic constant contrasts. And when you get close enough, it's usually fine."*

8.3.8 *Meso scale activity*

Despite the apparatus and activity constraints orienting participants firmly towards the micro scale, some participants demonstrated urges to disrupt the apparatus or activity briefs and explore higher levels of design. Not all attempts to do so were successful, and some responses stayed within the micro-meso border discussed in Section 8.3.7.1. This section presents examples of what in terms of this apparatus and activity could be described as meso in scale. The first example describes a case where a participant looking for timbral extremes managed to introduce distortion, opening up an adjacent design space in the realm of audio effects. The second example describes some participants' use of the sculpting tools as sculpting materials in addition to the clay, which was the default and only suggested option for sculpting. In each of these cases, the responses are related to the specific participants' backgrounds for further context.

8.3.8.1 *Re-purposing of advanced sculpting techniques*

Two slightly more advanced sculpting techniques were demonstrated to participants during the latter stages of the Demo (Section 8.1.3.2). One technique enabled them to more easily add rather than remove resonance by subtracting sculpting clay (Section 7.5.3), and another where they could use resonance models they had created themselves as presets for new sculpture, as opposed to being limited to the four provided preset models (Section 7.5.4). While the first of these techniques was intended to address a potential bias towards dampening rather than increasing resonance, participants realised that by calibrating the apparatus with a large amount of clay and then removing it, they could create much louder, more aggressive sounds (see Sections 8.3.6.2 & 8.3.7.1). The second technique was intended to provide a means of exploring a sound in deeper detail, by decoupling it from the physical configuration that had created it and allowing re-exploration of a sound from a new physical starting point, almost like zooming into a sound. However, **L5**, a music technology researcher working with creative machine learning, used both of these techniques to do the opposite of zooming in, instead using them to broaden the instruments' sound palette.

In order for small physical changes to be audible, the mapping algorithm needed to be "zoomed in" such that small differences in frequency response measurements resulted in noticeable changes in resonance model parameters (Section 7.5). As a result of this, large physical changes would actually clip the model parameters, which was compensated for by controlling the Piezo input gain. However, **L5** used the subtractive sculpting technique to an unexpected extent, and audible distortion was created (Figure 8.20). When this happened in the Tuning Task, **L5** embraced it and adopted as part of their instrument, to create contrast in timbre. This represented a meso scale change to the instrument, breaking over the micro-meso boundary described in Section 8.3.7.1. As a result of **L5**'s session, the piezo input gain was lowered further to prevent this distortion effect (which was less invasive than re-writing the mapping algorithm while the study was running), and **L5**'s data was not discussed in the main outcomes.

Furthermore, **L5** used their intuitions about machine learning to realise another use of the sculpt-as-preset technique. Assuming correctly that the instruments' sounds were made up of a high-dimensional parameter space, they realised certain relationships between the sculpting process and the sound space, after doing similar sculpts with different model presets and getting different results:

L5: *"It occurred to me that perhaps all the [sound] space wasn't available at any one time, like all the sound space wasn't controllable by a one mic [piezo] sound sculpture, and you had to kind of move. And so before that, I hadn't really thought of that [...] When I made a new sculpture [using a different preset], I had some stuff [clay] in quite similar places and it sounded quite different. I was like, oh, I've not heard the sound move like that before, whereas the first time I was doing it, the kind of axes, like variations that I was moving in the first time, it was like a kind of metallic-ness of the sound that was changing quite a lot. Whereas, I got some more pitch modulation type stuff."*

Based on this intuition, they applied further analogies with machine learning to understand sculpting process at a deeper level, re-framing the sculpt-as-preset technique as a way to reject "optimisation" towards details:

L5: *"That that comes from like, experience of machine learning and stuff, where it's like a local minima. You can kind have some force which is like, okay, no more optimisation, let's kick it, introduce some variations [...] I think it's maybe more of almost a reset, like a mutation, evolutionarily, like to just kick you into somewhere. Like, if you're kind of stuck in something, like making changes or sculptures isn't really getting you where you want, you can just kick it somewhere else."*

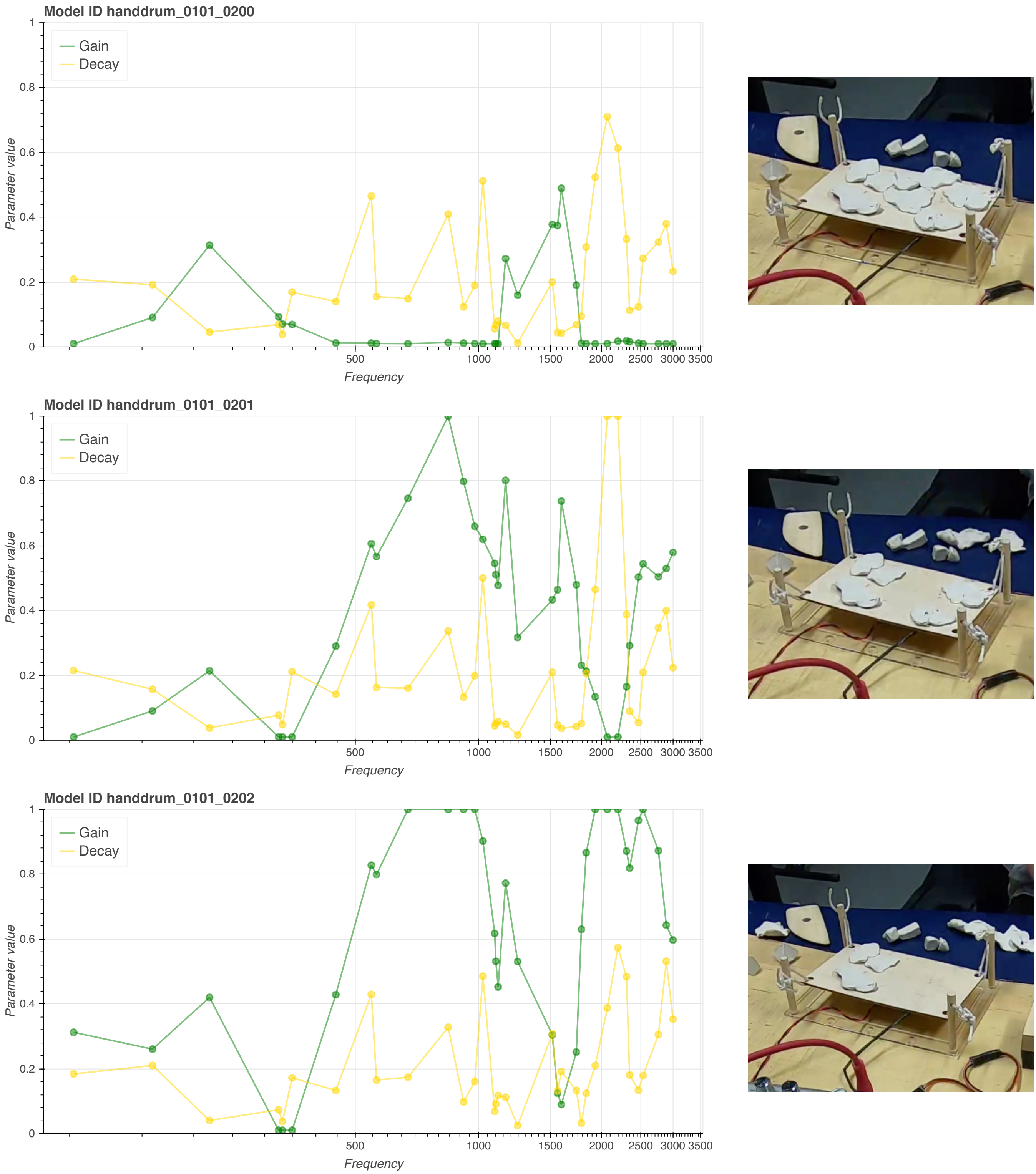


Figure 8.20: Resonance models and sculpting surface states taken from three sequential sculpts made by **L5** which resulted in audible distortion.
Top: **L5** combined two advanced techniques, by creating a new sculpture using a previous sculpt as the preset (Section 7.5.4), and with material added to the surface which could be subsequently subtracted to increase resonance (Section 7.5.3).
Middle: when **L5** started removing material, dampening decreased and so gain parameters increased, with one parameter clipping.
Bottom: after removing more material, eight resonator's gain parameters had clipped.
See Section 8.3.8.1.

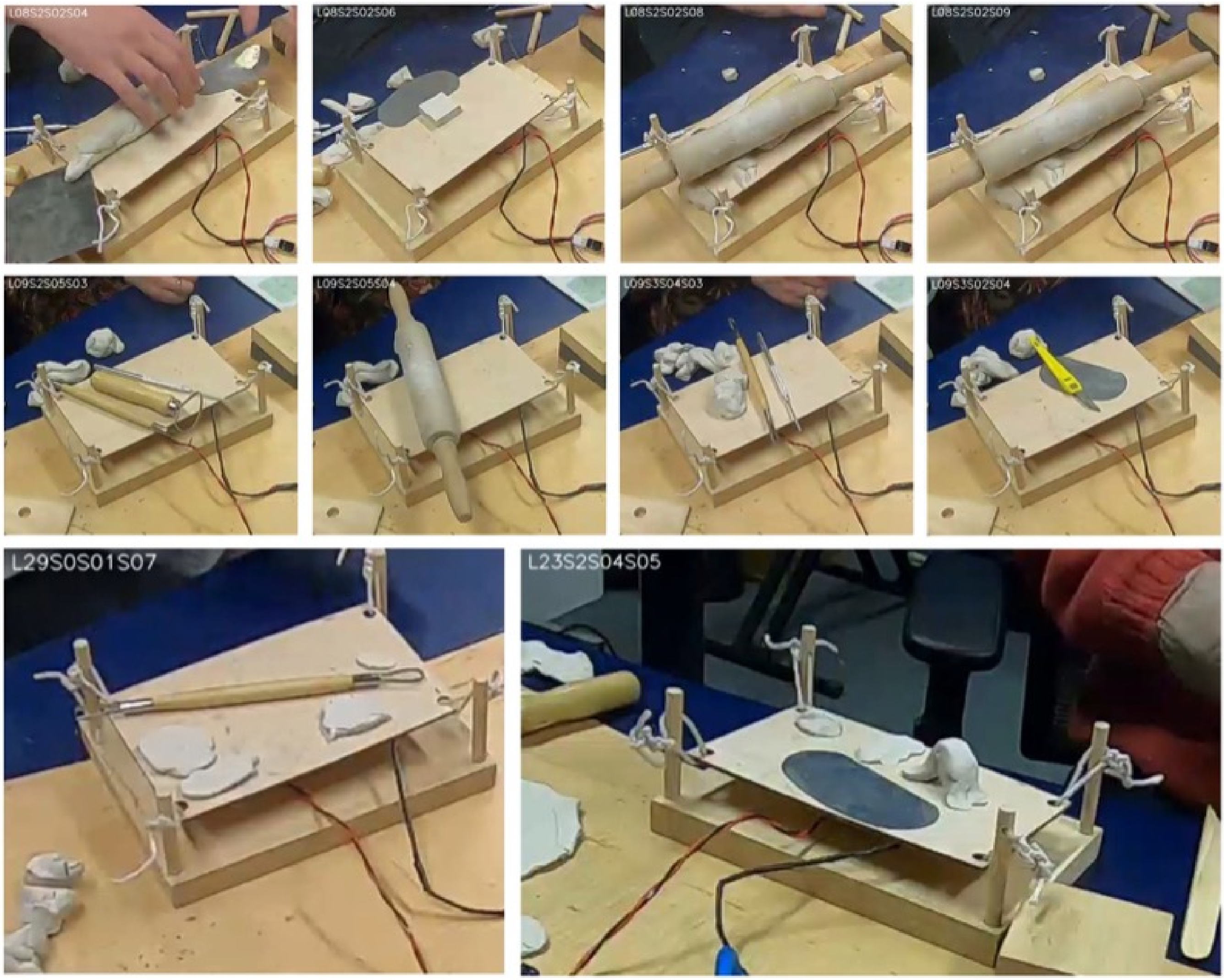


Figure 8.21: Examples of participants using the sculpting tools as sculpting materials alongside the clay.

8.3.8.2 *Tools as materials*

Figure 8.21 shows a number of sculpting examples where participants (**L8**, **L9**, **L23** & **L29**) decided to appropriate one or more of the sculpting tools as a sculpting material, placing or balancing the tools on the sculpting surface. In some cases the tools were used in isolation, and in others they were combined with the clay either in a collage manner or physically, resulting in multi-material composite sculptures. **L8** in particular (top left of Figure 8.21) shows an attempt to suspend metal slicing tools over the edge of the sculpting surface, presumably to allow them to vibrate while the sine sweep is taking place.

8.3.9 *Macro scale activity*

Two responses in particular stood out as going beyond meso scale responses and into a macro scale design space. In one response to the Tuning Task, L9, a musician with a practice in experimental performance went beyond the brief to create instrument timbres suitable for a concert, instead electing to include the entire apparatus into an elaborate, theatrical performance. L27 strayed further still from the activity brief, when they were heavily influenced by their background in narrative design and ceramics, to devise clay characters and produce a narrative using the instrument blocks as scenes on a timeline. In both cases, the participants' reimaginings of the apparatus and activity were unprompted and unexpected, but were nevertheless given space to continue uninterrupted.

8.3.9.1 *Experimental performance scenario*

Towards the end of the Tuning Task, when **L9** was silently sculpting, they suddenly began using the clay to interact with the percussion blocks, through dropping, throwing and hitting, and then rearranged the blocks to facilitate rolling (Figure 8.22). As the task came to an end, **L9** said "this is ready for some storytelling [...] you could throw different heavy objects on it, instead of drumming, it would sound differently, and you could throw things while you could mess up the setup", implying usage of the TUI during performance. **L9** went on to say "[the sculpting surface] is also very good because it is like a boxing ring", explaining how the sculpting surface could be used as a storytelling stage ("Yeah, you can have a lovely story thing going on with this"). At this point their performance included the entire apparatus, including the sculpting tools, and took one final twist to add a pedagogical element: "and then you can explain to the people or the kids, what is a sine sweep".

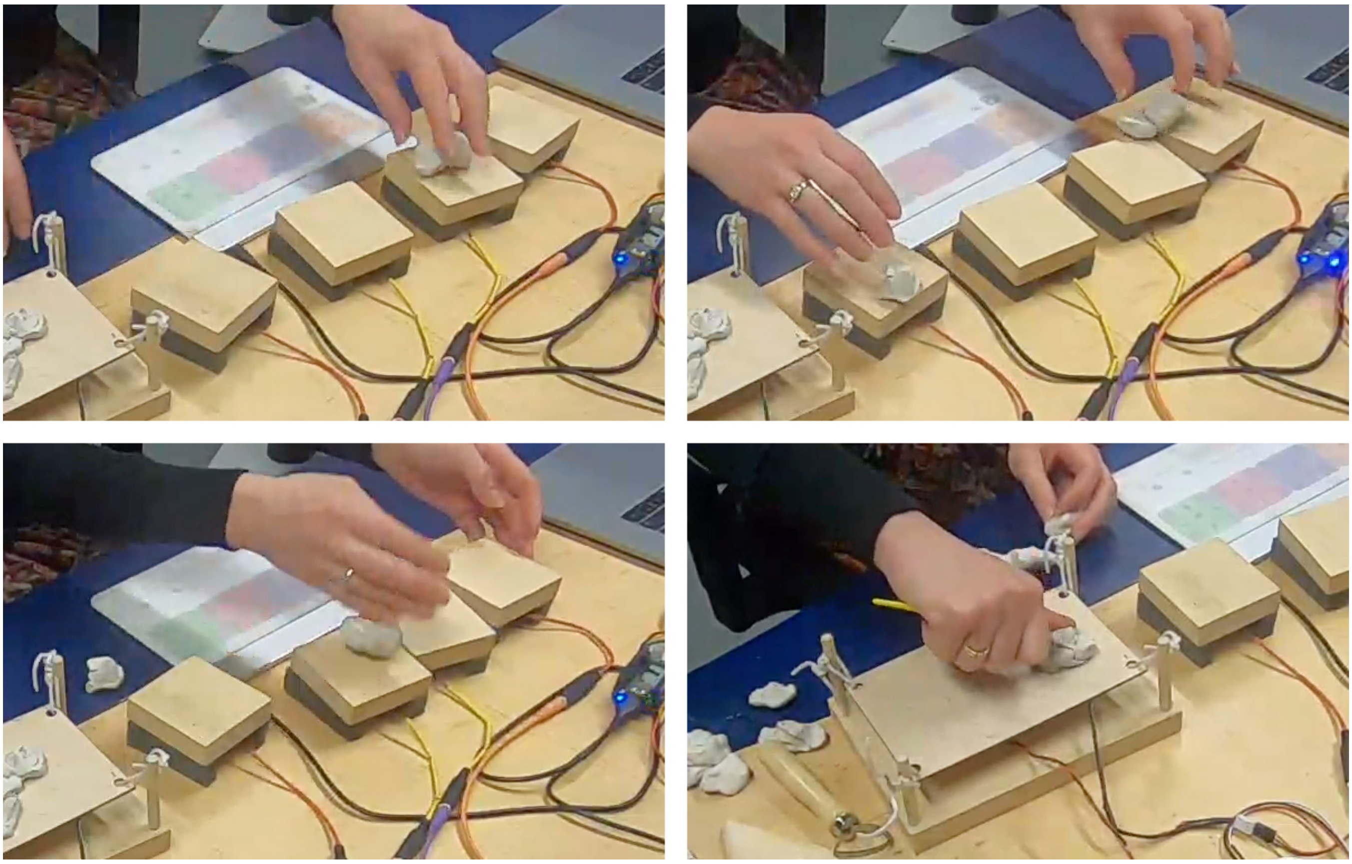


Figure 8.22: **L9**'s excursion into experimental performance captured in four video frames.
Top left: dropping clay on the percussion blocks.
Top right: dropping and rolling two pieces of clay on the blocks.
Bottom left: moving the blocks together and rolling the clay across.
Bottom right: acting out performative use of the scalpel while making comedic noises.

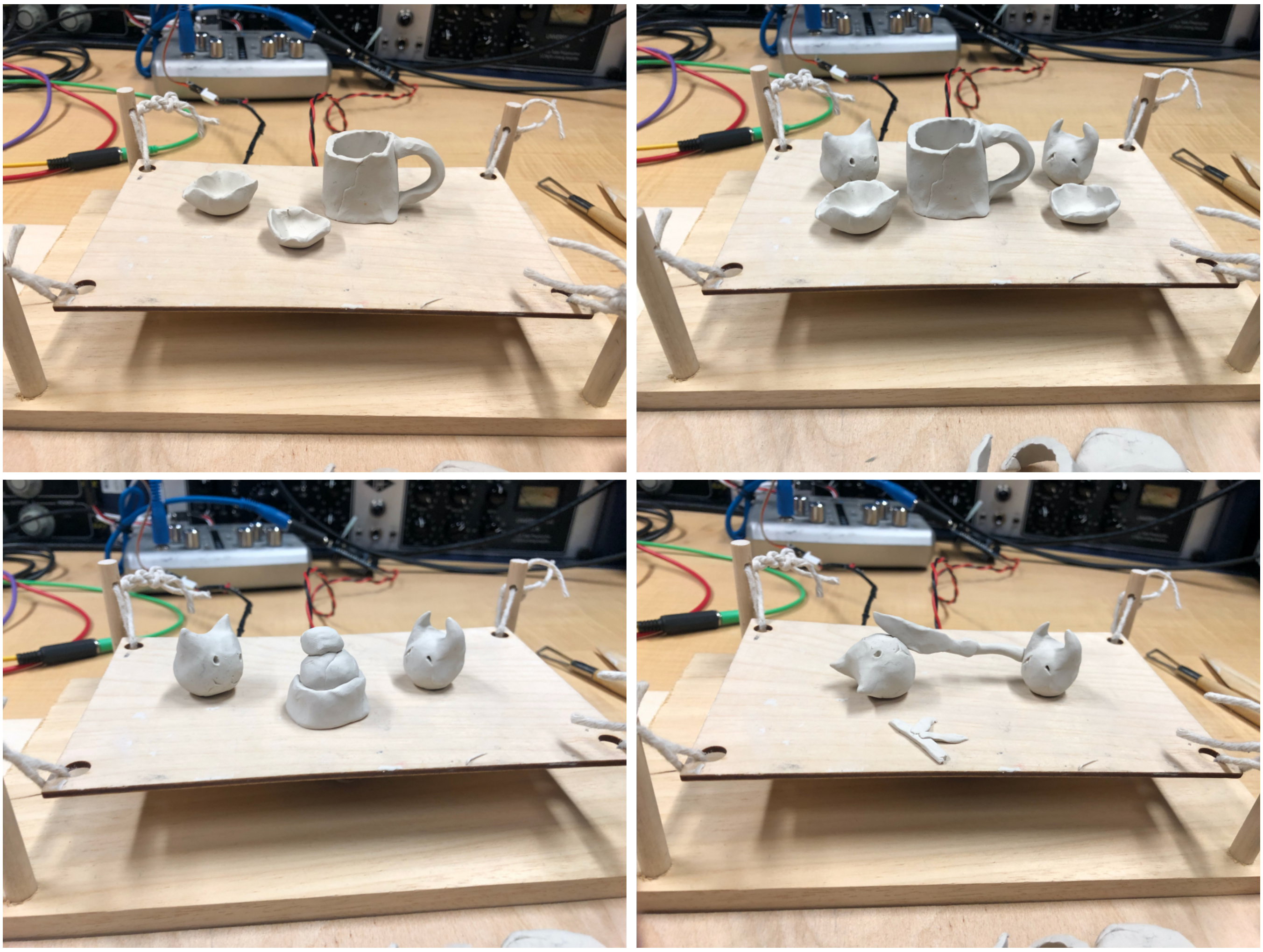


Figure 8.23: **L27**'s clay narrative, with each of the four "scenes" associated with four sounds on the percussion instrument.

8.3.9.2 *Storytelling with clay and sound*

During their interview, **L27** reported that "I decided at the very beginning, I just have an idea. Okay, I want to make a story using these instruments", which is exactly what they did (Figure 8.23). The story consisted of four scenes, each like an individual comic storyboard, with one sound/instrument block associated with it, turning the percussion blocks into a musical timeline for their story. **L27** explained that: "I don't much care about using this [apparatus] to create a very beautiful sound, but what is the meaning of every note it can stand for. So I created a very simple story: these are two animals, and they have a tea party in the afternoon. And after drinking the tea, they have cake. And after that, we'll have the animal kill another one [...] I just thought well, how to make this story much more dramatic, and what will happen to the music if I add a knife".

In discussing what inspired their response, **L27** explained they had been studying creative ceramics ("this work table is really similar to the workshop where I do ceramics"), and that their "undergraduate project is about storytelling in toy design". **L27** "made a shadow book using the cardboard [where children] can pick some elements from the book, and assemble it as a theater, a cardboard theater, and they can cosplay a story".

8.3.10 *Research questions*

This section reviews the outcomes in terms of the research sub-questions of this study, as described in Section 8.2.

8.3.10.1 *Motivation to focus on subtle details*

QUESTION This section discusses the outcomes in terms of the first sub-question of Research Question 5:

What motivates instrument makers and creatives to focus on subtle and detailed design or not in a one hour activity?

Overall, the activity and apparatus were rich and engaging enough to constrain and sustain focus towards micro scale details for one hour. Motivating and demotivating factors are first summarised and then related to Section 8.3.

Motivating factors included:

- Immediate intimacy with the apparatus due to its focus on tactility.
- An open-ended crafting material to create with.
- Creatively constrained task briefs.

Demotivating factors included:

- Non-real time interaction in the design iteration cycle.
- The lack of explicit visual memory of design artefacts (sculpts).
- The time constraints precluding preferred systematic methodologies.

Factors which were motivating and demotivating to different participants included:

- The overwhelming complexity of the relationship between inputs and outputs (sculpts and sounds).
- The requirement of using the GUI/TUI as part of the creative process.
- The emphasis on acoustics and vibration in the sculpting tool.

Although there was a reasonable level of confidence that the outcomes would focus on micro scale design, it was not clear what proportion of the outcomes this would represent. In this regard, the outcomes exceeded the expectations. Based on the definition of micro scale details as "the differences between otherwise identical instruments", the majority of the responses were micro in scale, apart from the few specific episodes of meso and macro scale activity described in Sections 8.3.8 and 8.3.9. Within this micro scale, the responses were further compared in terms of their level of detail in Section 8.3.7, revealing a spread of interest and activity.

As expected, there was some frustration with the apparatus, in particular that it did not provide a visual representation of the sculpts, and that the sculpting process was discontinuous (Section 8.3.2). In addition, some participants whose practices were more handcraft-oriented found the session navigation interfaces (GUI/TUI) to be complex and slightly overwhelming given the time constraint, which could also be considered as demotivating. Despite this, the overall encounter with the apparatus was motivating for participants, initially as something they wanted to understand (Section 8.3.4), and later as something they didn't need to understand to enjoy (Section 8.3.6.4). The tasks were attended to positively by the majority of participants, even though at times sculpting processes appeared to continue uninterrupted across the tasks (Section 8.3.3). Overall, the creative Tuning Task was more rewarding than the technical Matching Tasks (Section 8.3.6.5).

Participants were able to project a wide variety of assumptions and ideas onto the sculpting surface, and no matter how technically incorrect these ideas were (as in Section 8.3.5.1), in every case a sound was always produced, and this lack of errors or silence seemed to encourage divergent exploration (Section 8.3.5). This open-endedness also meant it was easy to change and combine ideas freely (Section 8.3.5.4). As the realisation dawned of the immense complexity of the sculpt-to-sound relationship, there was a mixed response from the participants. It seemed to be equal parts intriguing and frustrating that sculpting outcomes were largely unintelligible compared to expectations of a more straightforward mapping (Section 8.3.6.1). This largely precluded obvious approaches to orientation and navigation of the sound space, which a number of participants actively sought out (Section 8.3.6.2). Despite this, some participants were still motivated to project order onto the process, resulting in distinctive sculpting patterns (Section 8.3.6.3). While these patterns seemed to be satisfying to make and iterate on in themselves, it was still apparent that systematic control of the process was not possible in one hour, which was again inspiring to some and less so to others.

In contrast, some participants pursued an intuitive approach to sculpting, while others turned to this approach later on when their technical approaches were not providing expected results (Section 8.3.6.4). For participants with musical backgrounds, this meant using their musical intuition to guide their aesthetic evaluation of the sounds they were producing. The apparent validity of this area of expertise, and the subsequent realisation by participants that they didn't have to understand the process to obtain useful results, was seen as liberating. In one hour, participants were able to become comfortable and somewhat fluent with the process (Section 8.3.6.5). Participants cited subtle improvements to their process that had not necessarily led to greater pre-determination of outcomes, but had led to greater confidence in their ability to find interesting and pleasing sounds.

During the sessions, participants looked for and in some cases found strategies and methods that matched their skills and interests (Section 8.3.6.7). Looking beyond the one-hour session, for musicians, integration of the apparatus into their musical practice would drive their manner of usage, and it was not clear this would necessarily focus on micro scale details, since their ideas involved meso or even macro scale adaptations and applications (Section 8.3.6.6). In contrast, acoustic instrument makers also proposed changes to the apparatus to experimentally integrate it into their practices, but it seemed likely their focus would continue to be on micro scale details. While some participants were clearly demotivated by the idea of working almost exclusively in detail for a sustained period (Section 8.3.7.2), others were outliers in the other extreme, and engaged in extreme levels of detail throughout (Section 8.3.7.1). When comparing the activity against their own practices, interesting comments arose about how the lack of cultural memory of this apparatus' details was a demotivating factor (Section 8.3.7.2).

8.3.10.2 *Influence of participants' backgrounds*

QUESTION This section discusses the outcomes in terms of the second sub-question of Research Question 5:

How do instrument makers and creatives from different domains approach subtle and detailed design?

The participants in this study were mostly multi-disciplinary practitioners, and were not formally split into groups, and so any generalisation of these outcomes must be considered with adequate caution and acknowledgement of the study's inherent limitations (Section 8.4.4). With those considerations in mind, there were three practitioner archetypes that not only felt present across the outcomes, but also were associated with particular approaches: digital luthiers, acoustic luthiers and musicians. The approaches of these practitioner archetypes are first summarised and then related to Section 8.3.

- Digital luthiers assumed the apparatus consisted of low-dimensional, high-level input and output parameters with simple orthogonal mappings between them, and used intuitions and skills related to digital musical interfaces to guide their sculpting.
- Acoustic luthiers treated the sculpting surface as an acoustic or instrumental soundboard, did not appear to make many assumptions about the implementation of the mapping or synthesis, and used intuitions and skills from acoustics and vibration to guide their sculpting.
- Musicians did not necessarily make or rely heavily on specific assumptions about the implementation or parameterisation of the apparatus, and used musical intuition and skills to guide their sculpting.

Importantly, the acoustic luthiers did not just have more technically relevant intuitions and skills, they were also more likely to have deeper experience with and greater intrinsic motivation towards micro scale handcrafting. In this way, their practice provided them with an additional point of reference with which they could identify and contextualise the apparatus' complexity and depth (Section 8.3.6.4). In contrast, the other two archetypes were less likely to have experience of working in fine physical detail on artefacts with such complex behaviour, which made their technical approaches more naive.

From a high-level perspective, the participants all approached the apparatus and activity in a similar way, that is reflected by the structure of Section 8.3. Initially, there was a sense of intention towards understanding that appeared to cut across backgrounds (Section 8.3.4). This was followed by participants assuming that certain ideas and skills from their respective backgrounds would be relevant, and testing them out in the form of various motifs (Section 8.3.5). Subsequently, participants took these initial motifs and deployed them in a variety of sculpting strategies and methods (Section 8.3.6), and by the end most participants felt they had made some kind of progress towards improving their sculpting (Section 8.3.6.5). Within these similar stages of response, significant differences appeared based on participants' backgrounds, that in some instances met expectations, and in others were completely unanticipated.

One unanticipated issue related to participants' backgrounds was that those with little or no digital media in their practices struggled to use the GUI/TUI, in terms of remembering sequences of actions, reading the GUI, and navigating sculpts (Section 8.3.2). In hindsight, the assumption that the apparatus would be easy to work with for the entire range of participants was incorrect and biased, and was a barrier to some participants' fluidity and confidence with the sculpting process. Participants with acoustic instrument making backgrounds reliably interpreted the sculpting surface as analogous to the soundboards and instrument plates they were familiar with (Section 8.3.5.3), and in some cases successfully applied techniques for manipulating resonance from their domain (Section 8.3.6.5). However, they did not progress as far as expected in one hour, and in hindsight this seems reasonable given how practically different it was to their experiences, and how unintuitive aspects of the mapping algorithm were (Section 8.3.6.4).

In contrast, although the digital luthiers were expected to make less technical progress than acoustic instrument makers, it was not expected that they would make and then fixate on categorically incorrect assumptions about the apparatus (Section 8.3.5.1). In particular, it was assumed that it would be quickly obvious that the sculpting surface did not operate based on some spatially orthogonal sensing mechanism (i.e. the inputs were not XYZ axes). Furthermore, it was not anticipated that these participants would also assume a straightforward mapping between an XYZ input space, and a low-dimensional, high-level audio parameter space (brightness, reverb, etc.), rather than the high-dimensional, low-level parameter space that was present. While some participants made these assumptions initially, and then abandoned them when they contradicted their experiences (Section 8.3.5.4), others clearly maintained similar ideas throughout. Again, in hindsight, it was clear that for digital luthiers and electronic music producers, these were entirely reasonable assumptions to make based on the types of interfaces they encounter on a regular basis.

What intuition-led meant was different for each participant, depending on their backgrounds (Section 8.3.6.4). For musicians, analogies were made to working with both hardware and software synthesisers, where they commonly navigate based on emotional reactions to sounds. This approach necessitated only a modest technical understanding, which in turn promoted a beginner's mind approach to sculpting. While some took this approach from the outset, others reached a similar perspective after failing to devise precise control methods or uncover underlying principles. There was also a third way which experienced acoustic instrument makers took, which appeared to be informed by their pre-existing experience with complex, micro scale domains. In this approach, the apparatus was not seen as solvable, and there was no goal of understanding, because from this perspective there was ultimately none to be had. Instead, there was only practical experience, which could be acquired, built up, and then called upon as intuition to guide each decision. Indeed, this may perhaps have explained how one participant in particular, who is both a musician and instrument maker, dove deep into the apparatus' details with no concern for exploring its timbral limits (Section 8.3.7.1).

The sessions concluded with participants relating the role of subtle details in their own practices to the apparatus and activity they had just experienced (Section 8.3.7.2). For performing musicians, attention to detail was seen as a device for concentrating an audience, whereas for music producers it was seen as necessary for maximising the emotion or pleasure response to a sound. Acoustic instrument makers celebrated the infinite amount of detail in their practice as a source of pleasure, which was starkly contrasted with numerically machined precision, which had no appeal to them. From a designer's perspective, detail was seen as presenting an opportunity cost dilemma, if it was developed before macro and meso scale issues were fully constrained, and instead a top-down, hierarchical approach to detail was preferred. Through this lens, violin luthiers are free to invest fully in detail, since their craft is already suitably constrained.

8.3.10.3 *Comparative activity during detailed design*

QUESTION This section discusses the outcomes in terms of the third sub-question of Research Question 5:

What kinds of comparative activity are present when subtle and detailed design is taking place?

Despite the apparatus issues described in Section 8.3.2 that precluded more quantitative analysis of comparison, comparison was still a prevalent theme in the outcomes. In fact, it is also accurate to say that for the comparative behaviour that was present, some was actually a direct response to the limitations described above. These responses are discussed in Chapter 9 under three emergent themes that all relate to comparison in different ways. In Section 9.2, a first theme describes how participants used comparisons to map the sculpting process, both through comparison with their own practices (Section 8.3.5), and between the greatest differences possible between sounds (Section 8.3.6.2). In Section 9.3, a second theme describes how comparison facilitated logical, combinatoric and spatial reasoning about sculpt-to-sound relationships. In Section 9.4, a third theme describes how the distinctive sculpting patterns (Section 8.3.6.3) can be considered as an informal and intuitive form of *algorithmic pattern*, which served to compensate for the lack of visual memory, to better facilitate case-based reasoning about the apparatus (Section 8.3.6.4).

8.4 DISCUSSION

This section reflects on Research Question 5 and its sub-questions:

What methods and processes emerge when instrument makers encounter a subtle and detailed design space?

a. What motivates instrument makers and creatives to focus on subtle and detailed design or not in a one hour activity?

b. How do instrument makers and creatives from different domains approach subtle and detailed design?

c. What kinds of comparative activity are present when subtle and detailed design is taking place?

In each case, interpretations of the outcomes are suggested and related to relevant literature, and possible implications are put forward for consideration. In other words, our interpretations seek to posit what the outcomes mean and compare the possible meanings to existing ideas put forward by other authors. Under implications, we take this one step further and ask what could or should be done in response to our interpretations.

Implications are considered from the perspective of DMI design practitioners, technologists and researchers and are summarised in Table 8.2. This is not meant to imply that the implications apply exclusively to one group. Much has been written about the fluidity of roles within DMI design ecologies. In reality, the majority of people in these communities are some mixture of these roles. By delineating the implications into these perspectives, it is hoped that this makes it easy for the reader to recombine them as they see fit. Table 8.2 summarises the implications for Sections 8.4.1 and 8.4.2.

Theme	Practitioners	Technologists	Researchers
Motivation (Section 8.4.1)	• Reflect on motivational factors towards subtlety and detail. • Interrogate creative constraints based on their scale of detail. • Explore systematic methods as a path to subtlety and detail.	• Analyse affordances & constraints in terms of scale of detail. • Leverage physical skills & promote tactile intimacy and open-ended play. • Support rapid systematic exploration by displaying design process data.	• Study of subtlety & detail is not limited to in-the-wild studies. • Study of acquisition of tacit & knowledge about details possible. • Study of community tacit knowledge transfer also more tractable.
Background (Section 8.4.2)	• Reflect on beliefs about subtlety and detail, and their effects. • Consider depth over breadth from outset of next project. • Hybridise digital practices with physical crafting practices.	• Design simple, open-ended tools instead of complex, closed ones. • Augment users' hands, eyes and ears, rather than their brain. • Reflect on why tool makers often abstract away the micro scale.	• Study micro scale wisdom in digital luthiers in more detail. • Systematically compare micro scale wisdom across lutherie domains. • Investigate complexity management applied to digital lutherie tools.

Table 8.2: Summarisation of implications for DMI design practitioners, technologists and researchers of study outcomes regarding two themes: motivation towards subtle and detailed DMI design (Section 8.4.1), and impact of different background practices on the same (Section 8.4.2).

8.4.1 *Motivation to focus on subtle details*

QUESTION This section reflects on the first sub-question of Research Question 5:

What motivates instrument makers and creatives to focus on subtle and detailed design or not in a one hour activity?

8.4.1.1 *Interpretations*

As expected, both motivating and de-motivating factors emerged, some of which were specific based on participants' backgrounds. Overall, the apparatus in this activity was rewarding enough to warrant continued exploration at the subtle and detailed level, and even if some adherence to the briefs were based on politeness, participants were still positively engaged throughout. These outcomes support DMI design literature about the usefulness of constraints in curating musical activity [123, 168], in this case showing that attention to subtle and detailed design can be increased by constraining the macro and meso scale aspects of an apparatus and activity, and by offering a micro scale domain which is simple yet rich to engage with. The success of this study apparatus supports the idea that motivation to do micro scale design is reinforced by intimate interactions [121] with open materials [225]. This activity featured two role-playing scenarios, one where the participant was an instrument maker working for a performer, and one where the participant was a performer making their own instrument, and in each case the participants' relationship to micro scale details changed. This indicates that the ecological context of a DMI [75, 260], even if imagined, can not just motivate but actively guide micro scale design activity.

There was a strong motivation towards systematic approaches to subtle and detailed design, but due to the time constraints and the limitations described in Section 8.4.3, this was only possible to a limited degree. Regardless of whether this is an optimal design strategy for the participant, it seems reasonable that study apparatus for micro scale design in under one hour should seek to enable rapid systematic exploration. Based on these outcomes, the affordances that would most readily support this, in addition to those mentioned already, would be real-time, automated documentation, annotation and display of the experimentation process. In general, working at the level of subtlety and detail takes a lot of time [70, 290], and so an activity seeking to compress this into one hour should aim to provide an apparatus which is streamlined, fast, and relatively self-explanatory, which this study did manage to do successfully. Where apparatus are not self-explanatory (e.g. the mapping algorithm implementation and data were deliberately hidden as part of the study design), rapid familiarisation is needed through hands-on, guided demonstrations which must be carefully designed and tested. Another useful feature of this apparatus was that any physical sculpt was valid, and a sound would always be produced, meaning that there were no possible errors, and no "aesthetics of frustration" that usually characterises digital sound programming experiences [21]. Based on these outcomes and interpretations, overall it seems that technical progress in micro scale design with an unfamiliar apparatus is proportional to both the speed and sophistication of systematic exploration affordances, and the applicability of existing knowledge and skills.

In terms of creative engagement with micro scale design, these outcomes suggest that it is influenced by the micro scale domain's context [75, 260], and by participants' intrinsic motivation to work with subtle details in general. In this case, the activity briefs did not specify much context around the meaning of the micro scale details of the musical instrument, and instead this was left unfamiliar and open-ended. For certain participants, their motivation would have been greater had there been more explicit briefing around this element of the activity. Finally, in spite of meso and macro scale constraints, participants with high intrinsic motivation towards meso and macro scale changes will likely seek out the upper extremes of the micro scale domain, and potentially subvert the apparatus or activity to explore meso and macro scale re-interpretations.

8.4.1.2 *Implications*

"In vitro" study of micro scale details is possible even within the scope of one hour, if the apparatus and activity are rich enough and provide enough context as to why the micro scale is the main focus. Not only is this type of motivation possible, there are apparatus and activity constraints which can amplify and attenuate it, which are to a degree also impacted by participants' backgrounds. What might these interpretations imply for DMI design practitioners, technologists and researchers?

From a DMI design practitioner perspective, these interpretations imply that reflecting on intrinsic and extrinsic motivational factors with respect to subtle and detailed design, as opposed to other forms of design present in a practice, could provide valuable insight. Attending to the way that constraints impact differently on the macro, meso and micro levels of a practice could be similarly beneficial, especially in considering whether they are technically arbitrary or creatively informed. Although many practitioners may prefer not to pursue systematic methods, the interpretation of the outcomes in this case imply that systematicity and subtle and detail design may in fact have an intricate relationship, that could be surprisingly interesting for practitioners to explore and nurture. For example, as part of spending more time with subtle details, practitioners may want to approach any potentially overwhelming complexity from a mindful position, and use systematic methods as part of the process of contextualising this complexity and then making meaning with it.

DMI design technologists interested in facilitating subtlety and detail in DMI design, or reflecting on the ways existing tools impact it, may find it useful to review the set of affordances provided by the apparatus used in this study, and contemplate which existing tools if any already support this type of design. While this apparatus itself is not suggested as a recipe that all successful subtlety and detail-oriented DMI design tools must follow, the underlying design principles and approach could be beneficial to consider. These include leveraging existing physical crafting knowledge and skills, promoting tactile intimacy and open-ended material play, eliminating disruptive errors, and making DMI design tools as real-time as possible. Similarly to practitioners, technologists could also ask how specific tools constrain macro, meso and micro scale design, and what impact this has on the tool user's motivation. If certain biases are subsequently found to be present, were they designed accidentally, intentionally, or retrospectively after an accident? Technologically supporting rapid systematic exploration of micro scale details seems like an interesting area to explore, as affordances that do this may take very different forms to existing DMI design tools due to them being perhaps more process-oriented. Based on this study, rapid systematic exploration is positively augmented by making design moves navigable and thus comparable, through automated documentation and display. Tools that are already reified may resist interventions to this effect, in which case, novel tools with fewer or different assumptions about the user's relationship with micro scale details might be necessary to pursue.

This study was fairly high-level and exploratory, and so for DMI design researchers the interpretations may raise many issues and questions, which could only be suitably addressed by more detailed and controlled studies. However, the overall conclusion seems reasonable, that it is possible to motivate micro scale design within a one hour activity with an unfamiliar apparatus, something that was not previously demonstrated, and that has certain implications. Primarily, it means that study of subtle and detailed DMI design is not limited to longitudinal, in-the-wild studies [261] that are constrained to small cohorts. This makes "in vivo" study a viable, complementary alternative with favourable pragmatic factors of economy, specificity and unfamiliarity [315], the latter of which has been used constructively across numerous DMI design studies [102, 195, 321]. This being the case makes certain types of questions far more tractable. Of notable interest are questions about the physiological and sensorimotor processes and mechanisms underlying the acquisition and application of tacit and embodied knowledge about subtle design details of DMIs. Beyond this level of questioning, studies could address how this knowledge is transferred and co-developed between makers in different types of community settings, from individual and in-person workshops, to group and online settings.

Reviewing the interpretations around motivation in more detail suggests a number of paths for future inquiry regarding motivation itself. It seems likely that creatively constraining unfamiliar micro scale details further would affect motivation to do micro scale design, as opposed to leaving it fairly open-ended as was the case in this study. Examples of this in the context of this apparatus could be briefing participants to sculpt sounds that sound like a specific material such as wood or metal, or elicit certain emotions like calm, humour or nostalgia. Briefs could of course become much more abstract and creative than this, by integrating fictions and absurdities [160, 162]. Relatedly, it could be worth investigating what other demotivational factors emerge if the demotivational factors of this study are addressed. What drives motivation towards systematic exploration, and how does fully addressing this desire technologically affect motivation? Would the introduction of technical visualisation, as opposed to open-ended photographic imagery, increase or decrease motivation towards subtle and detailed design? Finally, intrinsic motivation towards subtle and detailed design could be more deliberately compared across specific practices and communities. Pirsig defined two major personality types in terms of whether they were interested in knowing the complete details of an object or craft or not [244], which raises questions about whether communities of practice exhibit similar attitudes. For example, does the NIME research community's focus on novelty bias it away from micro scale design, either in the context of practice, technology or research, and if so, why? A survey of motivational factors for DMI designers would appear to support this idea [73], but as other recent studies of the NIME community have shown, the reality is usually more complex than any simple explanation would suggest, and all the more valuable to explore for it [216, 217].

8.4.2 *Influence of participants' backgrounds*

QUESTION This section reflects on the second sub-question of Research Question 5:

How do instrument makers and creatives from different domains approach subtle and detailed design?

8.4.2.1 *Interpretations*

To a significant extent, the outcomes relating to this sub-question were related to this study's specific apparatus, and what types of expertise it responded to. Counterfactually, if the apparatus' inputs, mappings and outputs more closely resembled that of a graphical software instrument (and somehow did so without reducing the richness of the design space), then the archetypal digital luthier would perhaps have had a more direct and deeper engagement with subtle and detailed design, and the archetypal acoustic luthier the opposite. In reality, the digital luthiers' expertise was in some cases a hindrance leading to fixation [272], and as expected, acoustic luthiers' expertise was more relevant, leading to greater control of the apparatus within the time constraints, even if this was exhibited to a lesser degree than anticipated.

Both the reality and the counterfactual above raise an issue which perhaps ought to be considered important, that is the skills and knowledge gaps between these two archetypes of instrument making practitioner. Why were the perspectives and expertise of digital luthiers generally less suitable for subtle and detailed design activity, to the extent that the musician archetype was in some ways better suited? A survey of DMI designers' motivations showed, perhaps unsurprisingly, a distinct interest in "humanising" new technology, as an end in itself rather than a means to a musical end [73], which already suggests that finer details might not be a primary concern. In addition, a study aimed at revealing latent assumptions about materiality in DMI design revealed significantly biased interpretations towards perceiving "controllers and not instruments" which "promoted XY-thinking" [242]. Sound designers, when introduced to a novel, highly embodied practice of augmented vocal sketching, were also found to lack the physical skills and creative practices to make the best use of them [259]. These outcomes together suggest that digital luthiers, and perhaps more generally practitioners whose interactions are primarily with digital tools, are culturally conditioned to expect "pushes" in familiar directions by interfaces [296], even if they have not encountered them before. They expect to be pushed toward instantaneous usability and thus simplicity, rather than the complexity and sensitivity that micro scale domains tend to consist of. Encountering micro scale domains then becomes a surprise, and when this is met with oversimplified expectations, fixation occurs, which itself is difficult to escape from without self-awareness and deliberate re-orientation [229].

Turning to the acoustic luthiers, where did their technical struggles originate, and why did some of their technical skills not generalise as readily as was expected? Though they could adapt their material practice and principles to the sculpting surface and clay relatively well, in many cases it appeared they suffered (and in some ways benefitted) from an absolute lack of familiarity with DMIs in general. In addition to being less fluent with the TUI/GUI, the concepts of parametric resonance models and data mapping algorithms seemed to be entirely unfamiliar. It could be suggested that the impact of these differences in experience meant that they did not possess any frames of reference for how their physical material engagements would co-mingle with the rest of the apparatus, which limited their technical imagination. Although this was in some ways creatively beneficial in this activity, in the context of a longer-term practice this would clearly limit their ability to engage with subtle design details.

The above ideas are supported by research into hybrid or translational craft practices where significant investment is required from traditional handcraft practitioners to extend their practices to encompass digital materials and processes [4, 98, 223, 292] Considering the skills and experiences of these two archetypes in a Venn diagram, how big would the intersecting area be, relative to the whole? If this activity and apparatus lie in this intersecting area, the outcomes of this study would suggest that its size is small. Both archetypes clearly work with expansive bodies of knowledge, and yet there are significant barriers preventing both groups from adopting hybridised crafting tools such as this one.

Where digital luthiers appeared to possess almost a blind spot for recognising and addressing the apparatus' subtle and detailed design space, acoustic luthiers readily identified the similarities to their practice in its overall complexity. For acoustic luthiers, this seemed to confer more subtle methodological and strategic advantages, which were perhaps more transferrable to the activity than some of their more domain specific practical skills relating to the impact of removing wood on vibration. This suggests the existence of a more generalised form of wisdom about subtle and detailed design and craft. Part of this wisdom appeared to be that micro scale domains of musical instruments are not solvable, in the sense that they are not possible to fully and explicitly understand, nor is it possible to manipulate them with absolute pre-determination and precision. Characterising this as a tinkerer's wisdom as knowing what works without knowing why perhaps belies a deeper wisdom that, for an object as complex as an acoustic musical instrument, the question of why truly has no answer. Further, the complexity of these domains is such that every day, conscious thought is only partly useful at the design and planning stage, and only the body — hands, eyes and ears in particular — and the subconscious mind are powerful enough to make working with them possible. Improving micro scale design skills then becomes a matter of significant investment in hands-on experience, and sharing of those experiences within a community of practice. A simpler way of distilling this wisdom could be to say that being good at subtle and detailed design means not trying to control or understand everything, and instead working intuitively with material, with patience and perseverance, and with a clear contextualising goal or vision.

Since this wisdom itself can apparently be abstracted from the domain, an abstracted form of its antithesis, perhaps a naïveté or hubris about subtle and detailed design, may also help further place it in perspective. A naive view would superficially assume that a given micro scale domain is knowable, and is governed by simple rules and underlying principles, whose discovery leads to simplified methods, enabling the abstraction of the maker out of the process. The assumption of knowability leads to suboptimal making strategies, which over-emphasise conscious thought and rationalisation, and under-emphasise tacit and embodied methods. In terms of moving from naivety to wisdom, the wise perspective would contend that only hands-on experience can transform a beginner's naive outlook, while by comparison, an intellectual grasp of the wisdom being sought is by itself only of marginal value [257].

8.4.2.2 *Implications*

For an apparatus combining digital and acoustic instrument crafts, the digital and acoustic luthier archetypes derived from the outcomes each had their own advantages and disadvantages for addressing subtle and detailed design. For digital luthiers in particular, the notion of cultural and technological biases obscuring issues of subtle and detailed design was proposed. Separately, naïveté and wisdom about subtle and detailed design were considered, abstracted from any particular domain. What are the implications of these interpretations for DMI design practitioners, technologists and researchers?

For DMI design practitioners, the interpretations will resonate or not based on whether the digital luthier archetype is seen as a useful and relatable construct or not, and this may well not be the case considering how broad the DMI design landscape is. Regardless, practitioners could reflect on what beliefs they hold about subtle and detailed DMI design, and ask what has informed their beliefs, and whether they mirror common beliefs of particular DMI design communities. Further, how do these beliefs translate into assumptions about the material world, and influence making strategies and methods? Are certain fixations encountered, and are these desirable, or would it be beneficial to explore ways of re-orienting away from them (such as those suggested in [229])? Practitioners might also find insight in reviewing how much time they spend, and how much experience they have, with subtle and detailed design issues. How much emphasis is placed on rationalisation versus embodiment when working on these issues, and what kind of perspectives do the tools used provide on them? Practitioners who feel like they have never worked extensively with subtle design details may wish to consider depth rather than breadth as the starting point for their next project. They also may wish to consider hybridising their practice with non-digital disciplines, and consider collaborating with instrument designers working outside of digital lutherie.

DMI design technologists seeking to explore and foster micro scale design processes, and support hybrid lutherie practices where physical and digital processes co-mingle, may wish to consider the following questions:

- Is a particular tool accurate, precise and narrow, or simple and open, and therefore powerful?
- To what extent does a particular tool augment the hands, eyes and ears of the maker?
- What would it mean for tools to be predicated on unknowability as a property of the micro domain?
- How can tools support subconscious processing and insight?
- How can tools embody a supportive mindset for working with micro scale details?
- How can tools embody and promote cultures of shared community practice?

Like any novelist who cannot but write themselves into their own stories, technologists inevitably encode parts of themselves into the tools that they create. For technologists creating DMI design tools, perhaps then the most important question they could ask is how their own relationship to subtle and detailed design influences the tools they create, and those they dream of creating. As the adage goes, "we shape our tools, and then our tools shape us" (attributed to multiple sources), and it follows that the technologist's perspective on subtle and detailed design will subsequently shape the tool user's perspective, intentionally or not. Therefore, the implications explored from a practitioner perspective above apply equally to the technologist: how is a given tool's design a consequence of its inventor's relationship and level of experience with micro scale domains?

For DMI design researchers, the idea that experienced luthiers possess a form of wisdom about subtle and detailed design, which they can re-apply with relative ease in unfamiliar instrument design scenarios, is a tantalising one. This interpretation of the outcome has been fairly speculatively drawn out from accounts of particular participants, and is really deserving of its own dedicated study, which would likely benefit from both ethnographic and probe-based approaches. Characterising this wisdom further could lead to the development of a short micro scale wisdom questionnaire, which would have myriad applications in DMI design practice, technology development and research. In particular, teasing out general instrument making wisdom from expert practitioners from a variety of domains could have an impact in NIME pedagogy, a topic of considerable interest in the community [240, 287, 319]. Also relevant to pedagogy is the notion of wide skills gaps between the digital and acoustic luthier archetypes, which indicates that more diversity and cross-pollination is needed between practices at the level of curricula. The digital luthier archetype proposed is similarly speculative, but does perhaps hint at common beliefs which impact design practice. Do digital luthiers genuinely assume that all DMI design tools and interfaces are simplified, and abstract away direct control of micro scale details, no matter the appearance of the tool? While this study was not controlled enough to confidently make such an assertion, at the very least, future studies ought to consider including design fixation re-orientation in their protocols [229, 272], unless fixation itself is the topic of study. Finally, complexity management has been successfully applied by Pardue et al. in seeking to flatten the learning curve of complex instruments [233–235]. Is the complexity of micro scale details in the design process an inhibitory factor for digital luthiers, and would they similarly benefit from a complexity management approach, appropriate to their current level of wisdom?

8.4.3 *Comparative activity during detailed design*

QUESTION The third sub-question of Research Question 5:

What kinds of comparative activity are present when subtle and detailed design is taking place?

As described in Section 8.3.10.3, this question was not addressable in the way initially anticipated. Emergent themes relating to this question are described in Chapter 9. Addressing the limitations of the study regarding this question is further reflected on in Section 8.4.4.

8.4.4 *Limitations*

As this is a high-level exploratory study, there are plenty of limitations to acknowledge, all of which affect the strength and validity of our interpretations of the outcomes. Issues with the use of the study apparatus (Section 8.3.2) meant that the third sub-question of the study, regarding comparative activity, could not be addressed as originally intended. The apparatus' explicit comparison affordances would have been ideal for adding a quantitative dimension to addressing this research sub-question. Technical visualisation was omitted on the grounds that it would likely take up too much of the participants' attention, and potentially bias the responses towards technical, explicit reasoning rather than hands-on experimentation. Instead, it was assumed that the table of navigable sculpts in the GUI would adequately maintain the context between sound and sculpts, which turned out not to be the case. The preferable way to compensate for this issue would have been to automatically photograph the sculpting surface and present a table of sculpt images, and while this was considered in the apparatus development phase, unfortunately there was not enough time to implement this feature. It seems reasonable that if these issues were addressed, a study with a similar design and expectations could be beneficial. A researcher could benefit from piloting these changes to ensure that participants who use digital interfaces less often can still develop a reasonable level of fluency. However, this would not preclude other study designs examining the same type of question, and in fact more specific questions could be asked based on the emergent themes related to this question, which could take the discourse further.

Another limitation of the apparatus was the mapping algorithm (Section 7.5), which needed to build on participants' physical intuitions of resonance and dampening to some degree. However, we didn't have time to fully develop this, and mostly focused on mapping the gain parameters of the models. We decided to map the decay parameters as well, although this may have added confusion in the end, and the frequency parameters we did not map at all. The mapping algorithm was successful in the end despite its naivety, but could certainly be improved, which in turn would potentially allow for more detailed and interesting studies to take place.

Regarding the activity design, quantitative comparison across the two Matching Tasks would have been far easier if they were exactly the same. Although they were similar, the participants were sculpting model A to model B in the first time, and model B to model A the second time, which was necessary to sustain engagement in the second round. Due to those models having different numbers of resonators, set to different frequencies which weren't mapped, the results were not as comparable as they could have been. In the end, there was plenty of qualitative comparison to make across these tasks (Section 8.3.6.5), but supplementing this with quantitative analysis would have been interesting.

Although this study featured our largest cohort yet, it was still relatively small, and the most interesting responses came from those with specialist expertise, of which there were fewer. This is a general issue in such a domain specific field, and here it also follows that the scope of our insights are limited as well. In particular, there were a lot of sculpting responses where the level of detail changed accidentally, unintentionally or randomly, due to participants' lack of applicable expertise. In contrast, there were fewer examples where changes to the level of detail were closely connected to the participants' intentions, which make the data more valuable as a proxy for possible underlying design processes.

8.5 CONCLUSION

This chapter has explored the encounter between instrument makers and creatives from a variety of backgrounds with the subtle and detailed design space of a tuned percussion digital musical instrument, crafted via sculpting clay. In a one-hour activity, participants first learned to sculpt the instrument's digital resonance models out of clay, and then carried out three tasks which alternated between shorter, technical briefs and a slightly longer creative brief. Being met with an unfamiliar apparatus, participants used the clay to project assumptions onto the process, which was more helpful for acoustic than digital instrument makers. Participants developed a variety of sculpting strategies and methods, which included trial and error, timbral limit finding, ordered sequences of clay patterns, and more subtle, intuition-led approaches. At the end of the activity, participants felt they had made progress towards improving their sound sculpting process, although it was hard to define what exactly had improved. Reflecting on the apparatus and activity in relation to their own practices revealed a variety of attitudes to subtle and detailed design, as well as descriptions of learning how to work in fine detail which were comparable across domains. The outcomes were interpreted regarding three sub-questions, and in each case implications have been explored from the perspectives of DMI design practitioners, technologists and researchers.

The first sub-question enquired about what motivates participants to focus on subtle and detailed design or not in the context of a one-hour activity (Section 8.4.1). The outcomes suggested that the macro and meso scale constraints of the apparatus and activity, along with its micro scale design space, were both broadly effective in providing extrinsic motivation which could sustain for the duration of the activity, even when accounting for inherently low intrinsic motivation in some participants. Based on these interpretations, DMI design practitioners were invited to consider that macro, meso and micro level constraints might be latently present in their practices and projects, and that insight could be gained from reflecting on the alignment of these constraints with their intrinsic motivations and design goals. Demotivational factors included the apparatus' inability to match their desire to be empirical and systematic. For DMI design technologists, framing questions were provided to stimulate reflection on their tools' support for these behaviours, and how such support might be improved. Finally, some participants felt that the unfamiliarity and open-endedness of the micro scale domain in this activity made it difficult to meaningfully engage with, and a minority few simply couldn't resist making meso and macro scale interventions. From a research perspective, this was described as opening up the idea of actively constraining the micro scale, which was not explored in this study, and has the potential to enable more nuanced and controlled study of micro scale design processes.

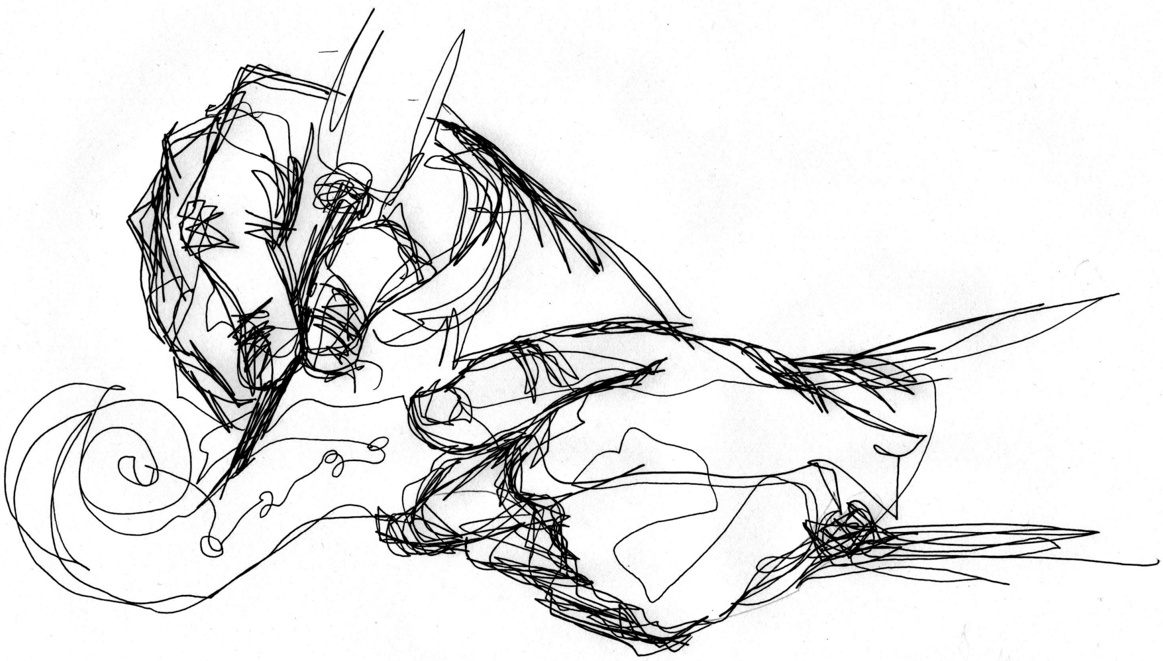
The second sub-question investigated how the participants' different backgrounds impacted on their approach to subtle and detailed design (Section 8.4.2). This study design did not feature formal groups or controls in terms of participants' backgrounds, so interpretations of this question were made with caution, and would need to be studied more deliberately in order to be in any way confirmed. Responses were typified into three archetypes of digital luthier, acoustic luthier, and musician. The acoustic luthier archetype was identified as being more likely to exhibit two advantageous characteristics; more relevant intuitions and skills when it came to an acoustics-driven understanding of the sound sculpting process, and greater experience with and intrinsic motivation towards micro scale handcrafting. Surprisingly, digital luthier archetypes were disadvantaged compared to musician archetypes, as they were more likely to make, fixate on, and then become bemused by, technically incorrect assumptions about simple, orthogonal mappings between XYZ inputs and high-level audio parameter outputs. These outcomes were interpreted as implying the existence of a more generalised wisdom about subtle and detailed design, which was suggested as being proportional to domain specific, hands-on experience with the same. DMI design practitioners, technologists and researchers alike were invited to consider the significant skills gaps between digital and acoustic luthieres. It was implied for practitioners and technologists that some overarching concerns in their practices may be inextricably linked to their own level of wisdom and experience with subtle and detailed design, and that bringing greater awareness and reflexivity to this issue may be revealing. For researchers, it was highlighted that the idea that acoustic luthiers' micro scale wisdom was transferable to this activity was highly intriguing, and that further systematic elucidation of this wisdom could go far beyond this study and have useful consequences.

The third sub-question asked about the kinds of comparative behaviour that were present during subtle and detailed design processes (Section 8.4.3). Due to technical limitations of the apparatus, this question was not addressable in the way that was originally anticipated. Nevertheless, three distinctive themes of engagement with the apparatus' subtle and detailed design space emerged, which all related to comparison. These three themes were micro scale cartography, metrology and algorithmic pattern, and are described in the next chapter (Chapter 9).

In conclusion, we have demonstrated the viability of observing subtle and detailed DMI design during a curated one-hour activity with unfamiliar probes. We have also shed some light on what encourages this type of design to occur, and shown how participants' background influence their responses and progression throughout the activity.

Part III

REFLECTIONS



9 MICRO SCALE DMI DESIGN III: OBSERVATIONAL THEMES ON MICRO SCALE DESIGN PROCESSES

To see the ordinary so intensely
that the ordinary becomes extraordinary, becoming
so focused, so specific about something,
that it becomes something other than what it ordinarily is.

— Edward Tufte, *Seeing with Fresh Eyes* [293]

Chapter 8 originally sought to address three sub-question of Research Question 5. The last of these sub-questions we were unable to address in the way we had designed for, due to the limitations with the apparatus discussed in Sections 8.3.10.3 and 8.4.3. This sub-question related to comparative activity:

What kinds of comparative activity are present when subtle and detailed design is taking place?

Though the apparatus limitations precluded us from pursuing our intended analytical approach, methods and processes still emerged that could be described as comparative, which were present in the video recordings and sculpting data. This chapter brings together our observations of these emergent methods and processes under three themes — micro scale cartography, metrology and algorithmic pattern — which will be introduced shortly.

This thesis aimed to specifically investigate the underlying processes of subtle and detailed DMI design, but since the earlier investigations resulted in macro and meso scale activity, we have had fewer opportunities to try to identify and characterise these processes. As a result, we offer these themes as potential starting points for modelling the underlying processes of subtle and detailed DMI design, for future research to consider. Since the themes were emergent and interpretive on our part, and the activity was not explicitly designed to look for them, they are closer to hypotheses than analytical inductions. Nevertheless, we hope they can help to seed ongoing discourse and future investigations into subtle and detailed DMI design, and to provide jumping off points for researchers seeking to build specifically on this work.

9.1 INTRODUCTION

This section reflects on three emergent themes in relation to Research Question 5:

Emergent themes based on the question "What methods and processes emerge when instrument makers encounter a subtle and detailed design space?":

a. Participants engaged with the micro scale domain cartographically, by overlaying familiar conceptual maps in the form of sculpting motifs, which embodied assumptions about similarities between domains, and by using spatial thinking to orienteer, navigate and identify points of interest within the domain.

b. Participants engaged with the micro scale domain metrologically, by developing systematic and efficient sculpting methods, by internally calibrating their sculpting process against their sensibilities, and by measuring sculpting outcomes holistically.

c. Participants intuitively used algorithmic pattern as a method of inquiry about the micro scale domain, by developing sculpting motifs into patterns and procedurally varying them over time, and by changing patterns and procedures improvisationally, as part of a dialogue with the sculpting process and outcomes.

These themes were arrived at using the same process described in Section 8.1.5.2, following the issues described in Sections 8.3.10.3 and 8.4.3. Each theme is described and reviewed against the outcomes of Chapter 8, as described in Section 8.3. Interpretations are suggested and related to relevant literature, and implications are put forward for consideration. Similarly to Section 8.4, implications are considered from the perspectives of DMI design practitioners, technologists and researchers. Table 9.1 summarises the implications.

The themes are not intended to be applied in mutual exclusivity, for example there is no attempt being made to define a boundary between what outcomes could be understood through cartography versus metrology. There are instances where it makes sense to describe certain responses as moving from the cartographic theme to the metrological theme, and vice versa. Equally, there are instances where it makes sense to describe certain responses as being both cartographic and metrological. In this way, these themes together aim to provide complementary perspectives on the micro scale activity observed in this study.

Theme	Practitioners	Technologists	Researchers
Cartography (Section 9.2)	• Identify common conceptual maps and reflect on their contents. • Identify desirable but missing maps and seek to acquire them. • Identify how one's own maps differ from those of other discplines.	• Provide users with cartography tools & encourage their use. • Ask what terrain a tool creates, and how easy it is for users to map. • What representations best support conceptual cartography?	• Work with cognitive neuroscientists on DMI design cognition. • Inquire about how micro scale maps are created and refined. • Assess the impact of cartographic tools on micro scale practices.
Metrology (Section 9.3)	• Reflect on metrological processes already present in practice. • Develop personal metrological tools that embrace subjective evaluation. • Actively curate aesthetic & social influences on measuring practices.	• Facilitate users to create personal and specialised measuring tools. • Facilitate richly embodied measuring experiences and methodologies. • Connect cartographic & metrological tools conceptually and practically.	• Compare sensorimotor abilities of DMI designers and players. • Compare sensorimotor abilities in beginner and expert DMI designers. • Investigate transfer of micro scale wisdom across DMI design projects.
Algorithmic pattern (Section 9.4)	• Examine where systematic activity is already present in design practice. • Develop notations for implicit patters in design processes. • Observe effects of systematic methods on emotions while designing.	• Add algorithimic affordances to non-algorithmic tools. • Transform algorthmic music-making tools into DMI design tools. • Enable practitioners to capture & display their design process data.	• Examine relationship between algorithmic pattern & the micro scale. • Investigate motivation towards systematic approaches. • Explore linkographic analysis of empirical DMI design data.

Table 9.1: Implications for DMI design practitioners, technologists and researchers of three themes in Chapter 9.

9.2 MICRO SCALE CARTOGRAPHY

9.2.1 *Description*

This section reflects on the first emergent theme, micro scale cartography, which is summarised as:

Participants engaged with the micro scale domain cartographically, by overlaying familiar conceptual maps in the form of sculpting motifs, which embodied assumptions about similarities between domains, and by using spatial thinking to orienteer, navigate and identify points of interest within the domain.

Cartography in this context refers to the literal mapping of concepts in physiological space in the brain, based on the following framework from cognitive neuroscience that researchers such as Peter Gärdenfors, a co-author of the following work, have proposed and investigated:

> *We propose cognitive spaces as a primary representational format for information processing in the brain [...] Place and grid cells might have evolved to represent not only navigable space, but to also map dimensions of experience spanning cognitive spaces governed by geometric principles. In these cognitive spaces, stimuli can be located based on their values along the feature dimensions mapped by place and grid cells. These spatially specific cells provide a continuous code that allows similar stimuli to occupy neighboring positions in cognitive space, encoded by overlapping population responses. In this framework, concepts are represented by convex regions of similar stimuli.* [23]

Participants used spatial and navigational metaphors in their sessions, and while this does support the idea that interesting forms of spatial cognition were taking place, this theme does not aim to make claims about neurocognition, which this study design would evidently not be able to substantiate. Rather, the aim is to take inspiration from this framework to describe the participants' creative encounters as a process of mapping between familiar and unfamiliar concepts, and increasing familiarisation with the apparatus' multidimensional terrain.

9.2.2 *Outcomes*

Due to the apparatus' unfamiliarity, and also because of its invisible complexities, a common theme in participants' responses came in the form of experimentally comparing it to familiar domains (Section 8.3.5). This theme frames this type of response metaphorically as overlaying existing conceptual maps on the new territory being encountered, to ascertain whether the existing map could suffice as an approximation of the new territory or not. This 'overlaying' was achieved by taking common ideas and figurative references from familiar domains, and manifesting them in clay and as sequences of sculpts. One of the most obvious instances of this behaviour was in digital luthiers and electronic musicians testing out graphical sculpting motifs based on overlaying conceptual maps from digital interface design (Section 8.3.5.1). Another noticeable instance was acoustic luthiers marking out violin templates and testing out barring techniques on the sculpting surface (Section 8.3.5.3).

Participants' responses to the activity tasks (Section 8.3.3) can be considered from a cartographic perspective. In the Matching Tasks, participants were given the task of arriving as close to point B as possible when starting from point A (Section 8.1.3.3). Section 8.3.6.5 points out the differences between responses to Matching Task 1 and 2. In Matching Task 2, there appeared to be an emerging strategy of dropping pins all over the terrain to see which one was closest to B, and in some cases then attempting to move closer still. The Tuning Task was much more concerned with the free exploration of space, or in some cases participants could simply move within the space without considering their relative whereabouts.

A number of participants reported that their sculpting methods and outcomes both felt at times random (Section 8.3.6.1). From a cartographic perspective, this might be thought of as a feeling or experience of disorientation, and of lacking directionality or a common frame of reference. This sensation was perhaps exacerbated by the issues encountered with the GUI/TUI, as described in Section 8.3.2. As a countermeasure to this disorientation, some participants deliberately invested their sculpting time in attempting to find the boundaries of the apparatus' ranges of operation, whatever those might be (Section 8.3.6.2). Participants' searched around for edges, limits, and extremes, not necessarily because these were destinations, but because they might reveal unique waypoints and landmarks, which when compared could be used to suggest shapes and contours between different points in the overall terrain.

When a point of interest was either identified or speculated to exist within the vicinity, examination of the terrain could proceed at a more localised and textural level (Section 8.3.7.1). Section 9.3 describes this type of approach as being metrological in character, which drove the need for sculpting with precise patterns (Section 8.3.6.3). There is overlap between these themes, however, as the sculpting patterns may also be interpreted as a form of map-making at a local level, rather than a global level as in the limit finding behaviour described in the previous paragraph and in Section 8.3.6.2.

The terrain provided by this apparatus was counterintuitive and unnatural, despite an appearance of simplicity and functional approachability, and attempts to design a physically-inspired mapping algorithm. For acoustic luthiers, this counterintuition was less severe, and some of their familiar maps of how vibration can be manipulated were in fact sufficient approximations (Section 8.3.6.4). Participants with technical approaches who lacked comparable intuition seemed to remain lost. While **L8** identified that the terrain had no "cultural memory" which made navigation in itself "a little bit wasted time" (Section 8.3.7.2), musicians did find that they could use their musical maps to interpret the outcomes of the sculpting process, which diminished the necessity to confront the technicalities of the sculpting process' inputs and mappings.

Despite best efforts, and as expected, no complete maps of the apparatus' terrain were arrived at after one hour of orienteering (Section 8.3.6.5). However, many familiar maps had been overlaid and then rejected, and participants claimed to have become better at identifying which maps were irrelevant, in effect revealing to them how little they in fact could assume about the apparatus based on what they knew. **L25** reflected on their process for working with micro scale details in cartographic terms: "it's walking the path through the steps of the process, many times, that allows your brain to start probing the different moments of the path, and thinking of different theories" (Section 8.3.7.2). Participants' descriptions of what they would hypothetically do with the apparatus in future included the continuation of map-making activities and improving their cartographic process (Section 8.3.6.6).

Despite the constraints of the apparatus and activity, some participants did still engage in meso and macro scale activity (Section 8.3.8 & 8.3.9). From a cartographic perspective, this could be considered as re-shaping the territory itself rather than mapping what is already there, which was in some cases approached technically and in other cases a purely creative and imaginative exercise. Transformation of the territory was deemed possible and necessary by these participants to fulfil the specific creative urges that characterised their practices (Section 8.3.7.2).

9.2.3 *Implications*

This theme has suggested that taking advantage of the brain's spatial reasoning abilities is fundamental not only to how familiarity and novelty are distinguished in a novel creative scenario, but also to how practitioners become aware of and navigate deeper levels of detail. From this perspective, conceptual mapping of subtle design details is a constant dialogue between direct contact with the terrain, and abstraction of it into simplified topographic models which help orient the practitioner within their creative process. DMI design practitioners, technologists and researchers interested in engagement with subtle and detailed design may wish to reflect on the following set of implications.

DMI design practitioners may wish to start by taking an inventory of their conceptual maps, and identifying which ones they most commonly use. Some of these maps may be dog-eared, having been drawn up a long time ago, with lesser map-making skills, and for terrains which may have since changed. Others may be scaled at a detailed level, heavily detailed and annotated, while others may be a high-level patchwork with missing areas and unanswered question marks. Some may be empirically derived, and precise as can be, while others might provide for impossible spaces, marking out hypocrisies, contradictions and fantasies. And finally, some may be general and trusty (perhaps these might be called wisdom maps, see Section 8.4.2), while others may be highly specialised, and at risk of becoming obsolete despite their hard-won value. Even in the most open-minded practice, these maps are present when encountering new terrain, and so reviewing them once in a while may be an insightful and rewarding thing to do. Also revealing might be which maps are absent from a practice, and where existing maps require the labour of repetition to become sufficiently detailed. While this study has dealt with conceptual maps at an individual level, there are also of course questions of shared maps, and shared map-making experiences.

Awareness of the primacy of conceptual maps, and constant cartographic activity in subtle and detailed design processes, could be relevant to DMI design technologists for multiple reasons. The need for tools which facilitate rapid systematic exploration, described in Sections 8.4.1 and 8.4.2, overlap with the needs of cognitive cartographers, and so similar questions of existing and new tools apply. Particularly, a technologist may ask themselves what kind of terrain a particular tool or material creates, and how amenable is it to conceptual mapping by luthiers, particularly when it comes to subtle and detailed design? Ingold's depictions of grain from a materiality perspective may be instructive for this type of reflection [120]. For example, it could be argued that the grain of deep learning models goes directly against conceptual cartography, emphasising further the need for explainability and interpretability by design [66]. Do or should DMI design tools feature specific map-making affordances, or can these be designed separately as standalone cartographic instruments, which treat design as a search problem [108]? What kinds of representations, visual or otherwise, support the development of detailed maps which necessarily go beyond written language or verbalisation?

This theme was primarily inspired by research about spatial cognition [23], and it goes without saying that this imposes limitations on the nature of any claims. Primarily, it could be of great interest to DMI design researchers to become more familiar with this domain, and to collaborate with cognitive neuroscienctists around the topic of DMI design cognition. Questions such teams might want to ask could include, how are the various maps — sensorimotor, design process, aesthetic, cultural, fictitious — at play in a design process constructed, and how do they interact? What is the relationship between the character of conceptual maps with the character of imagination [100]? How are novel encounters, and deepening levels of detail, compared with and assimilated into this labyrinth of maps? To what extent is it possible to make these implicit maps explicit, and is it possible to reveal and compare their relative levels of detail? Taking this one step further, how would the introduction of DMI design tools explicitly addressing cognitive cartography affect DMI design cognition? This last question could involve map-making briefs to contrast the effects of empirical versus fictional approaches [162]. These questions might require the development of new types of DMI design study probes, which would need to go some way to addressing the technological issues above, and then turn these into control variables. In fact, a fair assessment of extant DMI design literature may conclude that such approaches to study design are already present, in the case of probes which rely on defamiliarisation [102, 321], as this study did. This study has similarly shown that deliberate obfuscation of aspects of DMI design tools can be useful in drawing out interesting responses.

9.3 MICRO SCALE METROLOGY

9.3.1 *Description*

This section reflects on the second emergent theme, micro scale metrology, which is summarised as:

Participants engaged with the micro scale domain metrologically, by developing systematic and efficient sculpting methods, by internally calibrating their sculpting process against their sensibilities, and by measuring sculpting outcomes holistically.

The *Springer Handbook on Metrology and Testing* offers the following definition of metrology:

> *In science and engineering, objects of interest have to be characterized by measurement and testing. Measurement is the process of experimentally obtaining quantity values that can reasonably be attributed to a property of a body or substance. Metrology is the science of measurement. Testing is the technical procedure consisting of the determination of characteristics of a given object or process, in accordance with a specified method.* [53]

This theme views participants' attempts to sculpt sounds systematically, which was only some of the time, and only for some participants, through the lens of metrology. It identifies in these efforts an intention to measurably alter the instrument's resonance properties via manipulation of the sculpting clay, and to calibrate or model the measurement process itself [281]. The time constraint and technical limitations of the apparatus meant that they did not successfully develop methodologies that could be described as accurate or precise, but nevertheless their actions could be described as scientific, even if rudimentary (how all science begins).

However, this theme also complicates the notion of metrology being a purely scientific endeavour when discussed in the context of musical instrument making. This theme views instrument makers as embodying the metrological process [153], with their bodies literally becoming part of an extended measurement apparatus [47]. In addition, measurands are viewed as being only partially tangible, encompassing the results of a synthesis between the phenomenological results of embodied measurements, and the maker's holistic evaluation of the same. This holistic evaluation is itself an entanglement of intuitive and emotional reactions, comparisons with previous measurands and memories, and organological, musicological, and sociocultural reflections [310]. The result of a holistic evaluation is a feeling about the phenomenon, the totality of which is the measurand, which is then used as the basis for deciding what to do next. This form of embodied metrology is posited as a useful interpretation of why systematic approaches were attractive to some participants, how they went about them, and what they potentially gained from them.

9.3.2 *Outcomes*

In terms of participants' response to the apparatus (Section 8.3.2), the tactile intimacy of the DMI and sculpting clay, and the fidelity of the resonance models, created a high-bandwidth environment where participants could work in as much detail as they could perceive. These features encouraged participants to turn themselves into multimodal sensors, integrating touching, listening and seeing. Temporally, however, multiple participants noted their frustration with the non-real time aspects of the apparatus. This makes sense metrologically, as increasing the frequency of measurements would speed up their process, reducing friction between sculpting and listening, and enabling more elaborate methodologies. The GUI/TUI were meant to augment this process by providing a simple case-based reasoning system [177, 179], since auditory impressions quickly fade, however this did not work out as originally intended as Section 8.4.3 described. Based on the outcomes being more qualitative than anticipated, it is difficult to surmise whether the metrological approach was more present during the technical Matching Tasks than the creative Tuning Task (Section 8.3.3). In general, though, it was probably more prevalent with particular participants than with tasks.

The first two sculpting strategies that were described in Section 8.3.6 were trial and error, and timbre limit finding (Sections 8.3.6.1

& 8.3.6.2). From a metrological perspective, trial and error perhaps represents the most elementary approach possible, where no quantifiable relationships between test stimuli and responses are known or assumed. In the previous emergent theme (Section 9.2), participants' search for timbral limits was described as cartographic, and in this theme it is also metrological in that participants aimed to calibrate their measurements relative to the overall range of the apparatus. They sought a sense of overall scale or volume, which could then be used to put their sculpts in perspective.

The apparatus and time constraints both technically limited how rigorous the metrological approach could be. Perhaps in response to these limitations, participants developed sculpting patterns to increase the efficiency and sophistication of their process (Section 8.3.6.3). These patterns exhibited the clearest attempts by the participants to be systematic about their sculpting, applying combinatoric logic to test their ideas. Participants in multiple instances explained these patterns in terms of structuring comparisons. The benefits of these patterns metrologically are explored in detail in the final emergent theme (Section 9.4).

Participants' attempts at calibration were described above in relation to the timbral range of the apparatus, but there were also other ways in which calibration could be said to be taking place. Calibration took place at the empirical level with the apparatus, but was also taking place aesthetically and culturally, as part of the participants' internal process. This was most evident in Section 8.3.6.4 about intuition, where some (particularly musicians) described sculpting in a more implicit mode, compared to earlier in their sessions which were led by more explicit assumptions (Section 8.3.6). In this approach, participants were sensing and measuring their own emotional responses and enjoyment of the sounds they were creating, and beginning to calibrate this against their personal practices, and the apparatus' timbral range. In this way, the internal and external forms of calibration were being integrated, as part of a higher-level process of measurement and evaluation of sculpted sounds.

Participants later described the quality of their final outcomes as not having improved much, whereas their felt sense of their process had improved (Section 8.3.6.5). They found this hard to describe, but this theme suggests that it was partly their metrological process that had improved. The various levels of calibration that had taken place did not necessarily lead to an instant improvement in outcomes, but sculpted sounds were becoming more clearly situated within an emerging context. In addition, in the final task participants averaged faster and larger sculpts, suggesting the beginning of a convergence towards more efficient metrological processes. Part of this process involved eliminating parameters which turned out to be irrelevant, such as the precise geometric shapes that some participants started out with (Section 8.3.7.1). The entanglement of participants' use of the apparatus with their own practices, and the ecologies that they are part of, became clearer during the post-activity discussions (Section 8.3.7.2). Interestingly, the lack of "cultural memory" of this apparatus' subtle design details was highlighted as a factor which made evaluation difficult.

9.3.3 *Implications*

An embodied and entangled form of metrology emerged as a way to describe how participants attempted to understand the apparatus and activity. In particular, this initial encounter was characterised in terms of calibration processes happening both empirically and subjectively. For DMI design practitioners, technologists and researchers, a variety of implications can be elaborated based on this interpretation.

Applying the lens of metrology to DMI design practice can provide a bridge between the technical and the creative, and the empirical and the subjective, since it approaches these issues as parts of a whole. Starting from the technical and empirical, it is already useful to view DMI design practice as having metrological needs which need to be met. After all, the right components and materials need to be validated as fit for purpose through some kind of decision-making process, which variously entails situating, play-testing and evaluating them. However, in light of this theme, practitioners may want to pay extra attention to the role of the body in this process. Which bodies are involved, to what extent do they become extensions of the metrological apparatus, and how are measurands coloured by the varying physiologies and lived experiences of those bodies? With subtle design details in particular, key concerns are intimacy and attunement, especially regarding the ways that the practitioner's own hands and ears over time become precise metrological instruments. DMI design practitioners have major disadvantages here, since so many of their tools and materials are intangible and disembodying, which denies them depth of knowing. How can practitioners challenge and rebel against this status quo, and extend their embodiment of the metrological process? Partly, the answer lies in DMI designers accepting the need for, and embracing, specialised metrological instruments as part of the DMI design process.

In terms of subjectivity, as in the implications of the cartography theme (Section 9.2), practitioners may want to examine the what and how of their internal calibration processes. In any metrological process, practitioners can ask what are the aesthetic and sociocultural contexts and beliefs which are entangling with measurands, and as a result they may want to more deliberately amplify some and attenuate others. Kettley's craft principles may be useful here, as they describe not only multiple ways in which embodiment is part of craft practice, but also how craftspeople transform things (tools, bodies, networks) into material, similar to what this theme suggests [153].

Turning to DMI design technologists, this theme raises many interesting provocations and conundrums. While some metrological framings have been used in NIME papers, these have been limited in scope to technical concerns [34, 205]. Normative ideas of metrological quantification do not necessarily apply to musical instruments. For example, cheap components with unusual non-linearities might be ideal for certain kinds of instrumental behaviour. Music technology history is strewn with examples of technical imperfections becoming idioms, which are subsequently imitated and emulated in later incarnations.

On the one hand, a simple suggestion is to recontextualise existing DMI design technologies from the perspective of metrology, and to then investigate the development of novel DMI metrology toolkits. For DMIs involving complex electronic and electrical signals, the oscilloscope is clearly an important and relatively general purpose seeing tool, which migrates [175] into new DMI design contexts on a regular basis (for example in the Bela IDE, [64]). However, real oscilloscopes are often expensive, considered a luxury, and require fairly expert knowledge to operate to their fullest capacity. In reality, probably the most common DMI metrological method is print debugging, which should stir deep feelings of unrest in any technologist who cares for subtle and detailed design. Even in the most luxurious of cases, current DMI design tools do not tap into the full spectrum of sensorimotor capabilities that DMI designers possess, and DMI design practice is all the more impoverished as a result. The technology to address these deficits already exists, all that is lacking is the right perspective [305] and will of DMI design technologists.

Unfortunately, however, the problem is more complex still than designing more general purpose seeing and feeling tools, that enable DMI designers to integrate their bodies into metrological processes in the way that luthiers who handcraft are accustomed to. Subtle and detailed design processes require metrological apparatus to be specialised to a particular design issue of an individual DMI. Further, only the DMI designer can see what these specialisations need to be, since they are usually externalisations and augmentations of embodied processes that emerged as being metrologically significant. Therefore, technologists need to provide affordances at levels of abstraction that enable practitioners to develop their own specialised metrological apparatus, which themselves may have a high churn rate of obsolescence. In addition, the cost to practitioners of developing such specialised tools needs to be below certain thresholds of time and material investment, otherwise specialisation will not occur, which in turn stunts detailed design, a situation which describes the current status quo in DMI design.

Two guiding inspirations for addressing this challenge can be suggested, which were also inspirations for this study apparatus. The first is the concept of software *moldability* as defined by Chiş, from which the above line of argumentation has been adapted:

> *"To reduce the cost for incorporating and managing domain abstractions, software development tools need to support inexpensive creation of domain-specific extensions, and automatically select extensions based on the domain model and the developer's interaction with the domain model.*
>
> *We refer to software development tools that satisfy our thesis statement as moldable tools. Hence, a moldable tool is a development tool aware of the current application domain and previous interactions with the domain (i.e., development context) that enables rapid customization to new development contexts." [45]*

The authors have built these assumptions into a novel software development environment, which makes all software developers specialised toolmakers, enabling far more nuanced and domain specific ways of understanding complex software. The second is Victor et al.'s Dynamicland project, which addresses similar issues from a different angle, by reducing the amount of code that needs to be written by orders of magnitude. It achieves this through a spatial and communal operating system, which closely commingles software with the physical world, described in Section 2.2.2.

https://dynamicland.org

The other dimension to DMI design tools that needs to be addressed regarding metrology relates to the idea of affordances for rapid systematic exploration, described in Sections 8.4.1 and 8.4.2. A highly related field of technological research and development is case-based reasoning [94, 178, 179], which this study apparatus explored in what turned out to be too shallow of a way. The challenge for DMI design technologists is to critically explore the idea of what a *case* is for a DMI designer, for as has been described using the metrological term measurand in this theme, there are subjective and intangible entanglements that any such tool would need to account for [310].

A number of interesting issues and related questions emerge for DMI design researchers. Starting with the physiology of embodied metrology, to what extent do digital luthiers have physiological demands which are similar to musicians when it comes to embodied music interaction and instrumental performance? For example, do digital luthiers need similarly low latency [122] and high-bandwidth [212] tools, and are there other qualities that might be important such as liveness [276, 282]? The status quo seems to assume that luthiers do not have these needs, but this theme argues that these assumptions have no factual basis, and are instead predicated on DMI design tools and practices that are impoverished from an embodiment perspective, as has been discussed above. Relatedly, what are the physiological constraints related to comparison of subtle design details, and to what degree do these exhibit plasticity and variation among instrument makers with varying levels of experience? For example, are experienced makers able to extract more information in shorter time periods from comparative sensory stimuli, with sensory impressions exhibiting longer decay curves in immediate and short-term memory?

Embodied metrological measurands have been described as compound entities comprising instrumental quantities entangled with the luthier's body and their habitual wider ecologies. This raises epistemological issues when it comes to the evaluation of musical instruments, concerning boundaries between quantities and qualities, and objectivities and subjectivities. Early NIME literature sought to explicate prescriptive frameworks for evaluation based on linguistic constructs such as playability and responsiveness [18, 136, 137, 231], which have increasingly become problematised by ecological and entanglement perspectives [260, 310]. This theme responds to this discourse by taking the position that the luthier's tacit sense of fine instrumental quality, and the embodied practices through which it is constructed, is perhaps the richest manifestation of this kind of knowledge. Yet to date, researchers have largely neglected and ignored this primary resource for understanding what good musical instruments are, instead focusing on the miniscule fragment of it which can be articulated as words and numbers. The assumed existence of simple, explicable underlying truths about fine instrumental quality, is reminiscent of the naivety that characterises the absence of "micro scale wisdom" described in Section 8.4.2. It is implied here that the challenge for researching the evaluation of the subtle nuances of DMIs must begin with understanding the embodied practices of digital luthiers, and approaching these practices from the perspective akin to Pirsig's metaphysics of quality [20, 244]. Practical research might begin with reviewing epistemological frameworks for metrology [185, 281], and adapting them to compare embodied metrological processes and practices between digital luthiers of the same or different DMIs. Such studies could be designed to run "in vivo" using the idea of scale-based constraints contributed by this work, or equally through in-the-wild studies [261], and preferably both.

Finally, DMI design researchers working with issues of digital lutherie pedagogy may want to develop new areas of their curricula focused on ideas of subtle and detailed design, which would correspond well with the trend of practice-based approaches to NIME pedagogy [287, 319]. This could include incorporating the development of specialised tools for embodied metrology into students' independent DMI design projects, and encouraging them to encounter the difficulties of articulating instrumental quality first-hand. The pedagogical challenge is to create contexts which foreground issues of subtlety and detail, when design projects tend to be necessarily short. The applicable ideas from this work are scale-based constraints for design briefs, repetition as a conduit for deepening students' awareness of detail, and embodied metrological comparison of subtle details. A simple proposal could start with students devising a DMI with a simple build process, locking its macro and meso design features (students don't have to like them), and then iterating a single detail of this build 5-10 times, while documenting the progression of build methods.

9.4 MICRO SCALE ALGORITHMIC PATTERN

9.4.1 *Description*

This section reflects on the third emergent theme, micro scale algorithmic pattern, which is summarised as:

Participants intuitively used algorithmic pattern as a method of inquiry about the micro scale domain, by developing sculpting motifs into patterns and procedurally varying them over time, and by changing patterns and procedures improvisationally, as part of a dialogue with the sculpting process and outcomes.

The term algorithmic pattern was first proposed by McLean in 2020:

> *The words algorithm and pattern are synonyms; they both refer to structured ways of making. Therefore the phrase "algorithmic pattern" seems to be a tautology. The phrase is nonetheless useful for on one hand clarifying that we address algorithms not just as software engineering tools, but as formalised ways of making that can to a large extent be perceived in end-results. It also clarifies that we are interested in patterns that are not just simple sequences, but structural qualities. This builds a perspective on pattern as a generative and perceptual connection between creation and reception. In short, I define algorithmic pattern as the perception of systematic activity.* [204]

In this theme, pattern refers to the structural qualities of the participants' sculpts, related in terms of motifs, and algorithmic refers to the way these patterns were procedurally varied over time. However, unlike in McLean's description above, in this theme algorithms are not addressed as being necessarily formalised ways of making, since the participants did not explicitly notate, or otherwise externally represent, their sculpting procedures separate from their manifestation as sculpts. The procedures in this case were informally implied by the relationships between sequential configurations of clay, and only became truly visible afterwards by arranging video frames into matrices. If this can be described as a form of programming, it would be analog material programming [225] by example [52], similar to interactive machine learning [245]. Crucially, however, the program is only partially and implicitly synthesised in the participant's mind. Nevertheless, reviewing the highly patterned sculpt sequences again as will shortly occur, the "perception of systematic activity" as McLean defined, is unavoidable.

This theme is also not intended to be applied mutually exclusive to the previously described two themes (Sections 9.2 & 9.3), however some specific connections between them are suggested. Primarily, in this theme, algorithmic pattern is viewed as an approach to making which enhances both cartographic and metrological ways of responding to micro scale details. It is also more generally viewed as a method of enhancing the overall process of meaning making with an unfamiliar, subtle and detailed design space.

9.4.2 *Outcomes*

There were no prompts specifically relating to ordered or patterned sculpting, and participants who did engage in it did not otherwise remark on it in detail, either while sculpting or reflecting afterwards. Despite this, numerous episodes of ordered patterning occurred (Section 8.3.6.3), some of which are so precise that their formal notation would not be difficult to imagine. In respect of the patterns' invisibility during the session apart from in working memory, this suggests that participants were not necessarily always consciously aware of the patterns they were making. Nevertheless, whether arising subconsciously or consciously, a variety of reasons for sculpting in this distinctive way can be considered, which all seem to relate to the intention to understand the apparatus (Section 8.3.4):

- As a response to apparently random or chaotic results (Section 8.3.6.1).
- To make it easier to physically undo a sculpt and return to a previous state (Section 8.3.6.1).
- To uphold a systematic or consistent element in their sculpting (Section 8.3.6.3).
- To match input patterns against potential output patterns, which may hint at predictable control strategies and underlying principles (Section 8.3.6.3).
- To make it easier to remember sequences of sculpts (Section 8.3.6.3).
- To make it more efficient to try out certain sculpting ideas (Section 8.3.6.3).
- To test assumptions in logical combinations, in order to procedurally validate or eliminate them (Section 8.3.6.3).
- To produce complex results from simple, memorable rules (Section 8.3.6.2).
- To explore the implications of a motif (Section 8.3.5).
- To creatively generate new sculpting motifs and approaches (Section 8.3.6.7).

- To engage with the sculpting process, materials and tools in an aesthetically pleasing way (Section 8.3.7.1).
- Because of similarity to approaches taken in participants' own practices (Section 8.3.7.2).

While it is not possible in hindsight to judge the extent to which any of these reasons were influential, they indicate to varying degrees an approach of projecting order onto the sculpting process. That these patterns existed at all also implies that certain other processes must also have been present in some form. In particular, it seems reasonable to assume that there was an element of design planning occurring even if it was implicit, rapid, fragmentary and ad-hoc. Planning sculpts could involve envisioning patterns as extrapolations of existing motifs or other background references, concretising assumptions into combinatoric spatial logic (see Section 8.3.5.2) and temporal procedures, and deciding on suitable levels of granularity and frequency of change relative to the time constraints. The ease and fluidity of engaging with algorithmic pattern in this way suggests that it was a highly intuitive approach which the apparatus was amenable to (Section 8.3.6.4).

In some cases there was clearly an additional improvisatory aspect to patterned sculpting, whereby established sculpting patterns, rules and procedures were altered, composed, overlapped, interfered and morphed as they were being followed. These alterations could be due to the participant responding to an aspect of the environment — the sounds being produced, the state of the clay, the passage of time (with regular reminders coming from the researcher) — and equally they could be prompted by internal reflection by the participant on the patterns they were following. This continuous engagement with material manifestations of pattern and procedure is not dissimilar to artistic live coding, where algorithms that textually notate artistic media are rewritten while being executed [221]. In this case there was no formal notation, in part due to the unfamiliar analog input medium, and yet some temporal sequences are unmistakably algorithmic in character. Evidently, a dialogue of some sophistication and intrigue was unfolding between the participants and the apparatus.

9.4.3 *Implications*

This theme has identified algorithmic pattern as a flexible, intuitive, generative and efficient making approach which some participants were naturally drawn towards when encountering an unfamiliar micro scale design space. This approach was enhanced by the sculpting clay's analog and continuous characteristics, and the sculpting surface's simple rectangular shape, which presented open-ended affordances for designing and iterating patterns by hand. The analog, informal and potentially subconscious ways in which this approach was present challenges common notions of what algorithmic thinking is, and how certain activities can be read from a programming context. This theme thus has a number of interesting implications for DMI design practitioners, technologists and researchers.

Starting with DMI design practice, practitioners may want to examine where algorithmic pattern, or systematic activity in general, might already be present in their work, and compare it with how it has been discussed in this theme. Pattern will most clearly be present as part of musical composition and performance, but it may also lurk in unexpected places, perhaps even embedded deeply into design processes yet invisible to the naked eye. Noting and notating for possible implicit patterns in design processes may reveal hidden patterns, which themselves might hint at underlying influences, assumptions and methodologies. Conversely, deliberately applying pattern-based methods to design processes may produce surprising results, and be especially useful in the case of familiarising or deepening awareness of subtle and detailed design issues. With algorithmic processes, these might clearly be present in signal processing and other software methods, and as part of compositional strategies. But similarly to pattern, this theme calls for practitioners to investigate and observe where less formal algorithms might be playing out, and where algorithmic thinking can potentially be deliberately applied as a generative strategy for subtle and detailed DMI design. Finally, upon becoming more aware of algorithmic pattern in their work, practitioners may want to reflect on how it affects the meaning making process, and even perhaps their emotions while designing.

For DMI design technologists, algorithm pattern can be viewed as a systematic approach to making which supports the cartographic and metrological approaches previously described in Sections 9.2 and 9.3. The DMI design space is already full of tools for working with pattern, and for working algorithmically, and experimentally applying these in DMI design processes involving systematic exploration of subtle details may prove to be valuable. The most advanced tools for working with pattern in the music technology space lie in live coding languages, platforms and environments, which are predominantly used in audiovisual performance practices, and the majority of which feature sophisticated and terse pattern notations. The foremost example would be TidalCycles (or Tidal) [194], which defines itself as a pattern language. The Sema live coding language development and performance environment is also of particular interest here, since it promotes the creation of small, domain specific languages [24]. This ties in well with the argument made in Section 9.3 that micro scale domains require luthiers to develop specialised tools. It's important to note that the suggestion is not that DMI designers would use tools like Sema to create notations-as-instruments [166, 170] for DMI performance, but notations-as-instruments for reasoning and insight about

http://tidalcycles.org

micro scale metrology issues. Further than that, by encouraging DMI designers to create mini-languages that describe their micro scale domains and design processes, designers would be engaging in articulating and formalising algorithmic approaches which emerged from embodied making approaches. However, due to this link to embodiment, it may be counterproductive for DMI designers to attempt to start their process by trying to define language. Tools can still support this early stage of getting to know micro scale domains however, by supporting designers to make informal annotations, sketches and non-syntactical or 'secondary' notations [28] about their experimental design processes and outcomes. Alternative approaches still might involve inferring algorithmic patterns [138] from discretised design process data, and enabling designers to notate patterns informally using typed holes [230].

From a DMI design research perspective, this theme has made various interpretations about DMI design activity at the micro scale, which could benefit from further study under more direct and controlled conditions. A primary question is, to what extent was the emergence of algorithmic pattern in this context dependent on the apparatus design? It might be that these outcomes were much more a result of the analog and continuous sculpting surface and clay, rather than the detailed nature of the design space. Another important question relates to the extent to which the apparatus' counterintuitive and highly complex terrain motivated systematic approaches despite the time constraints. Design science studies of creative behaviour have theorised that the entropy level of empirical design process data could be correlated with the creativity of the design space [139–141]. Given that the participants felt that the apparatus was to a degree random and chaotic, were the systematic responses an effort to decrease entropy of the design space to a creatively preferable level? Further, could awareness of the entropy level of a given micro scale domain be a creatively useful metric to DMI designers? Is there a relationship between the amount of time available for a task and the amount systematicity in the DMI designer's response? Linkographic analysis (which we discussed in Section 2.1.4 but could not employ in this work) of empirical DMI design data may be able to unravel this and potentially many other aspects of DMI design activity concerning subtle details [95], by enabling non-linear connections to be made across design sessions, and by enabling the application of design process analysis protocols to DMI design activity.

9.5 CONCLUSION

In conclusion, this chapter introduced three emergent themes relating to the processes underlying micro scale DMI design. The theme of micro scale cartography described the ways in which participants overlaid familiar conceptual maps in the form of sculpting motifs, which embodied assumptions about similarities between domains, and used spatial thinking to orienteer, navigate and identify points of interest within the domain. The theme of micro scale metrology described how participants developed systematic and efficient sculpting methods, internally calibrated their sculpting process against their sensibilities, and measured sculpting outcomes holistically. The theme of micro scale algorithmic pattern described how participants developed sculpting motifs into patterns and procedurally varied them over time, and changed patterns and procedures improvisationally, as part of a dialogue with the sculpting process and outcomes.

10 DISCUSSION

The probability that something considered a waste of time today will eventually prove itself to have been time well spent increases with the length of time over which knowledge of it survives.

What has become obsolete may have qualities, properties, characteristics, and unfulfilled potential that will later be considered prophetic.

— Laurie Spiegel, *That was Then: This Is Now* [277]

Point of view is worth 80 IQ points.

— Alan Kay, *The Power of the Context* [149]

Overall, this thesis has demonstrated the viability of observing subtle and detailed DMI design during a curated one-hour activity with unfamiliar probes, shedding some light on what encourages this type of design to occur, and on the underlying processes involved in it. Over the course of this thesis' practical investigations, subtlety and detail in DMI design has gradually come closer into focus, at first through a process of elimination of macro and meso scale influences, and eventually through direct comparison of micro scale activity. This path ran counter to our expectations, that our first investigation would bear closer resemblance to what became our final investigation, and that we would subsequently be able to make increasingly analytical reports of subtle and detailed DMI design activity. Encouraging this kind of activity at all was far more difficult for us than we had anticipated.

Our initial, unforeseen results forced us to draw deeper inspiration from non-digital lutheries, and carefully mull over what exactly about them was tacit or explicit, resulting in much more tightly constrained study probes and activities. The outcomes have revealed sophisticated embodied responses, that in Chapter 9 we interpreted as suggesting certain micro scale DMI design processes, that could potentially in future be modelled and studied in further detail. The first section of this chapter reviews the contributions of this thesis in terms of five research questions. The second section then synthesises the contributions into a final response to the main research question (QM). Subsequently, we offer some suggestions regarding future directions for research, and concluding remarks.

10.1 REVIEW OF CONTRIBUTIONS

In Sections 1.2 and 1.3, we described separately the research questions and the contributions. In this section, we interleave them and provide additional summarisation.

10.1.1 *Researching subtle and detailed DMI design*

Q1 What environments and contexts can facilitate DMI design research on subtlety and detail?

Contrib. A: *Chapter 2 defines a scale-based ontology of DMI design that identifies micro scale details as the differences between otherwise identical instruments, and provides a literature review from this perspective.*

Contrib. B: *Chapter 3 describes a methodology for how DMI design toolkits and activities can be used as probes for investigating subtlety and detail. The design of such probes is described in Chapters 5, 6 and 7.*

We summarise the ontology in the following form:

Where each scale considers digital musical instruments,

and their underlying design processes:

the macro scale	defines	*roles, forms and functions of instruments across ecologies*,
the meso scale	defines	*configuration and mappings across taxonomically similar instruments*, and
the micro scale	defines	*subtle and detailed nuances between otherwise identical instruments*.

We asked Q1 because we needed a foundation upon which to base this research. We have made two main contributions in this regard, an ontology and a methodology. An illustration of the ontology is given in Figure 10.1 (originally shown in Section 2.3), and Figure 10.2 (Section 3.3) presents the methodology as an iterative loop where probes enable observational modelling of subtle and detailed DMI design processes.

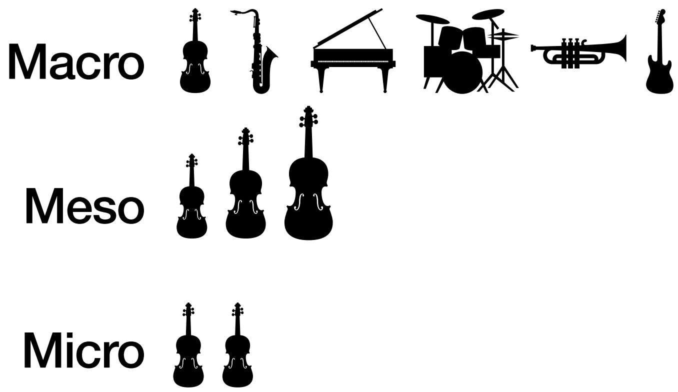


Figure 10.1: Illustrated examples of the scale-based ontology of DMI design:
The macro scale considers completely different kinds of instruments;
The meso scale considers similar instruments, and;
The micro scale considers instruments which are the same at macro and meso scales.

10.1.2 *Learnings from non-digital lutheries*

Q2 What can the DMI design community learn from violin luthiers about the design of subtle details?

Contrib. C: *Chapter 4 provides five key insights into subtlety and detail from violin lutherie, to serve as comparative inspiration for digital lutherie, and to problematise common DMI design tools and methods.*

This case study was felt to be necessary to bring in an external perspective to the problem, from a domain where micro scale details are already dominant. The insights, presented in Section 4.3, related to the following five topics:

- Frameworks and goals as foundations
- Tacit knowledge enables detailed craft
- Tacit knowledge needs open comparative tools
- Playing and testing as separate skills
- Verbal player feedback misses details

Based on these outcomes, we problematised common DMI design tools and methods in Section 4.4 from the following angles:

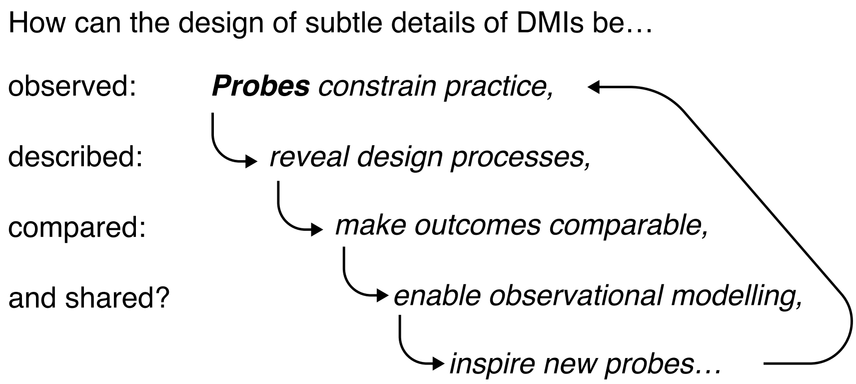


Figure 10.2: The methodological feedback loop (Section 3.3) underpinning the investigation of the main research question (QM, see Section 1.2).

- The micro scale in DMI design frameworks
- Dissemination of micro scale details in DMI research
- Micro scale digital luthier crafting tools
- Digital luthiers' evaluation of micro scale craft
- Reflections on the scale-based ontology

This case study added a grounded element to the contributions described in the previous section (Section 10.1.1), and served as inspiration for the design and evaluation of probes in the later investigations.

10.1.3 *Probing macro scale DMI design*

Q3 How does a community of DMI design researchers respond when encouraged towards subtle and detailed design of a gestural DMI via a physical design kit and crafting materials?

Contrib. D: *Chapter 5 presents reflections from the NIME community on subtle and detailed design, and demonstrates how the scale-based ontology can be used to interpret workshop outcomes, in this case identifying predominantly macro scale responses.*

The investigation in Chapter 5 did not produce micro scale outcomes, and instead the contribution is framed in terms of macro scale DMI design. Along with Chapter 6, this chapter mostly aided the overall thesis topic through a process of eliminating probe design approaches that did not constrain enough towards micro scale DMI design activity. Nevertheless, there were still interesting outcomes to observe upon, and we did so under the following headings in Section 5.5:

- Exploring constraints
- Sound, gesture and materials
- Collaborative process
- Reflections on the apparatus and activity

10.1.4 *Probing meso scale DMI design*

Q4 How do groups of DMI designers respond when encouraged towards subtle and detailed design of a gestural DMI via Pure Data patching?

Contrib. E: *Chapter 6 presents novel methods for analysing DMI design behaviour using visual programming languages by way of visual analysis and source history analysis of Pure Data patches.*

Contrib. F: *Chapter 6 suggests that visual programming languages in DMI design contexts are predisposed towards constraining macro and micro scale activity, and encouraging meso scale activity.*

As in Chapter 5, the investigation in Chapter 6 did not produce micro scale outcomes either, and instead the contributions are framed in terms of meso scale DMI design. For us, these outcomes legitimised the definition of a space between macro and micro scales, which we describe in Section 2.3.3. Triangulating between the probes that predominantly resulted in macro and meso scale DMI design processes taking place, both necessitated and drove the subsequent probe design.

An additional contribution of note relates to the methodology developed for this investigation. To interpret the scale of detail being worked at in the context of Pure Data, in created visual analyses of patch modifications categorised by type of edit (Section 6.3). These annotations were facilitated by automatically version controlling the patch every time it was saved, and then manually stepping through and labelling the updates that were made. Such analysis revealed the underlying design moves and progressions, in a way that facilitated introspection of the scale of detail being worked at. However, we believe this approach could easily lend itself to other questions, and the labelling could be automated based on a finer reading of the version control data.

10.1.5 *Probing micro scale DMI design*

Q5 What methods and processes emerge when instrument makers encounter a subtle and detailed design space?

Contrib. G: *Chapter 7 describes the design of an apparatus for investigation of subtle and detailed DMI design, inspired by handcraft in violin lutherie, and featuring interfaces for audio-tactile sculpting of digital resonance models using modelling clay.*

A standalone contribution towards Q5 are the apparatus (Chapter 7) and activity (Section 8.1) designed for the investigation. The detailed descriptions provided enable close reading of the design and implementation decisions, useful to any future researchers wishing to understand this research or take ideas from it. The other contributions to Q5 relate more directly to Q5's sub-questions. Table 10.1, originally presented in Section 8.4, summarises the implications for Q5A and Q5B. Table 10.2, originally presented in Chapter 9, summarises the implications for Q5C.

10.1.5.1 *Motivation towards subtlety and detail*

Q5A What motivates instrument makers and creatives to focus on subtle and detailed design or not in a one hour activity?

Contrib. H: *Chapters 7 and 8 demonstrate how a DMI design research apparatus and activity can be constrained at the macro and meso scales, and rich and open-ended at the micro scale, in order to motivate micro scale design responses.*

Contrib. I: *Chapter 8 shows that motivation towards micro scale details in an experimental setting is inextricably linked to the role of micro scale details in participants' creative practices.*

The first two investigations taught us that motivating DMI designers to do micro scale DMI design, in a closed setting and in one hour, was extremely difficult. Motivation thus became a focal point in the study outcomes (Section 8.4.1), and the design decisions were rigorously focused around providing adequate motivation and encouragement. This apparatus best encapsulated the lessons learned from violin lutherie, both in terms of macro and meso scale fixedness, and micro scale openness. This was apparent to the degree that violin luthiers who used it felt that comparison of it with their own handcraft practices was not out of place. The activity took the contributions of the first two investigations and synthesised them, resulting in a more intentionally constrained set of briefs.

The probe overall provided adequate extrinsic motivation relative to the participants, to sustain their engagement for one hour. Considering motivation towards subtlety and detail from an intrinsic perspective, we found variation between the participants in terms of their apparent interest in finer details. Post-activity interviews suggested that this variation was linked to the role of detail in the participants' respective practices. Though we did not attempt to explicitly measure motivation, we propose that intrinsic motivation towards subtlety and detail during a closed micro scale DMI design task is positively correlated with intrinsic motivation towards subtlety and detail of the participant in general. From our perspective, investigating possible sources of this intrinsic motivation towards subtlety and detail is an intriguing topic for future research.

10.1.5.2 *Impact of background practice*

Q5B How do instrument makers and creatives from different domains approach subtle and detailed design?

> **Contrib. J:** *Chapter 8 compares the advantages and disadvantages of different skills and knowledge between digital luthier and acoustic luthier archetypes, when encountering a hybrid lutherie apparatus and activity focused on micro scale details.*

The final investigation's cohort of 26 included violin luthiers of varying levels of experience, digital luthiers, music technologists, musicians and other creatives (Section 8.1.2). While we did not recruit and divide the participants into subgroups based on explicit categories, we did carefully interpret the outcomes based on the apparent impact of specific backgrounds, skills and experiences (Section 8.4.2). We reported these findings in the form of proposed archetypes of acoustic luthier, digital luthier and non-luthier musician. We found that acoustic luthiers' crafting practices were more relevant to hybrid handcrafting than digital luthiers. Digital luthiers tended to project assumptions onto the physical aspect of the process that were borrowed from ideas of how software and graphical user interfaces work. In some cases there was a fixation on these assumptions which prevented progress in using the apparatus. In contrast, musicians appeared less likely to make incorrect assumptions, and were more open to the experience, and more flexible in what they did with the results of their crafting.

Theme	Practitioners	Technologists	Researchers
Motivation (Section 8.4.1)	• Reflect on motivational factors towards subtlety and detail. • Interrogate creative constraints based on their scale of detail. • Explore systematic methods as a path to subtlety and detail.	• Analyse affordances & constraints in terms of scale of detail. • Leverage physical skills & promote tactile intimacy and open-ended play. • Support rapid systematic exploration by displaying design process data.	• Study of subtlety & detail is not limited to in-the-wild studies. • Study of acquisition of tacit & knowledge about details possible. • Study of community tacit knowledge transfer also more tractable.
Background (Section 8.4.2)	• Reflect on beliefs about subtlety and detail, and their effects. • Consider depth over breadth from outset of next project. • Hybridise digital practices with physical crafting practices.	• Design simple, open-ended tools instead of complex, closed ones. • Augment users' hands, eyes and ears, rather than their brain. • Reflect on why tool makers often abstract away the micro scale.	• Study micro scale wisdom in digital luthiers in more detail. • Systematically compare micro scale wisdom across lutherie domains. • Investigate complexity management applied to digital lutherie tools.

Table 10.1: Summarisation of implications for DMI design practitioners, technologists and researchers of study outcomes regarding two themes: motivation towards subtle and detailed DMI design (Section 8.4.1), and impact of different background practices on the same (Section 8.4.2).

Theme	**Practitioners**	**Technologists**	**Researchers**
Cartography (Section 9.2)	• Identify common conceptual maps and reflect on their contents. • Identify desirable but missing maps and seek to acquire them. • Identify how one's own maps differ from those of other discplines.	• Provide users with cartography tools & encourage their use. • Ask what terrain a tool creates, and how easy it is for users to map. • What representations best support conceptual cartography?	• Work with cognitive neuroscientists on DMI design cognition. • Inquire about how micro scale maps are created and refined. • Assess the impact of cartographic tools on micro scale practices.
Metrology (Section 9.3)	• Reflect on metrological processes already present in practice. • Develop personal metrological tools that embrace subjective evaluation. • Actively curate aesthetic & social influences on measuring practices.	• Facilitate users to create personal and specialised measuring tools. • Facilitate richly embodied measuring experiences and methodologies. • Connect cartographic & metrological tools conceptually and practically.	• Compare sensorimotor abilities of DMI designers and players. • Compare sensorimotor abilities in beginner and expert DMI designers. • Investigate transfer of micro scale wisdom across DMI design projects.
Algorithmic pattern (Section 9.4)	• Examine where systematic activity is already present in design practice. • Develop notations for implicit patters in design processes. • Observe effects of systematic methods on emotions while designing.	• Add algorithimic affordances to non-algorithmic tools. • Transform algorthmic music-making tools into DMI design tools. • Enable practitioners to capture & display their design process data.	• Examine relationship between algorithmic pattern & the micro scale. • Investigate motivation towards systematic approaches. • Explore linkographic analysis of empirical DMI design data.

Table 10.2: Implications for DMI design practitioners, technologists and researchers of three themes in Chapter 9.

10.1.5.3 *Methods of comparing micro scale details*

Q5C What kinds of comparative activity are present when subtle and detailed design is taking place?

Contrib. K: *Chapter 9 presents three emergent themes based on micro scale design activity, encompassing micro scale cartography, metrology and algorithmic pattern, and explores their implications for DMI design practitioners, technologists and researchers.*

Our learnings from violin lutherie practice in Chapter 4 told us that a possible key to understanding micro scale DMI design might lie in what kinds of comparisons were being made, and how they were being made, during DMI design activity. In this investigation we aimed for the probe to produce reliable quantitative data about comparative activity, however due to certain limitations this was not the case (Sections 8.3.10.3 and 8.4.3), and instead a qualitative thematic analysis was performed. The results were presented as three observation-based themes in Chapter 9, which we summarise as follows:

Cartography: *Participants engaged with the micro scale domain cartographically, by overlaying familiar conceptual maps in the form of sculpting motifs, which embodied assumptions about similarities between domains, and by using spatial thinking to orienteer, navigate and identify points of interest within the domain.*

Metrology: *Participants engaged with the micro scale domain metrologically, by developing systematic and efficient sculpting methods, by internally calibrating their sculpting process against their sensibilities, and by measuring sculpting outcomes holistically.*

Algorithmic pattern: *Participants intuitively used algorithmic pattern as a method of inquiry about the micro scale domain, by developing sculpting motifs into patterns and procedurally varying them over time, and by changing patterns and procedures improvisationally, as part of a dialogue with the sculpting process and outcomes.*

The implications and suggestions based on these three themes are summarised in Table 9.1.

In this section, we have reviewed the main contributions of this thesis in terms of the five research questions they respond to. The next section attempts a final synthesis of the implications in terms of the main question (QM) of this thesis.

10.2 IMPLICATIONS AND REFLECTIONS REGARDING CONTRIBUTIONS

In this section, we first reflect on the personal and ecological contexts that encourage micro scale DMI design, considering time, temperament, access, enculturation, apprenticeship, musical necessity, and the importance of replication. Then, we situate these contexts within environments that include space, materials and mediums that, based on our investigative outcomes, we believe would support micro scale DMI design. Finally, building on the emergent themes described in Chapter 9, we offer potential starting points for modelling subtle and detailed DMI design. We approach this by taking into account key insights and limitations of this work, reappraising the scale-based ontology of DMI design along the way.

10.2.1 *Encouraging micro scale DMI design*

The main research question of this thesis was the following:

QM How can the design of subtle details of digital musical instruments be observed, described, compared and shared?

In reality, this thesis has mainly contributed towards the observation of subtle and detailed DMI design in Chapters 5-8, and description thereof in Chapter 9, and less towards the systematic comparison and sharing that we envisaged. Observation, it turned out, depended heavily on examining what encourages people to engage with micro scale activity in the first place. In Chapters 5 and 6, this was pursued mainly in terms of our own reflections on our workshop designs, which revealed that we had been putting the proverbial cart (environment) before the horse (context). We tried to address this in Chapter 8, where our focus was expanded to include more about the participants' backgrounds and practices, which turned out to be insightful when interpreting the outcomes. This led to a greater understanding of how to observe micro scale DMI design, and here we attempt to synthesise what we have learned in this regard.

10.2.1.1 *Personal and ecological contexts*

Before embarking on our practical investigations, in Chapter 4 we interviewed violin luthiers to provide a foil to our aim of exploring subtlety and detail in DMI design. We drew a number of insights from this work that in a way served as guiding principles for the rest of the thesis. Violin luthiers find themselves in rich personal and ecological contexts that reinforce the value of subtlety and detail. Though we took inspiration from violin lutherie in some respects, the contexts we created in Chapters 5 and 6, which mainly consisted of a light brief about subtle details followed by a largely unstructured activity, were not specific or rich enough. It was only when we designed a much more structured activity in Chapter 8, built around specific design scenarios involving imaginary percussionists and audiences, that the context around subtle and detailed DMI design became palpable. Despite still being ultimately contrived, in both the setting and its severe time constraints, this context was successful in encouraging micro scale DMI design activity.

These outcomes appear to go some way to addressing experimental settings, but what about outside experimental settings? Why were some participants more interested and capable than others, when it came to the particular micro scale details of this apparatus (Chapter 7)? What participants told us about micro scale details in their own practices (Section 8.3.7) provided a window into these issues, which we discussed in terms of motivations and backgrounds (Section 8.4). The *temperament* of each individual with regard to subtlety and detail was a defining high-level factor, which could be characterised in extremes as either being utterly disinterested, or consumed by, as Kay relates:

> *A Venetian glassblower friend of mine once told me that if he could he would eat the molten blobs of glass on the end of his glassblowing pipe! I understand completely what he meant by that: he wanted to become his Art [...] Artists can't not do their Art: this is their basic personality trait.* [148]

Though we did not in this work explore where predispositions towards subtle and detailed design come from, it seems that they might well exist in some form. Another important personally contextual factor, perhaps inseparable from the temperament already described, is that a longitudinal perspective on time is required, for investment in micro scale details to be rewarding, as Spiegel seems to hint at [277]. We suggest that individuals with an appropriate temperament, approach micro scale details with a perspective of *time abundance*, which allows them to commit decades, or even a lifetime, to acquiring embodied expertise. Again, however, where this perspective comes from and what sociocultural factors influence it, is beyond the scope of this work.

From a personal perspective, temperament and time abundance favouring subtle and detailed design, seems to be conducive to contexts where individuals *repeat* the same making processes, and *replicate* the same subtle details. Micro scale details then become visible to the maker through this repetitiveness, with some inevitably due to the nature of embodied experience (Section 2.2.2). We suggest that it is impossible to repeatedly make something without becoming slightly more familiar with the micro scale details of the process and outcomes, due to the way each repetition encodes finer and finer details into the maker. When the next repetition occurs, attention is then free to perceive the sensorimotor differences between what has already been encoded, and what is currently happening. The error between these two is the lower bounds of a particular maker's current perception of the micro scale [46]. Through further repetition, this error is constantly resolving, revealing finer and finer levels of detail to the maker. At a certain point, the maker is rewarded with micro scale wisdom, a technology-agnostic, mindful awareness of subtle and detailed design, which allows them to notice these features in other domains (Section 8.4.2.1).

> *A fish on land still waves its fins, but the results are qualitatively different when the fish is put in its most suitable watery environment. This is what I call 'The power of the context' or 'Point of view is worth 80 IQ points'. Science and engineering themselves are famous examples, but there are even more striking processes within these large disciplines.* [149]

This thesis did not directly examine ecological contexts for subtle and detailed DMI design, yet even through the investigations made in this thesis, it became abundantly clear how important these are. Access to and enculturation into communities of practice (Section 2.2), where apprenticeship allows makers to draw from a heritage of time saving methods (increasing their time abundance), is water to the subtle and detailed designer fish. Within these communities in the DMI design space, musical necessity of some variety is a given (Section 2.3.2), which can be internal to the maker ('I have a musical need as a composer and/or performer'), external to the maker ('They have a musical need...') or both ('We have a musical need...').

An example of ecological context in action, came in Chapter 4, where a violin luthier recalled how they could not see a certain detail even after 25 years of making. For whatever reason, this luthier was unable to generate the perceptual information required for them to create their own predictive model for how to replicate that detail [46]. As a result, their conceptual map of micro scale details (Section 9.2) featured a blind spot. They visited and observed a colleague who was known to be good at executing that particular detail, which provided the right information for the luthier to learn from, which they could then reproduce and refine in their own practice rather quickly. In this case, the ecological context allowed the luthier to overcome this issue, and to become ever more subtle and detailed in their practice.

10.2.1.2 *Material environments and mediums*

As we have just discussed, under certain personal and ecological contexts, subtle and detailed DMI design is primed to take place. While the most obvious next ingredient might be time, as the violin luthiers in Chapter 4 explained to us, time abundance is something craftspeople actively create every day through commodification and specialisation of their environment. They are in fact trying to commit as little time as possible to any given process. A specialised environment is needed to manifest the potential of the contexts they find themselves in, which we therefore discuss here in terms of space, materials and mediums. We did not explore space in this thesis, nevertheless it is worth mentioning for the sake of referring the reader to Victor's *Seeing Spaces* [305], which draws attention to the many ways that space impacts design and making practice. This thesis was more focused on the things of DMI design within that space, that we commonly refer to as tools. However, in this section we discuss the properties of materials [153] and mediums [150], as higher-level ways of thinking about, for a given environment, what tools are possible and who is able to think of and make them.

Throughout this thesis, we have emphasised the need for materials to be open-ended and not coupled to predetermined functionality, and we can now relate this property to the emergent themes described in Chapter 9. In terms of micro scale cartography (Section 9.2), materials need to be open-ended so that practitioners can develop their own conceptual maps with them, rather than have to fight existing ones which do not account for every possible context. In terms of micro scale metrology (Section 9.3), materials similarly need to be open-ended to allow for the designer's evaluation of measurands to be entangled with intrinsic, embodied factors and extrinsic, ecological factors. And in terms of micro scale algorithmic pattern (Section 9.4), designers need open-ended materials so that they can freely develop and project their own patterns onto or with them.

Other material properties we have emphasised in this thesis are their suitability for hands-on manipulation, their agility within particular making processes, and their ability to commodify specialisation in order to increase time abundance (Section 10.2.1.1). Compare the 'sculpt' that represented each measurand, in the sculpting apparatus described in Chapter 7, with a violin luthier using a small hammer to query a violin plate. Our apparatus is inferior, both in terms of the speed of comparisons possible, and because with our apparatus, the system and not the maker receives the physical information from the material. In contrast, a violin luthier with a hammer becomes a high-fidelity and high-speed embodied metrological instrument. They can then devise a systematic methodology (Section 9.4) that accounts for the metrological affordances and constraints of their body, optimised around inputting the highest fidelity, most rapid, most repeatable sensory stimulus. In this case, the hammer vibrates the hand, arm and body and ear drum, and has a precise striking point which can be controlled and varied. The hammer sends a noise impulse through the material which the luthier's brain can decompose into a frequency response to pick out specific frequencies, as our apparatus did, but at a perceptually instantaneous or 'live' rate [282]. The time abundance this creates (Section 10.2.1.1), allows them to create detailed conceptual maps (Section 9.2) of the vibrational behaviour of violin plates. Different sizes and weights of hammers can easily be created, in an improvisatory manner using open-ended materials, which commodifies specialisation for the maker (Section 9.3.3), closing another feedback loop in the making process.

Contemporary 'digital' technology [193] presents difficulties for achieving the same open-endedness, time abundance and moldability described above. The effort to overcome these difficulties is described by researchers like Kay and Goldberg [147, 150], and Victor [306], as being about developing not tools or even toolkits, but thought mediums, as Kay implores:

> *The real printing revolution was a qualitative change in thought and argument that lagged the hardware inventions by almost two centuries. The special quality of computers is their ability to rapidly simulate arbitrary descriptions, and the real computer revolution won't happen until children can learn to read, write, argue and think in this powerful new way. We should all try to make this happen much sooner than 200 or even 20 more years!* [149]

In the 'non-boxed' computational medium that Victor is trying to create (Section 2.2.2), the overarching idea is that if you can do something already in the 'real world', such as tap with a hammer, you should be able to do it in the medium as well, with no arbitrary silos or isolation between reality and simulation. This framing almost suggests a cross-over between materials and mediums, for sufficiently open-ended mediums — we could call this a *materium*. Considering what DMI designers really need in the long term, to be encouraged towards and supported in subtle and detailed DMI design processes, we could envisage *digital lutherie instruments* (DLIs). However, a more quixotic framing would be to consider the possibility of *lutherie materiums* that combine the idealised properties of materials and mediums summarised here.

10.2.2 *Modelling micro scale DMI design*

Chapter 9 was our attempt to describe some underlying processes of subtle and detailed DMI design. We suggested that these themes could be useful as starting points for describing micro scale DMI design processes more formally. Models (we do not want to imply a singular 'correct' model) of micro scale DMI design would open the topic up to more detailed study, potentially via existing design studies methods which are already well understood. Developing protocols and methods around such models, could even lead to experimental comparison of micro scale design processes across different contexts, even straying outside the DMI domain itself. In this section, we summarise the main insights and limitations of the work in this thesis, with respect to commencing on such an endeavour.

10.2.2.1 *Insights from this work*

As already mentioned, one of the main insights of this work regarding modelling has been the identification of three possible underlying processes which appear to describe micro scale DMI design well. These are micro scale cartography, metrology and algorithmic pattern (Chapter 9). Starting to identify potentially general *processes* allows researchers to circumvent the critical issue of the non-generalisability of the *content* of micro scale DMI design, which, being necessarily specialised, is esoteric to each instrument and practice. In other words, until now we believe that the incidental aspects of micro scale DMI design, which are of lesser value in scientific publications, have obscured the fundamental aspects of micro scale DMI design, which we hope now have a basis for scientific discussion and investigation.

What enabled us to make these observations in the first place was a different kind of modelling process, that of modelling traditional handcrafting processes in our experimental probes. The general insight that we glean from this is the value of taking something explicit and making it tacit, as a means to experimentally investigate subtle and detailed DMI design, which perhaps might serve other design fields as well. In our case, we took the explicit parameter space of digital resonant filter banks, and designed a tacit and hands-on process around them (Chapter 7). Curiously, most antonyms of the verb *explicate* are negative in connotation — obscure, cloud, complicate, compress, conceal, confuse, hide, lessen, mystify, tangle, obfuscate, etc. — but counterintuitively, we found there is a certain beauty about making something more tacit, for what it can show about tacitness itself.

Another insight from this work has been the validation of constraining macro and meso scale design responses in one hour DMI design activities, to effectively filter those out and foreground micro scale DMI design activity, commodifying the experimental investigation of micro scale DMI design. In addition to this, we believe that another opportunity exists to filter out a large influence on design process data in one hour activities, namely the processes of familiarisation and exploration. Looking across the investigations in this study (and other DMI design studies featuring short activities with unfamiliar probes), each one featured clear design process patterns of familiarisation and exploration, regardless of the predominant scale of detail of the activity. This similarity suggests that there might be a way to abstract out or normalise away these processes, which would again further isolate processes and design moves that are specific to micro scale design, making experimental data more comparable with in-the-wild data, where familiarisation and exploration have already taken place.

10.2.2.2 *Limitations of this work*

In terms of the limitations of this work, we offered a non-exhaustive list of the limitations of the scale-based ontology of DMI design in Appendix A.1, and described some specific limitations of our probes and activity design in Section 8.4.4. Taking a step further back, a clear oversight in our experimental approach was to not consider the impact of social and collaborative settings. The first study (Chapter 5) involved a room full of groups of conference attendees, whereas the second study (Chapter 6) featured single groups at a time, and the final study (Chapter 8) involved individual participants. By the end, the latter configuration seemed to be much better suited for this research. Over time we suspected that verbal communication in group scenarios led away from tacit and embodied processes, and therefore away from micro scale details, especially where no pre-existing tacit knowledge existed shared between participants. As we lack expertise about group dynamics, we cannot be certain in any such claims, but we highly suspect that was the case. This unplanned, but ultimately necessary, methodological variation across the studies leaves counterfactuals open about this work that we cannot at this point answer. For example, if we repeated the study in Chapter 5 with individuals instead of a room full of groups, would the responses have been as macro in scale? Likewise, if we repeated the study in Chapter 8 with a room full of groups, would the responses have remained as micro in scale? In the end however, such hindsight does ignore the benefits of the hard truths we faced earlier on in the process.

Another limitation of this work is that although we just highlighted the benefits of making the explicit tacit, we did not do so in a particularly formal way. In Section 2.2.1 we glanced over Collins' various formalisations of explicit knowledge and explicit processes, which hampered our work in two ways. Firstly, this blunted our conception of the meso scale of the ontology as being predominantly explicit in Section 2.3.3. Secondly, in our probe design processes in Chapter 7, although we were aware of the idea of making explicit things tacit, we were still doing so in a practice-based, tacit way, which limited how analytical we could be with the experimental data that resulted. Addressing these limitations by approaching investigations with specific ideas about tacit-explicit boundaries, and examining specific transformations of affordances and processes from one to the other, we believe would provide more explanatory depth about subtle and detailed DMI design. Finally, despite our data including macro, meso and micro scale activity, we did not develop any means to segment and annotate transitions between them, which would be ideal for modelling purposes.

10.2.3 *Methodological reflections & considerations*

In Chapter 3 we described the methodological approaches taken in this thesis and our reasoning behind them. The practical investigations themselves each had specific methodological needs, challenges and limitations which have been noted throughout. Carrying out this research first involved addressing the lack of prior methodological art described in Section 3.2, and some of our methodological developments are now research contributions all of their own (Section 10.1). Here we return to methodological issues with the benefit of hindsight, drawing attention to the topics of researcher bias, replication, and applying ideas from this thesis in longitudinal and in-the-wild contexts.

First however, we return to the end of Chapter 3, Section 3.5, which discussed the importance of unearthing and addressing biases of all kinds. Although this is agreeable in principle, practice requires constant attention, evaluation and reflection on possible biases. In this work, it turned out that, as aficionados of small details ourselves, my supervisor and I were hampered by our own assumption that people who participated in our research would be as inclined to engage with micro scale DMI design details as we were, without needing much encouragement. This turned out to be completely wrong: when given a choice between macro, meso and micro scale DMI design directions, Chapters 5 & 6 indicated that, at least in the context of a one hour closed activity, the micro scale was the hardest to motivate towards. We partly addressed our error in the final study by interviewing participants after the activity about the role of micro scale details in their practices (Section 8.3.7), which told us almost as much about their responses and our biases, as our study design did. At first, I was surprised to learn that some people have absolutely no creative appetite for micro scale details at all, but later this became a clear, and welcome, indication of a lack of self-awareness on my part. Ironically, the scale-based ontology of DMI design that we proposed in Section 2.3, has been useful to me as a way of thinking that allows me to see my own biases and proclivities regarding each of the scales.

In Section 3.3 we presented a diagram showing iteration between observation and modeling of micro scale DMI design via activities involving DMI design probes. In the previous section (Section 10.2.2) we described how our observations, particularly the themes in Chapter 9, could become the basis for an initial model of micro scale DMI design. While it could be productive to attempt to formulate and evaluate such a model, a complementary, perhaps more cautious next step would be to focus on making replicable observations of micro scale DMI design, using both qualitative and quantitative methods. We do not suggest that researchers should attempt to replicate our work directly, instead we suggest that future work should use ours as a starting point for designing a replicable study observing micro scale DMI design, addressing the limitations we highlighted in Section 10.2.2.2.

An additional methodological issue affecting replication in our work was the presence of the researcher in the activity, which was described as being necessary for methodological and technical reasons in Chapter 3, but nevertheless problematic. With our experience to refer to, future work could obviate both of these needs. In terms of methodology, think aloud methods are ultimately of limited use during micro scale DMI design activity, which is inherently tacit and embodied (Section

2.2). Instead, activity participants could review, narrate and annotate their session videos during the post-activity interview (perhaps even in slow motion), employing what is known as video-cue recall, which has already been used in a augmented DMI evaluation setting [215]. Alternatively, following the suggestions in Table 10.1 regarding rapid systematic exploration of micro scale DMI design, video-cue recall could even be built into the probes themselves, enabling real-time recall and review. This would affect the design process itself perhaps in interesting ways, but it would not guarantee verbal articulation.

Technically, researchers could also reduce the need to teach, assist and support participants during sessions by embedding such resources into the probes and activity environment, which would itself require deeper mastery and pilot testing of the probes. Addressing all of the issues just mentioned would make replicable qualitative observation more feasible. The limitations described in Section 10.2.2.2 also covered quantitive data acquisition from DMI design probes, and if these could be also addressed, then attention could become much more specifically focused on assessing quantitative analytical methods (see Section 2.1.4 for suggestions) validating quantitative interpretations via more robust qualitative observations. Formulating a model of micro scale DMI design based on such data, would likely be more specific and testable as a result, and of course it would be interesting to compare this model with our suggestions in Section 10.2.2.

Future DMI design probes that might be inspired thereafter, could also strive towards DMI design process data production of not only micro scale activity, but also meso and macro scale activity. These could be compared against our scale-based ontology described in Section 2.3, and the outcomes of Chapter 5 & 6 which we described as being predominantly macro and meso respectively. Replicable and streamlined methods for qualitative and quantitative of DMI design processes at all scales could eventually lead to a tighter feedback loop between observation and modeling, enabling more detailed questions to be asked, some of which we explore in Section 10.3.

Regarding longitudinal and in-the-wild contexts, Section 3.3 contrasted the pros and cons of these approaches with short, closed activities, emphasising that our decision to pursue the latter was motivated by playing a certain long game with regards to the research topic. Naturally however, a full account of subtle and detailed DMI design processes must also involve longitudinal investigation, in particular to understand the evolution of these processes, and the gradual deepening of expertise related to the perception and manipulation of subtle details. Indeed, the synthesis of outcomes in Section 10.2.1.1 hinted towards this, referring to the micro scale wisdom and perspective of time abundance that we perceived in more experienced luthiers. We used DMI design probes that were concerned with ideas of *future* lutheries involving hybrid handcraft, and we designed activity briefs to create contexts that transcended the activity time limits.

What does this work have to offer for researchers wishing to investigate micro scale DMI design processes in the *present* day, longitudinally, with one or more practicing DMI designers? First, we believe the scale-based ontology (Section 2.3) would be useful in such a scenario for isolating what scale a practitioner is working on at any given moment, and we offer ideas and highlight potential issues for adapting it to different DMIs in Appendix A. Designing customised DMI design probes in this scenario may not even be necessary, instead the DMI designer's working environment and DMI prototypes might be considered as the probes, which could be potentially augmented to produce DMI design process data relating to the scale-based ontology. An obvious opportunity to study micro scale DMI design in practice would be to investigate the replication of the exact same DMI by the same practitioner or by a group of practitioners [322]. We propose the following set of investigations (which can be but do not have to be interpreted linearly) as an example of a possible longitudinal study of micro scale DMI design processes, in which DMI design probes are adapted from closed to open contexts:

1. Background interviews with DMI design practitioners about their relationship with detail.
2. Initial observations of DMI design practice, coded in terms of scale of activity.
3. DMI and/or DMI design environment augmentation, in order to produce quantitative data about scale of activity, and subsequent evaluation.
4. Identification and modeling of specific micro scale DMI design processes already present in the practitioner's work for more detailed study.
5. Customised DMI design probe and constrained activity design based on identified process(es) to enable comparative study across practitioners.
6. Pilot testing, participant recruitment, closed study, and analysis of this DMI design probe and activity, evaluating outcomes against any proposed model.
7. Relaxation of the technical and creative constraints of the DMI design probe and activities.
8. In-the-wild deployment of the generalised DMI design probes and activities.
9. Further interpretation and analysis in an open or closed capacity as dictated by the research goals and experimental outcomes.

10.3 FUTURE DIRECTIONS

So far in this chapter we have reviewed the contributions of this thesis and their implications from a DMI design perspective in Section 10.1, and synthesised them into a set of overarching observations, insights, limitations and methodological considerations in Section 10.2. Throughout these sections, specific guidance and recommendations for future research directions have been offered. These are the main entry points for researchers wishing to build upon or take inspiration from any aspect of this thesis, and in this section we provide further sign-posts, supplementations and provocations for future research directions, regarding the domains of DMI design, design studies, and HCI.

10.3.1 *DMI design*

In Section 10.1.5 we presented suggestions regarding future directions for DMI design from three perspectives - practitioners, technologists and researchers - across the themes of motivation and backgrounds (Table 10.1), and cartography, metrology and algorithmic pattern (Table 10.2). In this section we provide slightly more elaborated summaries of some of the possible directions for future DMI design research based on the outcomes of this research. We do so in relation to the scale-based ontology introduced in Section 2.3, identifying future directions *within* each of the three scales of the ontology (Section 10.3.1.1), *across* all of the three scales (Section 10.3.1.2), and *outside* of the ontology altogether (Section 10.3.1.3). In each case, we focus mainly on the micro scale, since that is the main focus of this work, and because, as we originally posited in Section 2.2 we believe a probably majority of existing research in DMI already focuses on the meso and macro scales.

10.3.1.1 *Within each ontological scale*

Within the micro scale, Tables 10.1 & 10.2 make a number of suggestions for future research. In addition, Section 10.2.3 identifies a number of methodological developments that future research would need to address in order to strengthen the robustness of studies investigating micro scale DMI design, which would ideally lead to replicable outcomes across the literature. Were replicability of outcomes to be achieved, what other kinds of questions might become much more tractable and therefore tantilising to researchers?

Perhaps one of the most interesting questions that such a situation would lend itself to, is the question of what actually distinguishes experienced luthiers from beginners or students? There is a large amount of precedent for making such comparisons in design studies - see [11, 146, 275] for examples across three decades (90's, 00's, 10's).

We argued for the existence of micro scale wisdom in Section 8.4.2.1), but what does this actually consist of, how is it acquired, and under what conditions is it transferred (Section 2.2.1) between practitioners and across DMIs? Although some such wisdom is obviously extant in the NIME community, probably the majority of it exists in professional, industrial and commercial contexts, which is difficult for researchers to gain access to due to intellectual property leakage issues. This thesis provides a means to elide this issue; designing unfamiliar DMI design probes and activities to study this topic would enable access to non-academic experts without compromising their employer's secrets. Revealing this expertise for all to see could be hugely beneficial for the research community, and could go on to inspire new approaches to DMI design pedagogy and apprenticeship, as well as DMI evaluation methods.

Regarding the meso scale, in Section 2.3.3 we argued that many existing DMI design tools primarily emphasise the meso scale by turning macro and micro scale decisions into abstractions that hide them from so-called users. This is admittedly quite a broad brush with which to paint so many inventions in our field, which leaves the opportunity of seeking nuance within our slightly provocative suggestion up to future research. How meso-focused is a particular DMI design tool? When it comes to so-called high and low level programming languages, environments and systems, how do their affordances and their impacts compare within the meso scale? What about environments which claim to make all levels of abstraction available (we argued Smalltalk and its descendants might be such environments) - do these abstraction levels correlate with macro and micro scales, or do they merely broaden meso scale affordances? Do different programming paradigms impact the scale of DMI design activity differently? Given a DMI programming language creation tool like Sema [24], do DMI designers create languages which also converge around the meso scale, or not? Conversely, what would programming experiences eschewing the tendency towards the meso scale look and feel like?

For more inspiration regarding future directions directly relating to the meso and macro scales, see Sections 5.5 & 6.4 respectively.

10.3.1.2 *Across the ontological scales*

This section considers research directions spanning across the micro, meso and macro scales. In Section 10.2.3 we elucidated methodological improvements upon this thesis, that would hopefully enable the fruitful application of more robust and sophisticated qualitative and quantitative analysis methods to DMI design process data. An obvious research direction from that point onwards would be to assess DMI design probes and activities that are designed to facilitate practice at all scales. Such research could ask, what scales do DMI designers spend their time at, how do they transition from scale to scale, and how would a heatmap of scale-based DMI design activity relate to design decisions, and other higher level concerns regarding DMIs? Addressing these questions would again necessitate more sophisticated methods for coding DMI design process data, to ensure that macro-meso and meso-micro scale boundaries are coded coherently.

In terms of breadth versus depth of future research across the scales, studies could begin in a top-down manner, as suggested above, by looking at all scales simultaneously, then later look at only two scales, then within each scale as in Section 10.3.1.1, and later still looking at scale boundaries. We described the macro-meso and meso-micro scale boundaries as potentially fuzzy in Section 2.3.1. Should future research attempt to make them clearer, or would any attempts lead indireclty to culturally subjective boundary definitions? Regarding the macro-meso boundary, how do meso scale tool designers decide what macro decisions to make, and how do these decisions impact DMI design process, practice and culture? Conversely, how are the users of such tools macro-constrained by meso scale tools? Can DMI design methods be conceived to make these often opaque constraints visible? Regarding the meso-micro boundary, what DMI design probes can be created which facilitate more detailed study of this space? Suggestions for such probes might lie in fringe venues like the Hybrid Live Coding Interfaces (HLCI) workshop [1], in craft HCI [85], and in spaces investigating algorithmic pattern [204].

The studies in this thesis were influenced by considerations for what future lutherie might look like taking inspiration from handcraft (Section 3.2), and in Section 10.3.1 we have mainly explored future research directions relating to contemporary DMI design practice. This begs the question of how the scale-based ontology might be applied to DMIs, DMI design literature, and indeed non-digital musical instruments and writings of the past. We applied the ontology to a subset of the NIME literature in Section 2.3, but what would a detailed NIME-ological study that tags all NIME literature based on the ontology reveal, and would any of our positions actually hold? Relatedly, what would a survey of practicing DMI designers in the NIME community reveal about their aesthetic interests with regard to the three scales, and subtlety and detail in particular? The ontology, and all of the associated concerns around it that we have discussed in this thesis, could equally be explored in organological contexts, to describe for example what Magnusson refers to, after Simondon, as the concretisation of musical instruments over time [174]. Other instrument making cultures and movements could be studied using this approach, such as Bart Hopkin's Experimental Musical Instruments magazine collection [2], the Guthman competition (which is arguably subtly different from

1 https://hybrid-livecode.pubpub.org
2 https://barthopkin.com/experimental-musical-instruments-back-issues/

NIME)[3], and to commercial musical instruments. In Chapter 4 we used violin lutherie as an inspiration for investigating the micro scale, but what about traditional and heritage instrument making cultures that do not emphasise micro scale variation in the same way?

Finally, what would the possible implications be for DMI design practitioners, should any of the questions posited in this section be addressed by future research? We cannot predict all of these, instead we return to some of the ideas mentioned in Section 10.2.3, regarding DMI design probes which feature rapid systematic exploration affordances, automatically produce quantitative design process data, and enable real-time video-cue recall methods. Combining this scenario with the suggestions for DMI design practitioners in Tables 10.1 & 10.2 to reflect on subtlety and detail in their own processes and practices, suggests an avenue to translate tools originally intended for DMI design research into practical design-aids. While doing DMI design, a practitioner might be accompanied by a constant stream of design process data being filtered and displayed back to them, encouraging design metacongition about their direction of travel - macro, meso or micro - relative to their goals and intentions, completely in-situ. Given enough data, it is conceivable to imagine human-machine co-creation of real-time linkographic analyses [95].

10.3.1.3 *Outside of the scale-based ontology context*

When all you have is a scale-based ontology of DMI design, everything has to fit into macro, meso or micro scales, and anything that doesn't may well be missed. As we mentioned in Section 2.3, all models are wrong and we do not wish to encourage a monocular perspective on DMI design. We further emphasised in Section 3.5 that our ontology undoubtedly embeds within it cultural and epistemological frameworks which it should not be dissociated from. In addition, in Appendix A, we demonstrated how attempting to apply the scale-based ontology of DMI design in a wider variety of DMI design contexts than we did in our investigations, led to interesting problems and possiblities, that future researchers may find intruiging to delve into. What does the scale-based ontology not encapsulate about micro scale DMI design? What other ontologies or frameworks are needed to problematise our definitions given in Section 2.1, and diversify the ways of making subtle and detailed DMI design visible? What non-ontological and/or non-representational approaches are there to studying subtle and detailed DMI design? Subtle and detailed DMI design being so closely tied to craft usefully implicates vital characteristics of craft, that it is as Kettley describes values-based and undefinable (Section 2.2.4).

3 https://guthman.gatech.edu/

10.3.2 *Design studies*

Sections 10.2.3 and 10.3.1 described the ways that design studies could positively influence future DMI design research. Likewise, we see possibilities for translating our work in the other direction, and experimentally applying it in design studies. Investigations in the field of design studies often focus on design engineering where requirements are eventually concrete and explicable. In this work we have demonstrated an approach to looking at design processes in much more underspecified and open-ended scenarios that are closer to the arts and humanities in nature than engineering, but nevertheless feature design as one of the central practices of concern. Practicing design engineers might learn from our work how artistically-leaning design practices embrace underspecification, and based on our DMI design probes, design studies researchers might find ways to design better tools to support the early stages of design processes which are underspecified even in engineering contexts.

A key question regarding the applicability of our work to design studies rests in the question of whether the scale-based ontology of DMI design can be generalised outside of the DMI design domain. Appendix A goes some way to further connecting the ontology to design studies, but does not go as far as to formalise any kind of generalisation. There are clearly similarities and differences, and an exacting investigation identifying what these are would be the next step towards evaluating any possibility of generalisation. Such an exacting account would also depend on the methodological considerations described in Section 10.2.3. Following this, the natural next step would be to attempt to apply the scale based ontology in a DMI design context that does not concern DMIs.

In the scenario where the scale-based ontology could be agreeably generalised to design more broadly, a number of fascinating research directions would open up. From my perspective, one of the most interesting possibilities would be to apply the scale-based ontology in a protocol analysis of design activity, and apply the most commonly used and empirically validated protocols in design studies. While I do not possess the expertise to offer a categorical list of such protocols, I was indirectly influenced during this research by Gero's function-behaviour-structure (FBS) protocol, which has been used in many studies over a number of decades, extended in different ways [92], and critiqued by other researchers [65]. Were a design data set to be coded with both the scale-based ontology, and FBS, what might be revealed about subtle and detailed design and its relationship to the structure, function and behaviour (Gero terms these the three main *issues* of design) of design artefacts? A simple correlation between for example the macro scale and function, the meso scale and structure, and the micro scale and behaviour, seems naively logical but probably vastly over simplifies things, but how so?

Finally, what is the relationship between design and craft? When the design ends, the craft begins according to the violin luthiers we interviewed for Chapter 4, implying some kind of hand-off or transition. Design studies offers means of diagramming design through models of design, but Kettley has argued that no such diagram of craft exists [153]. Does the scale-based ontology, with its emphasis on the micro scale as a domain of embodiment and tacit knowledge, hint towards a bridging of sorts between design and craft? Design studies also offers a means of discretising design into design moves (collections of actions that advance the design state space), which inspired the DMI design probes in this thesis (Section 2.1.4). But how does one truly represent the craft process either discretely or continuously, and what picture would such representations paint of the relationship between supposed craft moves and design moves? Would these representations enable a similar methodology of iteration between observation and modeling that we employed (Section 3.3), leading to diagrams of models of craft? Hypothetically, a linkographic analysis of design-craft border transitions might suggest ways of addressing these questions, or at least fail to do so in interesting ways.

10.3.3 *Human-computer interaction*

While HCI is far too broad to review every possible adaptation of our work, we believe that the critique of DMI design tools and methods that we provided in Section 2.3 would at least be relevant to HCI subfields or disciplines such as interaction design and tangible interfaces. HCI researchers might ask themselves in this regard, what design tools, methods and studies focus too heavily on the macro and meso scales, and miss the opportunities that we have identified as lying in wait at the micro scale? Are there HCI evaluation methods that can capture the micro scale, or do these need to be invented, and could our work provide some clues as to how these should be developed and validated? Similarly, we would like to suggest that in general all of the future directions identified throughout Section 10.3 could equally apply to issues in HCI as in DMI design, although the direct applicability will vary on a case-by-case basis.

Creative AI is one current HCI research area that we would like to draw attention to in terms of the relevance of this thesis, which is a not well defined area connected to domains such as computational creativity, interactive machine learning, explainable and interpretable AI, and other forms of human-AI co-creativity and collaboration. From the perspective of this thesis, the most important way to characterise and compare creative AI systems, and all systems describing themselves as AI, is in how they fail to recognise, capture, simulate, imitate, co-create, generate, respect and honour important nuances and subtle details, from the perspectives of their human interlocutors. In other words, AI systems are their edge cases, in the same way that musical instruments become their micro scale details. What does this imply? We suggest that creative AI interface designers consider that their interfaces should focus on enabling micro scale handcraft on the part of human collaborators, for all of the reasons which we have argued for in this thesis. Such interfaces, in engaging with the deep wells of tacit and embodied knowledge, in my opinion stand a markedly better chance of addressing the apparently infinite surface area of AI edge cases. As one violin luthier put it in Section 4.3.2, "I can't stand in front of thousands of doors knowing that if I open a door it might be the wrong one [...] I'm relying on my feeling, what I feel when I make". What if interfaces could harness this feeling to good effect, and turn machine learning modeling literally into a form of physical sculpture?

10.4 CLOSING REMARKS

This thesis has attemped to shed some light on subtle and detailed DMI design processes, which at the beginning of Chapter 1 we described as being usually invisible. We have strived to understand the becoming of DMIs and their ergodynamics [174], so that we can support DMI designers with more appropriate tools, and liberate their bodies from keyboards, computer mice and screens in the process. Specifically, our contribution has been to take a subject which was previously only possible to study through longitudinal and in-the-wild approaches, and make certain aspects of it amenable to study in a controlled setting within a short duration of activity.

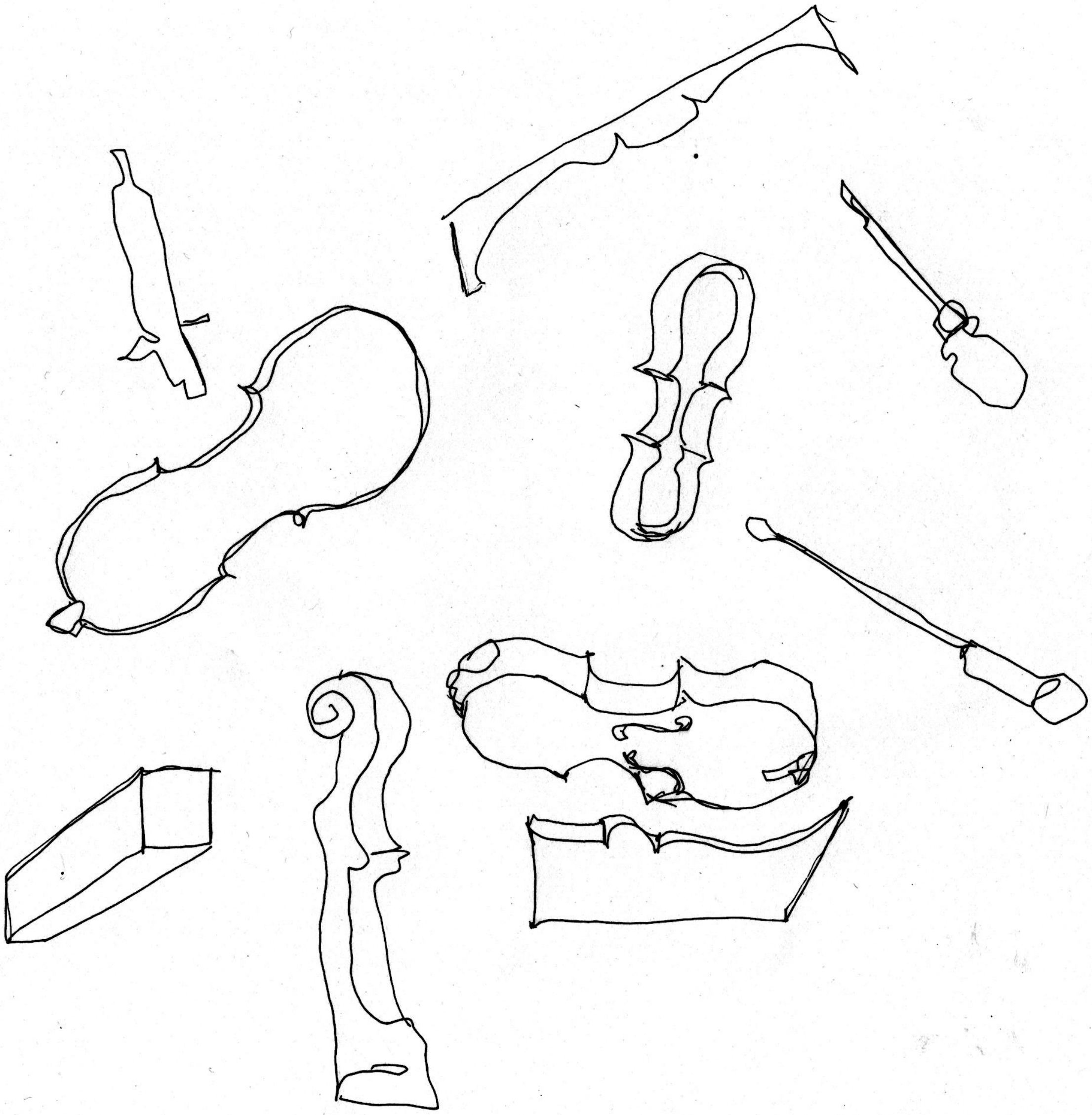
This thesis was originally borne out of a personal frustration with digital technologies for musical instrument creation, and a sense that improving digital luthiers' tool belts would lead fairly straightforwardly to new musical instruments that were previously unthinkable (Section 1.1). What began as an effort to define that frustration in a researchable way, ended up becoming an ontological interpretation of the field of DMI design, an object requiring its own dedicated study. Not only articulating, but practically investigating subtle and detailed DMI design has turned out to be a highly exploratory endeavour, where almost nothing made sense until it finally did, long after the final study responses had been collected. We see this as a humble first step towards much greater possibilities, and we hope those reading will be inspired to take one of the next steps we have suggested throughout this final chapter.

Subtlety and detail in DMI design remains after this thesis an under-researched topic, that deserves more attention, and hopefully anyone coming across this work will agree. In this work, we were able to separate subtle and detailed DMI design from things that it is not, and have made some foundational observations on what processes might underlie it. Compared with the mountains of tacit knowledge that DMI design practitioners, and luthiers of all kinds, possess in abundance and make use of casually and effortlessly, there is still a long way to go, with many more fascinating discoveries to be made. I find it even more staggering now what musical instrument makers are able to achieve, than when I began.

As Bill Buxton said, creating tools for artists is "hardest (and most important), but if you can nail it, then everything else is easy" [35]. Rather than being a boast, I think Buxton here is referring to how incredible the realisation of human potential is in artists, and that anything that approaches satisfying their needs, holds great promise, intrigue and value for the rest of humanity. Hopefully this thesis has in some way highlighted how interesting it could be if we focus our efforts on understanding and nurturing this potential, to its subtlest and most detailed extents.

Part IV

APPENDIX



A BACKGROUND APPENDICES

Appendices for Chapter 2.

A.1 FURTHER DISCUSSION OF THE SCALE-BASED ONTOLOGY

In Section 2.3, we provided an overview of the three scales and presented them in relative isolation, and although we provided some examples, these were mostly convenient in some way, and not at all representative of the diversity of DMI design practices. In this section, we first clarify possible misinterpretations accrued thus far, before discussing the three scales together in more complex scenarios, framed thematically from the perspectives of space and time. Considering the scales in space, we address decoupled DMIs, for example controllers that produce no sound, along with assemblages, networked and distributed DMIs, and other emergent DMI practices. Then, considering the scales in time, we address the curious ontological states inhabited by prototypes, and the non-linearities inherent in design processes, which together encourage relating the three scales heterarchically.

The overview in Section 2.3.1 offered clarifications that were necessary before discussing each scale, and we can supplement these now that the three scales have been individually discussed. Firstly, it is not our intention to imply that tacit expertise and embodied craft processes exclusively apply to the micro scale, and that the meso and macro scales somehow involve only explicit knowledges and disembodied processes. As Section 2.2 described, all knowledge is tacit and some just happens to also be explicit, embodied design methods target all stages and levels of design [2, 160–162, 186, 189, 295], and craft practice we view ultimately as broad and subjective. Secondly, we do not seek to imply that DMI designers do not dedicate time and effort to realising micro scale details, rather our concern is that this important aspect of practice is essentially invisible, not well represented in the literature, undervalued in general, and can be much better supported by DMI design tools. Thirdly, we critiqued the way that DMI design tools and approaches that we feel to be meso scale in nature, mediate the micro and macro scales in unsupportive ways. We do not however advocate that the goal for design tools is instead to be mediation-less, which would be fallacious and technosolutionist [164]. Blind mediation is at best fortuitous and at worst dangerous; ideally, tool designers should understand how their tools mediate, such that they can do so intentionally and respectfully. And finally, though we conceive of this scale as having infinite detail and abstraction at either ends, it isn't our goal to encompass instrumental identity, or instrumentality [290], which after Kettley we see as being more powerful when treated as undecidable [153].

A.1.1 *Scales in space*

There are over 100 NIME papers, roughly 5% of the total literature, that feature controller in the title, and probably many more about controllers which do not. While acoustic and electronic musical instruments have demonstrated decoupled mechanisms for centuries [174], decoupling is almost an overt idiomatic feature of many DMIs, since current technology affords it so arbitrarily and discretely. The separation of source from sound has many benefits, among them pedagogical [237] and aesthetic [190], but also gives rise to the 'problem' of mapping, as suddenly DMI design decisions have to be made where no choice previously existed. Entire practices are built around this notion, most visibly modular synthesis [82], and in the NIME community gestural music controllers have become a specialised sub-field [36, 126, 206, 280, 308]. These cases might be challenging enough for the scale-based ontology, but DMI practices extend even further beyond these.

If a controller is considered in isolation, is it merely a meso scale device, since it cannot be used to produce any music, and only becomes part of a macro when paired with a sound source? Controllers clearly have their own roles, forms and functions, which could be compared across, which would appear to contradict this, but both positions seem to be truthful. What is the ontological status of DMI practices centred around assemblages, which are always evolving and never the same [30, 241, 283, 324]? How would one characterise the scales of networked and distributed DMIs [37, 158, 207]? Are the instruments created with meta instruments meso scale [29, 79, 81]? Is it possible to interpret composed instruments [269] from both the perspective of Jordà's scales of musical diversity (Section 2.1.3), and the scale-based ontology of DMIs? What of instruments as scores [286, 288], and live coding as both instrument [258] and score [169]? In all of these cases, asking what the identifiable macro, meso or micro scale is becomes quite difficult, and in some cases the ontology does not appear to necessarily provide additional clarity or insight. However, as soon as two very similar artefacts are considered, again subtle details start to reveal themselves. Sensor calibration and processing in controllers, latency and jitter characteristics in networked music systems, and domain-specific syntax in live coding, are all subtle yet important. Ultimately this thesis does not deal with any of these cases, but this does not necessarily mean that the ontology provides no value to them, where subtlety and detail is concerned.

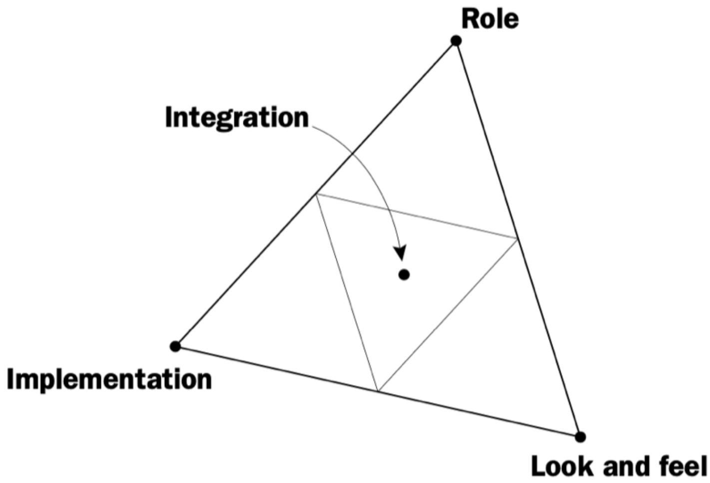


Figure A.1: "Four principal categories of prototypes" described by Houde and Hill [112].

Even considering more familiar instruments, the applicability of the scale-based ontology can be stretched. The guitar is perhaps the instrument whose decoupling and reconfiguration has been explored the most in recent cultural memory. In the talk accompanying their paper *When is a Guitar not a Guitar?* [107], Harrison et al. begin posing this question by collaging performances including GuitarHero, air guitar, keytar, and a Seaboard [157] controlling an emulated guitar. At what point does guitar-ness become so unstable as to cause it to have an identity crisis and collapse? Clearly the answers are subjective and contextually situated, and acknowledging this is important for DMI designers and researchers, especially so, Harrison argues, in the case of Accessible DMIs (ADMIs) [106]. From an ontological perspective, at what scales are these guitar permutations comparable? Does the macro scale bending and twisting of the guitar only serve to extend the commonly accepted notion of what it can be? How would one systematically compare the micro scale differences between two air guitars, as competition judges and competitors presumably do to a degree? These are not necessarily questions we hold or want to propose answers to at this stage of the research, but we believe they are important ultimately in coming to terms with the advantages and disadvantages of this approach.

A.1.2 *Scales in time*

Prototypes often isolate specific design issues and demarcate phases, as Houde and Hill (Figure A.1) describe:

> *These three prototypes were developed almost in parallel. They were built by different design team members during the early stages of the project. No single prototype could have represented the design of the future artifact at that time.*

> *The evolving design was too fuzzy – existing mainly as a shared concept in the minds of the designers. There were also too many open and interdependent questions in every design dimension: role, look and feel, implementation. Making separate prototypes enabled specific design questions to be addressed with as much clarity as possible. The solutions found became inputs to an integrated design.* [112]

Though DMI designers are perhaps more often designing solo compared to product design teams, DMI designers are known to use similar iterative prototyping methods [84, 291, 298], which stretches the scale-based ontology in interesting ways. The separation of concerns that designers employ, could be considered as a temporal equivalent of the decoupling described in Section A.1.1, in terms of stages of the design process. Considering the visualisation of Houde and Hill's model of the space of prototypes in Figure A.1, a simple analogy could be made between their *Role*, *Implementation* and *Look and feel* prototypes, and the ontology's macro, meso and micro scales respectively.

However, another analogy would be to consider the areas around the four points as areas of high subtlety and detail, and the areas furthest from the points as areas of low subtlety and detail; a prototype which only explores implementation, will necessarily do so in more detail than one exploring both implementation and role. Designers prototype separate issues in parallel so that they can resolve designs in more detail, faster, and so that they can begin to acquire tacit knowledge about the micro scale details of their designs, long before the final design is ready. This perspective would perhaps be more flexible for comparing two prototypes of the same kind, for example two implementation prototypes might have comparable micro scale details. In contrast, an *Integrated* prototype's macro, meso and micro scales might be more suitably analogised to role, implementation and look and feel. Indeed, Houde and Hill highlight that prototypes say different things to different design stakeholders, at different stages of the design process, and this ambiguity can be a source of many headaches.

Plotting the level of detail of a design in an idealised process, in terms of the prototypes produced, might from a distance appear to show a smoothed line from macro to micro over time. However, unsmoothing and zooming in on this line would probably reveal noisy oscillations between different levels of detail, which altogether would tell a different story. In reality, there is no correct level of detail for the first prototype in a design process, and there are also no rules about how detailed a given prototype should be at a given stage in a design process; these parameters are determined by the designer's needs, and are relative to the shape of the design space, at any given point in the process. Stepping outside an idealised process, the idea of a line from macro to micro is also probably only truly applicable to designs done 'from scratch', and again in reality designs can start and end anywhere in terms of scale, and don't necessarily end at all.

So far we have argued that for DMIs to be comparable at the meso or micro scales, they must be identical at the scales above them, in short suggesting a hierarchical or transitive property of the ontology, for example, altering the meso scale of a DMI will necessarily alter its micro scale, but not necessarily its macro scale. Additionally, we have argued that changing one scale alters any scales below it, as in where keytars and air guitars might have macro scale guitar-like properties, but completely different micro scale details. We have also argued that micro scale details are unique to a given DMI and are non-transferable to other DMIs with different macro or meso scale domains. These arguments might be true in the large (or perhaps more acutely, in a normative sense), but really only suffice as general rules of thumb, and in practice they can easily be contradicted.

Magnusson introduces the terms ergomimesis and ergophor [172–174], to describe the migratory patterns of musical instruments across cultures over time [175]. These terms usefully highlight that at an ecological level, instruments with differing macro scales do borrow or imitate meso and micro scale details from each other, and to say that these details suddenly become incomparable is too extreme. Furthermore, instrument manufacturers who specialise across multiple instruments presumably share their trade secrets among their products constantly. Likewise, considering the radical alteration of an instrument's micro scale details, at some point these changes will inevitably propagate into meso or macro scale changes, particularly where the levels are tightly coupled (where an instrument's role or form might be more or less inseparable from its most subtle features). Engelbart neatly encapsulates this through his concept of a capability hierarchy:

> *The important thing to appreciate here is that a direct new innovation in one particular capability can have far-reaching effects throughout the rest of your capability hierarchy. A change can propagate up through the capability hierarchy; higher-order capabilities that can utilize the initially changed capability can now reorganize to take special advantage of this change and of the intermediate higher-capability changes. A change can propagate down through the hierarchy as a result of new capabilities at the high level and modification possibilities latent in lower levels. These latent capabilities may previously have been unusable in the hierarchy and become usable because of the new capability at the higher level.* [74]

Similarly, Gero's function-behaviour-structure ontology of design and design processes [92] also accommodates for heterarchical changes to the design state space, through processes he describes as reformulations, in which any aspect of the design is free to trigger a transformation of the other:

1. Reformulation type 1 addresses changes in the design state space in terms of structure variables or ranges of values for them if the actual behaviour is evaluated to be unsatisfactory.

2. Reformulation type 2 addresses changes in the design state space in terms of behaviour variables or ranges of values for them if the actual behaviour is evaluated to be unsatisfactory.

3. Reformulation type 3 addresses changes in the design state space in terms of function variables or ranges of values for them if the actual behaviour is evaluated to be unsatisfactory.

Even though the scale-based ontology we have proposed is in essence hierarchical, changes to the hierarchy are in practice free to occur in heterarchical ways.

B

INTERVIEW APPENDICES

Appendices for Chapter 4. Note that the following questions were used as prompts by the researcher and not posed to participants verbatim, or necessarily in the sequence they appear here. Interview structure:

1. Background in lutherie and music
2. An instrument they are currently working on
3. Violin lutherie more broadly
4. Their thoughts about manufactured violins
5. Digital technology in music and violin lutherie
6. Any other topics

B.1 BACKGROUND

- Is luthier your primary occupation?
- How long have you been a luthier?
- How did you decide to become a luthier?
- How did you learn?
- Did you attend any courses?
- How many hours do you spend on average a week?
- What instruments have you made since you started?
- What instruments are you working on now?
- What is your musical background?
- Do you have an overall goal or vision with respect to making instruments?

B.2 INSTRUMENT

- Tell me about this instrument
- Was it a commission? If so, who for? What was the brief?
- How did you conceive of it? Did you have a vision for it? Did you "hear" it?
- Did you use reference designs? Which ones if so, and did you have direct access to them?

- Describe the development of this instrument
- Describe a difficult decision you had to make whilst developing this instrument
- Describe some important details about this instrument and how you approached them
- Do you try to validate your work as you go?
- How did it/will it become "finished"?
- How many hours did/will it take to make/finish?
- What do you like about it, and is there anything you don't like about it?
- Were there any particular lessons learned from this process?

B.3 LUTHERIE

- What is the hardest part of learning to make instruments?
- What is the hardest part of making an instrument?
- What technical skills are most important for a luthier?
- What non-technical skills are most important for a luthier?
- What would you say you care about the most when making an instrument?
- How important is it to play your own designs? How well do you need to play them?
- How important is it to get feedback on your designs? Where do you get feedback from?
- What is a "master luthier"?
- Describe the perfect violin
- What do the best players know about lutherie?
- What do even the best players not know about lutherie?

B.4 VIOLIN MANUFACTURE

- What are your future plans as a luthier?
- Do you think it would be possible to mass manufacture violins? What would be the challenges?
- What do you think of carbon fibre violins and bows?
- Are there any other noteworthy material innovations happening in violin making?

B.5 DIGITAL TECHNOLOGY

- Do you see any role for digital or electronic technology in the violin world?
- Are you interested in digital musical instruments?
- Are you familiar with any digital musical instruments in particular?
- How would you describe digital musical instruments generally?
- How would you compare what you do to digital musical instrument design?

B.6 ANY OTHER TOPICS

- Are there any other comments you would like to make about lutherie?

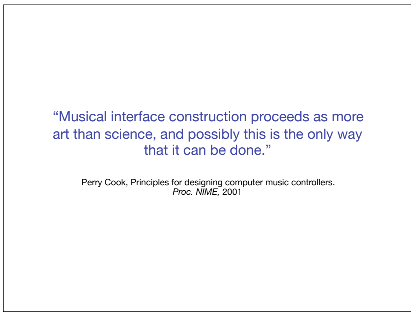
C MACRO SCALE APPENDICES

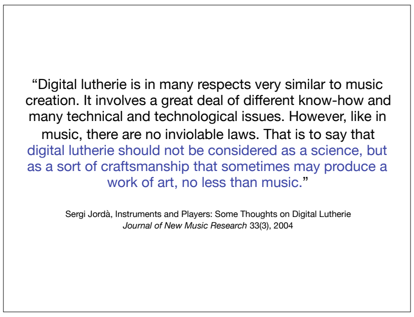
Appendices for Chapter 5.

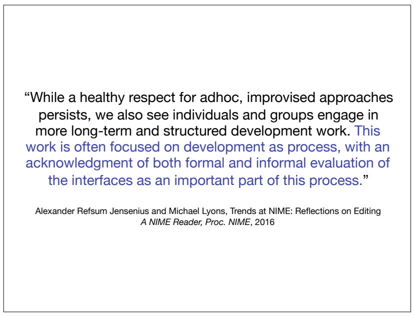
C.1 CALL FOR PARTICIPATION

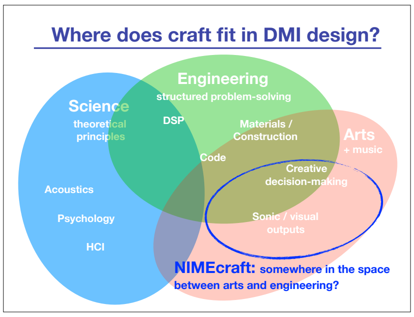
Dear all,
As part of the New Interfaces for Musical Expression (NIME 2017) conference, we would like to invite you to a hands-on instrument design workshop entitled "NIMEcraft: Exploring the Subtleties of Digital Lutherie". This half-day workshop runs in the morning of 15 May 2017.
The goal of this workshop is to explore and develop the craft of digital musical instrument creation as distinct from its science and engineering aspects. In particular, we seek to identify aspects of the DMI creation and refinement process that go beyond what is published in typical conference and journal papers. These aspects might include subjective or personal aspects of a designer's craft, subtle differences between otherwise identical instruments, or the ways in which craft knowledge can be shared and disseminated.
Further context on these ideas can be found at:
https://github.com/AugmentedInstrumentsLab/NIMEcraftWorkshop
The workshop will feature open discussion plus a hands-on instrument design activity, in which participants will adjust and improve the subtle details of an existing instrument design. Instruments will be provided, and no programming or circuit-building skills are required.
The workshop is open to conference attendees but attendance may be limited based on the amount of available hardware. No preparation is required to attend, but if you are planning to attend, we would encourage you to contact us at j.d.k.armitage@qmul.ac.uk so we ensure adequate materials are available.
We look forward to meeting you in Copenhagen.
The NIMEcraft Workshop organisers Andrew McPherson, Jack Armitage, Astrid Bin, Fabio Morreale, Robert Jack and Jacob Harrison
Augmented Instruments Laboratory, Centre for Digital Music, Queen Mary University of London

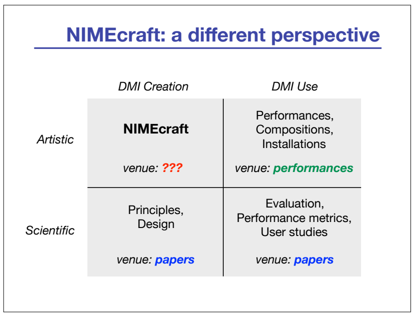
C.2 ACTIVITY PRESENTATION











Unpacking the term *NIMEcraft*

- "Craft" is both a noun and a verb
- Similarly, "NIMEcraft" could describe:
  - The object (aspects of the DMI itself)
  - The activity (how the DMI creator works)

NIMEcraft:

1. The subtle details which distinguish otherwise identical instruments
2. The art and craft of digital lutherie as distinct from its science and engineering aspects
3. .....?

NIME frameworks

	Comparison between performances	*Comparison between instruments*
Macro	macro-diversity (Jorda) ability to support playing in different styles	interactive paradigms e.g. embodied vs. symbolic (Magnusson)
Meso	mid-diversity (Jorda) ability to support playing different pieces	instrument taxonomies hardware, control and mapping strategies (many)
Micro	micro-diversity (Jorda) ability for performances of the same piece to differ	**NIMEcraft**

Applied instrument taxonomies

A. Stradivarius, 'Lipinski' (1715)

- Continuous excitation via stick-slip friction
- 3+ control dimensions in bow, 1+ in left hand
- Monophonic or duophonic
- Continuous pitch, range G3-C8

Stentor student violin (2017)

- Continuous excitation via stick-slip friction
- 3+ control dimensions in bow, 1+ in left hand
- Monophonic or duophonic
- Continuous pitch, range G3-C8

Elements of NIMEcraft

"Beyond the paper..."

- Materials
- Feel: shape, size, weight, texture
- Look: colour, finish
- Response: audio, tactile
- Subtle details of sensor placement and mapping
- Some of these overlap with publishable engineering decisions, but many do not

DMI micro-comparisons

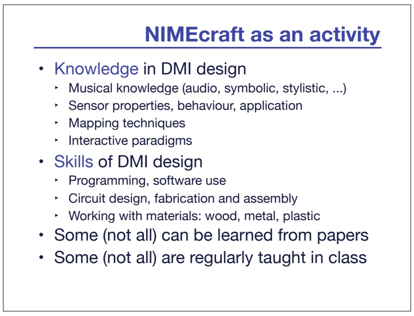
Keyboard action:
Size, feel, weight, sensitivity

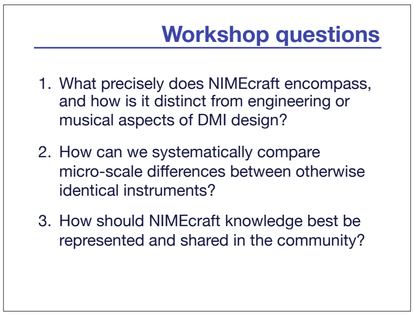
Drum pads:
Size, texture, uniformity, sensitivity

Eurorack module knobs:
Texture, smoothness, resistance

Craft as an activity

- Not the what but the how of design
- Craft knowledge is often *tacit*
  - What you "know but can not tell" (Polanyi 1966)
  - Classic example of riding a bike: eventually you know how, but you don't know why!
  - Relational (weak), somatic (medium), collective (strong) (Collins 2010)
- Tacit and *explicit* craft knowledge interact:
  - "One's ability to articulate an idea always lags behind the understanding of the idea, and the understanding of an idea often lags behind the embodiment in which it is first given life." -Bret Victor
- How to understand the tacit aspects of DMI craft?





C.3 INTERVIEW AND ONLINE SURVEY TOPICS

- How much of your time is spent making instruments?
- How long have you been making instruments for?
- How many instruments have you made? Tell us a little bit about them.
- What ideas or comments stood out for you during the opening presentation and discussion?
- Did you have any initial goals at the start of the crafting activity?

- What was the process like in your group?
- How did the instrument develop?
- What did you think of the results of your crafting?
- Do you think the focus not being on software and electronics influenced the way you worked?
- What did you think of the results of the other groups' crafting?
- Have you had any further reflections about the workshop since it occurred?
- Do you think the workshop will have any influence on your work going forward?
- What do you think the NIME/DMI community can do to improve sharing of craft knowledge?

D MESO SCALE APPENDICES

Appendices for Chapter 6.

D.1 CALL FOR PARTICIPATION

> ***Digital Musical Instrument Design Study***
> *You are invited to join a fun study on digital musical instrument design, run by the Augmented Instruments Lab (http://instrumentslab.org). In the study you will be asked to collaborate in a small group on the design of a digital musical instrument, called the Unfinished Instrument. As its name suggests, the Unfinished Instrument seeks your design intervention to determine how it should play and sound. The design session will last for one hour and you will be compensated £10 for your time. Participants should have experience making or playing digital musical instruments, and some familiarity with Max/MSP, Pure Data, or equivalent sound and music computing environment. Please fill in this form to indicate your availability. Sessions will take place at Queen Mary University of London between Tuesday 9th and Saturday 20th January. If you have any questions please contact Jack Armitage at j.d.k.armitage@qmul.ac.uk.*

D.2 PRE-ACTIVITY SURVEY

"I have experience with the following" (> 5 years, 1-3 years, < 1 year, or No experience):

- Playing digital musical instruments
- Making digital musical instruments
- Max/MSP
- Pure Data
- Other sound computing environment(s)

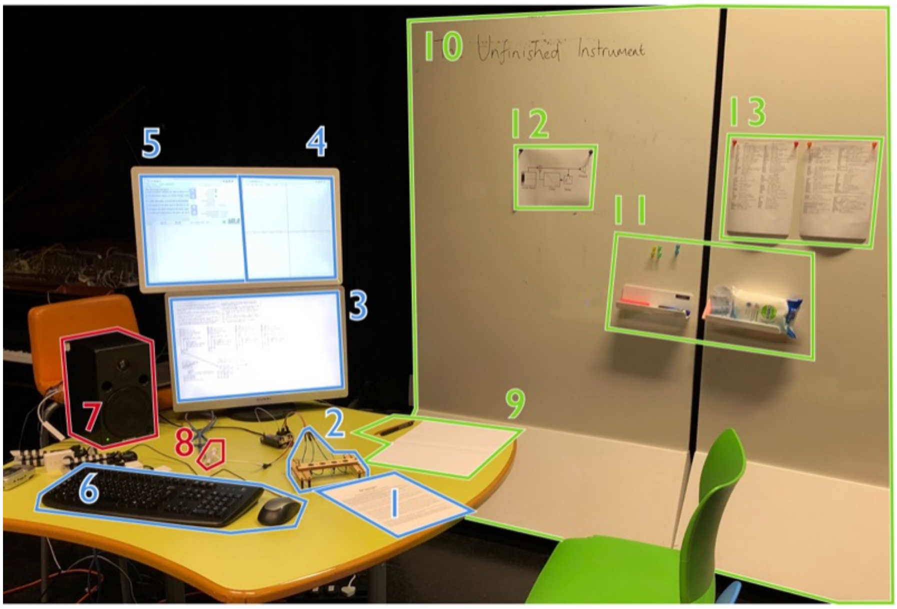


Figure D.1: The study environment, visually annotated.

D.3 ACTIVITY BRIEF

D.3.1 *Crafting environment*

Items numbered in Figure D.1:

1. Consent form and activity brief
2. Unfinished Instrument
3. Pure Data patch
4. Bela IDE and text console
5. Keyboard and mouse
6. Bela Oscilloscope
7. Loudspeaker
8. Headphone multi-splitter
9. Paper, pen, pencil
10. Whiteboard
11. Whiteboard stationery
12. Karplus strong block diagram
13. List of Pure Data objects

D.3.2 *Consent form activity brief*

In this study we are interested in observing cooperative design behaviour in a typical digital musical instrument design scenario. An "Unfinished Instrument" and software for modifying it have been prepared, which the researcher will explain in more detail after you have completed this document. An overview of the procedure is detailed below. Please let the researcher know if you have any questions.

You will be randomly assigned into a group with other participants. You will be introduced by a researcher to a musical instrument, known as the Unfinished Instrument. For 50 minutes, your task with your design partner is to refine the instrument into something more finished; this could mean adding subtlety or nuance to the gestural input or modifying the timbral response. You will use the software Pure Data to refine the instrument, and you will find some helpful suggestions are available in the instrument's Pure Data patch. The computer screen and audio will be recorded, and a camera will record video and audio of your interactions with the instrument. The recordings are for analysis purposes only and under no circumstances will they be shared or published without your explicit consent. A researcher will be on hand throughout the activity to provide technical support and answer any questions about the instrument or the software. ***You are encouraged to discuss your thoughts and observations out loud with your co-designer.*** *After the design activity, you will be asked to complete a final short survey. Remember you may exit the study at any time by letting the researcher know.*

D.3.3 *Pure Data patch*

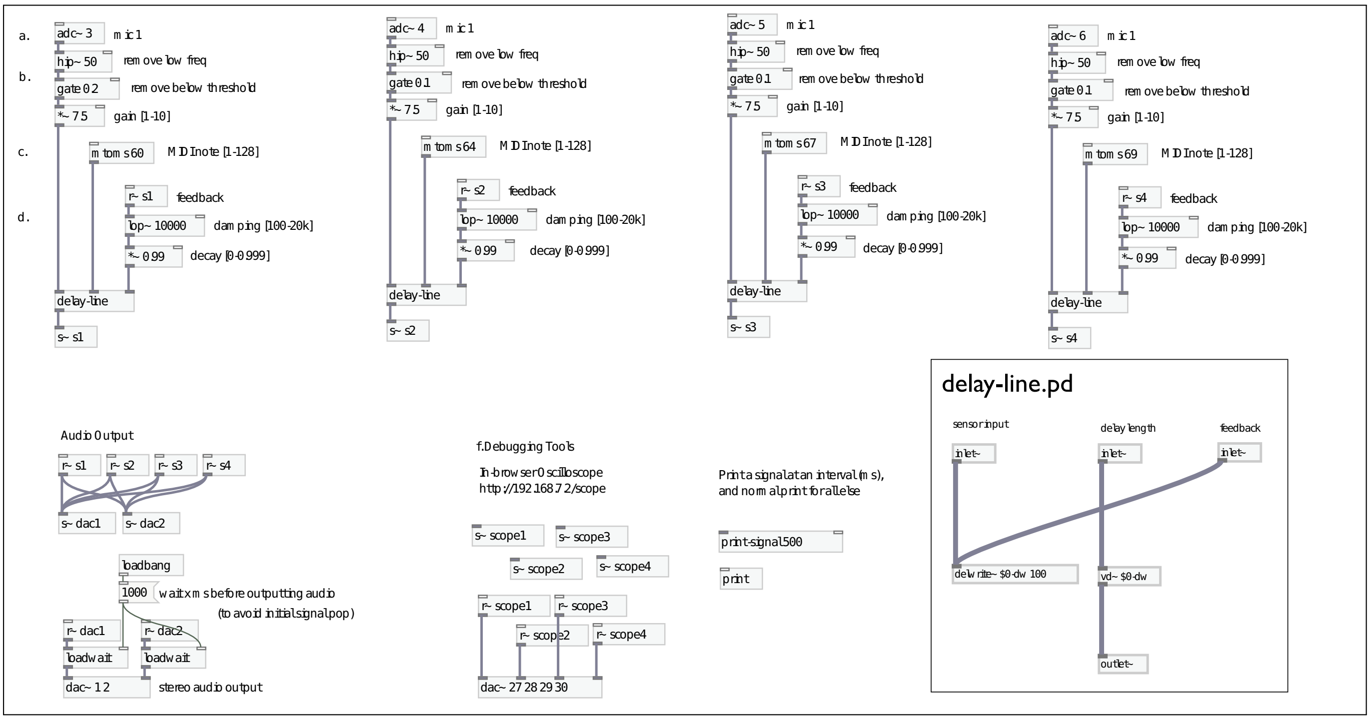


Figure D.2: Pure Data patch for the *Unfinished Instrument*.

D.3.4 *Pure Data patch description*

1. Four microphone capsules are used to excite a simple model of a string using a delay and filtered, decaying feedback
2. The microphone signals are passed through a high pass filter and gate in order to remove the DC component and any consistently present noise
3. A MIDI note number is converted to milliseconds to define the delay time of the delay line, which defines the pitch of the string
4. The output of the delay line is fed back in, after being filtered through a low pass filter, and decayed
5. To update the patch running on the board, save any open patch (it will take a few seconds before you hear any changes)
6. To help with understanding the patch, you can visualise signals in the browser-based oscilloscope, and you can print text and signals to the browser-based terminal (see bottom of patch)
7. The model is similar to a typical Karplus-Strong digital waveguide. For more, see the printed handout or search for "Karplus Strong" in Google

8. Your goal in this task is to 'finish the instrument' by your definition and by any means - there are no other rules!
9. If you have any questions please ask. Thanks and have fun!

Tips

- Remember you can right-click on an object to see it's helper patch
- Browse the 'Help>List of objects...' patch for ideas
- Be careful with gain and feedback parameters to protect your ears!
- If you need more Pure Data help, try the manual at https://Pure Data.info/docs/manuals/pd/

D.4 POST-ACTIVITY SURVEY

- What was your first impression of the Unfinished Instrument?
- How would you describe your goals at the start of the activity?
- What was the process like in your group?
- How did the instrument develop?
- What do you think of the results?
- Do you feel that the workflow affected your process and results?
- What are your general reflections about the activity?

D.5 ANNOTATED PURE DATA PATCHES

See Figures:

- Group 1: Figure .
- Group 2: Figure .
- Group 3: Figure .
- Group 4: Figure .
- Group 5: Figure .

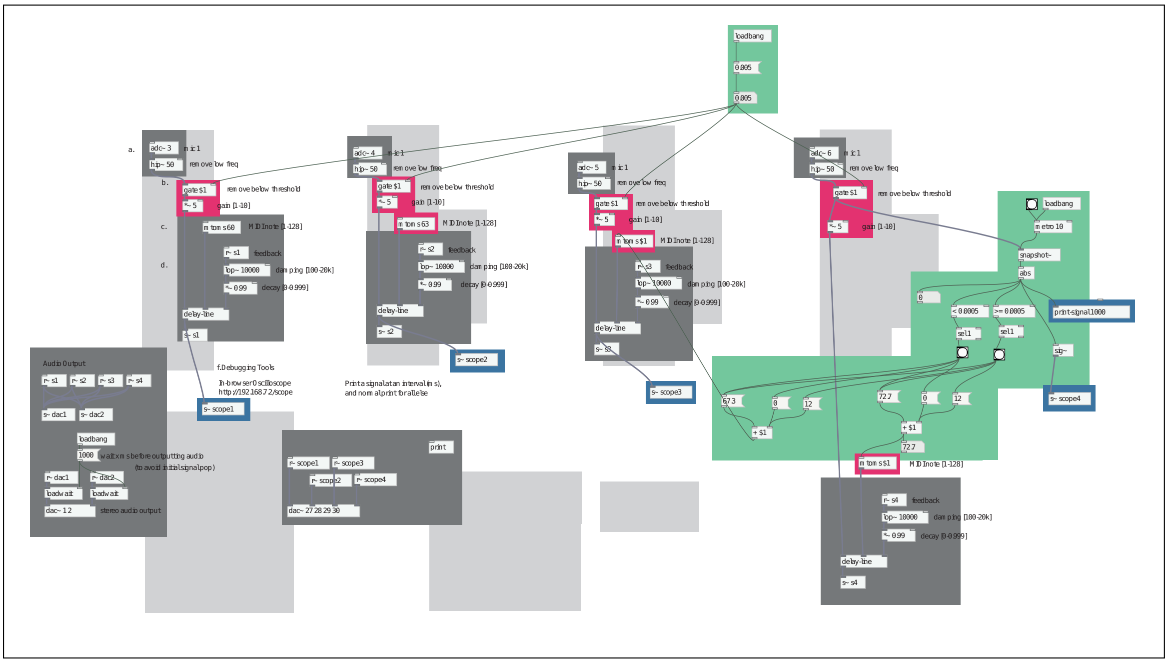


Figure D.3: Group 1 patch.

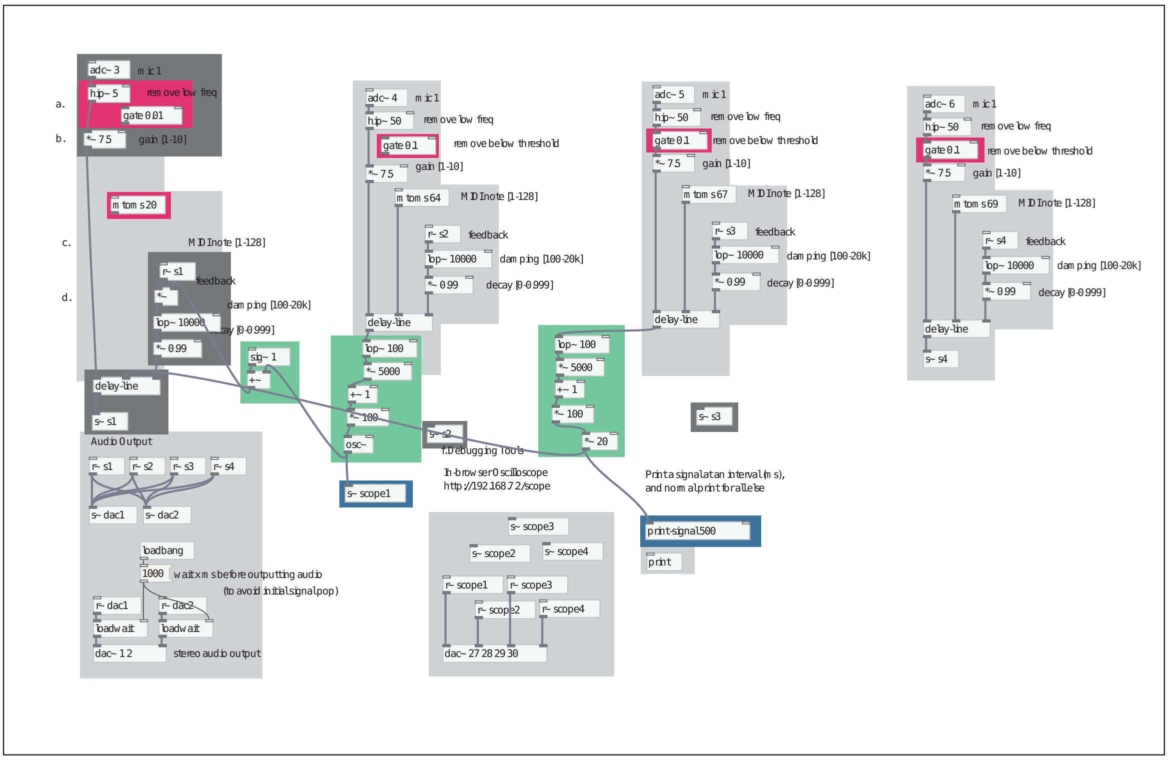


Figure D.4: Group 2 patch.

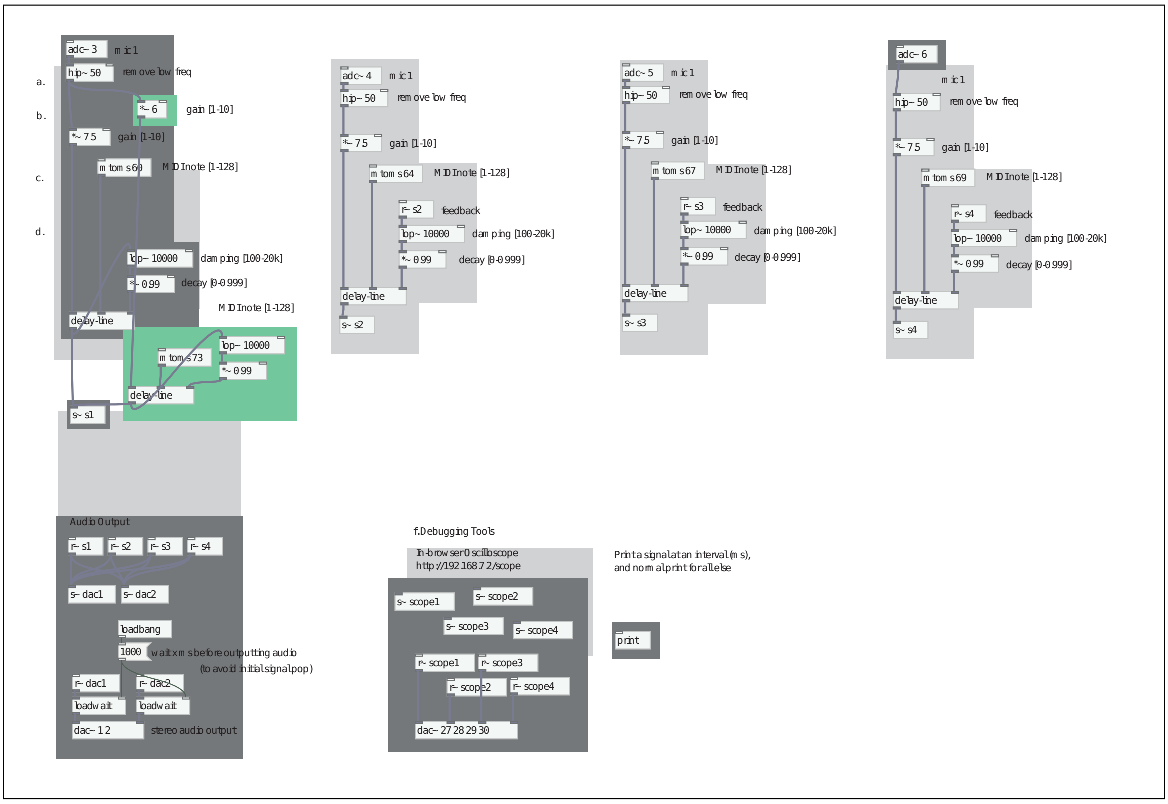


Figure D.5: Group 3 patch.

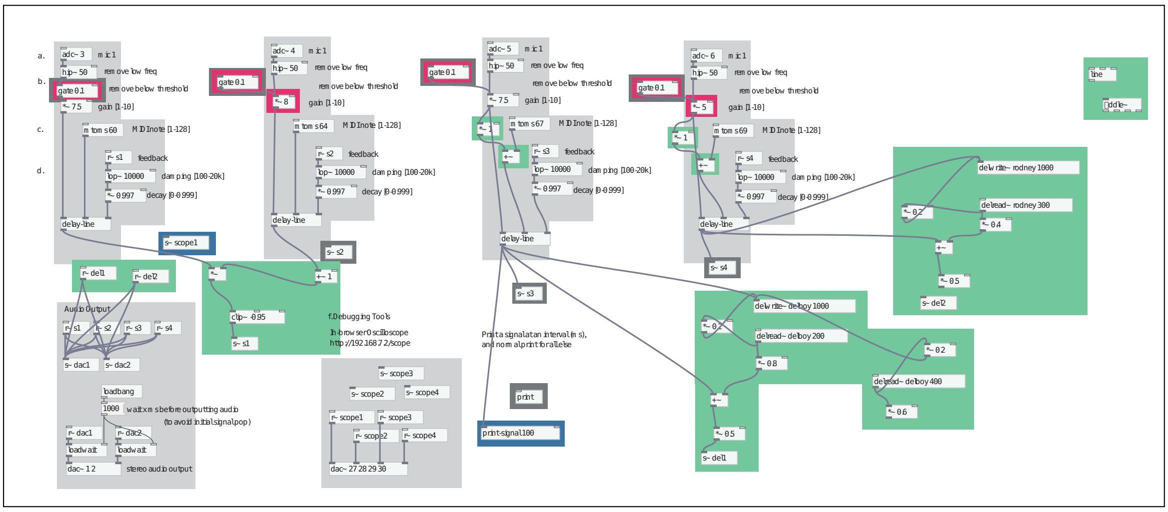


Figure D.6: Group 4 patch.

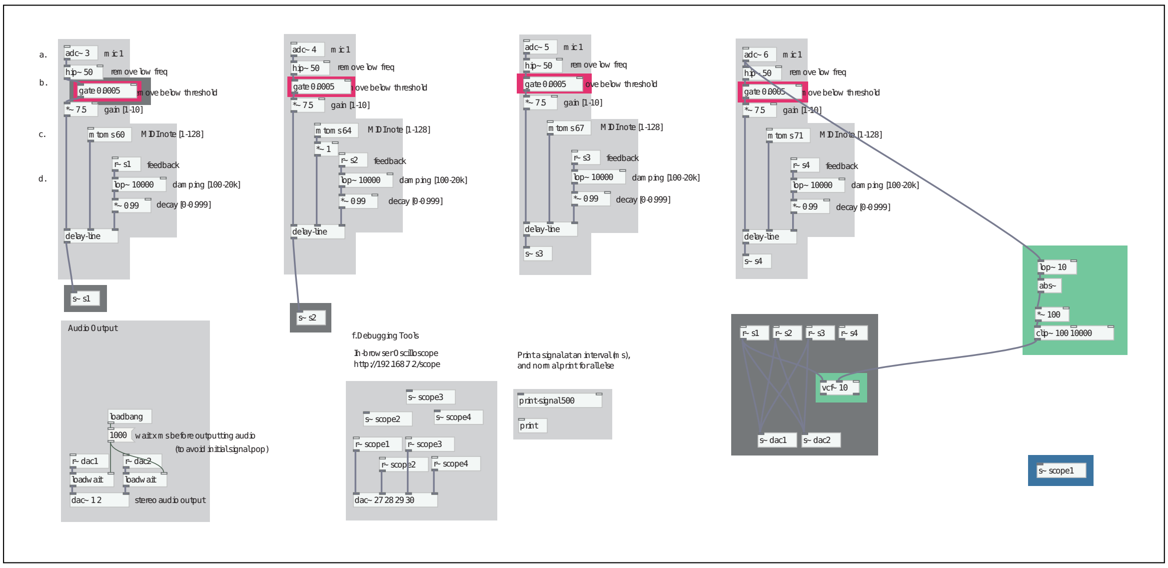


Figure D.7: Group 5 patch.

E APPARATUS APPENDICES

E.1 GLOSSARY

E.1.1 *System architecture*

Glossary for Section 7.2.3.

Bela. A real-time embedded system for interactive audio and music applications `https://bela.io`.

Svelte.js. A web application framework for building reactive user interfaces `https://svelte.dev/`.

Store. A functional data structure which holds web application state.

WebSocket Server. A computer communications protocol, providing full-duplex communication channels over a single TCP connection.

JupyterLab. A web browser-based, programming notebook-based scientific computing environment based on the Python programming language `https://jupyter.org`.

Jupyter Kernel Gateway. A web server that provides headless access to Jupyter kernels and notebook. `https://jupyter-kernel-gateway.readthedocs.io`.

AppleScript. A scripting language created by Apple Inc. that facilitates automated control over scriptable Mac applications.

FuzzMeasure. An audio and acoustic measurement tool `https://rodetest.com`.

Sensel Morph. A tablet-sized pressure sensor with swappable interface overlays `https://morph.sensel.com/`.

E.1.2 *Tuned digital percussion instrument*

Glossary for Section 7.3.

Block. A small square of hardwood with a piezo sensor mounted underneath, resting on a foam and wood base.

Resonance model. A representation of an object's resonance based on an array of filters controllable via frequency, gain and decay parameters.

Preset model. One of four resonance models available to the participant for basing their sculpting on (see Appendix E.2).

E.1.3 *Digital resonance sculpting tool*

Glossary for Section 7.4.

Sculpting surface. The area of the sculpting tool where sculpting with physical materials takes place.

Sculpting clay. Commonly available plasticine.

Clay sculpting tools. A curated set of handcrafting tools to be used with the sculpting tool.

E.1.4 *Frequency response to resonance model mapping algorithm*

Glossary for Section 7.5.

Mapping algorithm. An algorithm which takes as input setup and current frequency response measurements of the sculpting surface, and a preset resonance model, and outputs a mapped resonance model.

Additive sculpting. Sculpting by adding clay to the sculpting surface.

Subtractive sculpting. Sculpting by setting up the sculpting surface with clay added, and subsequently removing the clay.

Sculpt-as-preset. Using an existing *Sculpt* as the basis for a *Sculpture*, instead of one of the four preset models.

E.1.5 *Session navigation and workflow*

Glossary for Section 7.6.

Sculpt. A cycle of the workflow where a single handcrafting material is applied to the sculpting surface and sampled, and the comparison tool is subsequently updated.

Sculpture. A sequence or run of *Sculpts* that have the same base resonance model.

Session. A collection of *Sculptures*.

Workflow. The combined use of the sculpting tool and tunedd percussion instrument to handcraft resonance models.

Navigation interface. A pair of interfaces that enable participants to audition previous *Sculpts*.

- **Tangible user interface (TUI).** A physical control surface based on the Sensel Morph[1] that allows browsing through *Sculptures* and *Sculpts*, and control of the *Workflow*.
- **Graphical user interface (GUI).** A visual representation of the *Session* which mirrors the state of the percussion instrument and use of the *TUI*.

1 https://morph.sensel.com/

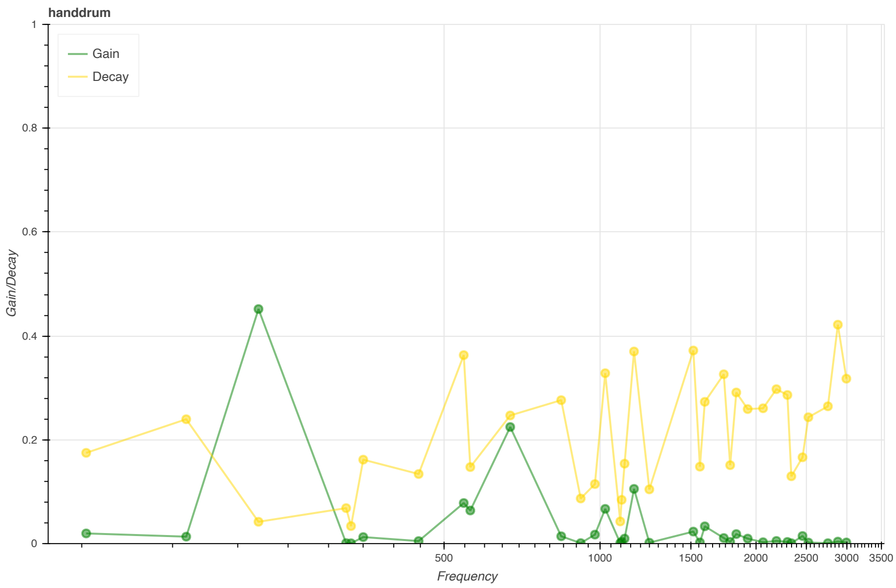


Figure E.1: Preset resonance model 1.

Lock (a percussion block). Assigning a *Sculpt* to a specific percussion *Block*, preventing it from automatically updating when the next *Sculpt* is added.

E.2 PRESET RESONANCE MODEL

E.2.1 *Preset 1: Handdrum*

See Figure E.1.

E.2.2 *Preset 2: khol-5.m6*

See Figure E.2.

E.2.3 *Preset 3: metallic*

See Figure E.3.

E.2.4 *Preset 4: Mirdangam-4.m5*

See Figure E.4.

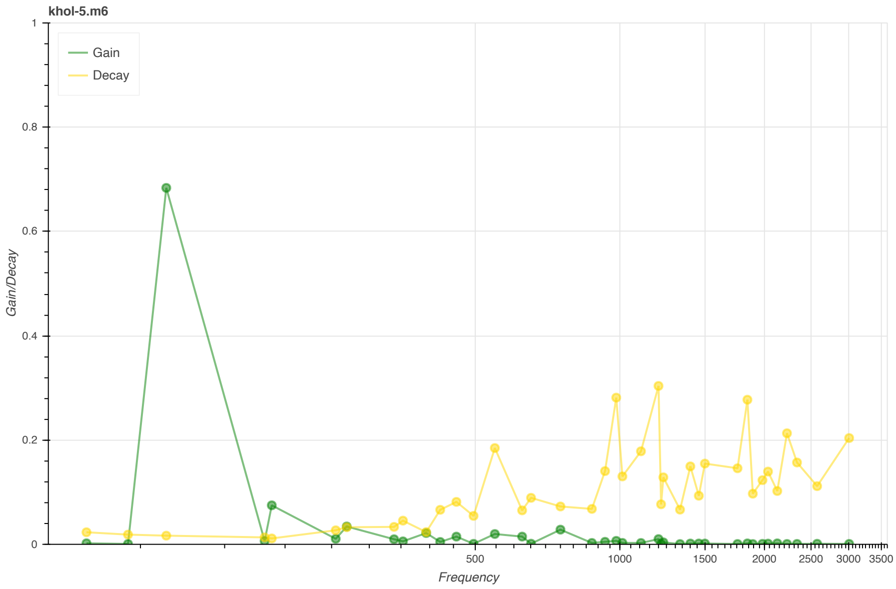


Figure E.2: Preset resonance model 2.

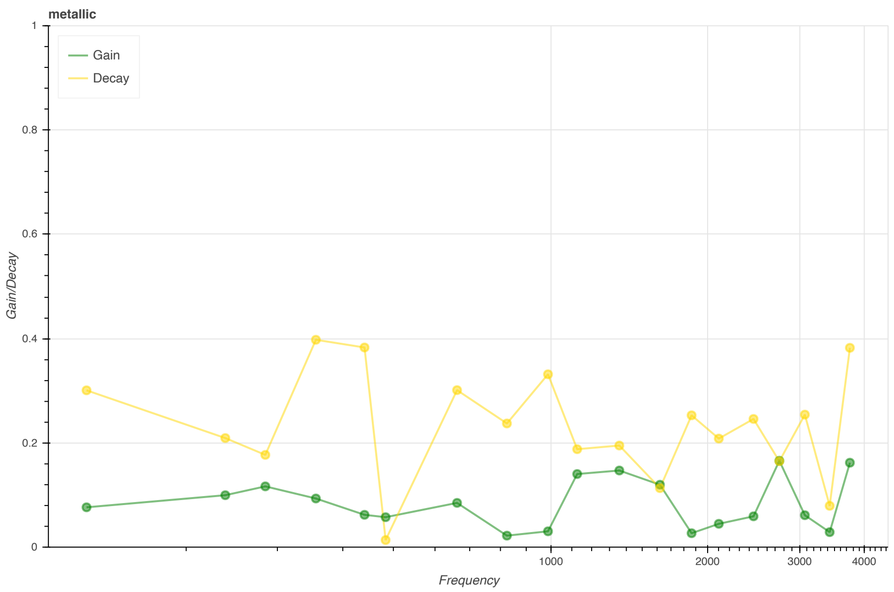


Figure E.3: Preset resonance model 3.

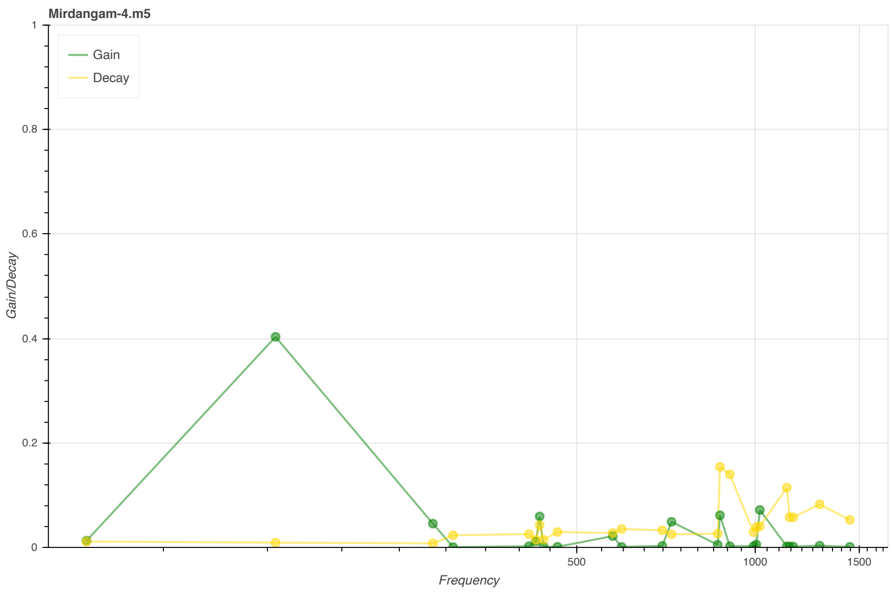


Figure E.4: Preset resonance model 4.

F

MICRO SCALE APPENDICES

Appendices for Chapter 8.

F.1 ACTIVITY SCRIPT

F.1.1 *Introduction script*

Introduction (1-2 mins)

- *P reads and signs the Pro-forma.*
- This is going to be a 60 minute activity, followed by a 25 minute discussion, so in total around 80-90 minutes.
- For the first 5-10 minutes, I am going to introduce you to the tools and materials you see in front of you, and you will have some time to explore them.
- Then I am going to give you some tasks, some shorter and some longer.
- At the end we will finish with a discussion.
- Does that sound ok?

F.1.2 *Demo script*

F.1.2.1 *Demo 1: Basics (5 mins)*

The Instrument and the Sculpting Tool

- *Bringing attention to the Blocks* Starting here, we have a percussion instrument with four different blocks, that you are welcome to start playing with.
- *Wait until P has played and stopped*.
- As you can hear, the four blocks have a similar sound or timbre, each being heard at a different pitch. Do you agree? *Confirm P response*.
- What you are going to be doing in this activity is sculpting the timbre of these blocks, using the sculpting surface to your right *bring attention to the sculpting tool* along with the plasticine material and tools also to your right.
- By adding and removing material to this surface and analysing it using a sine wave sweep, you can manipulate the timbre of the instrument's blocks.

- Each time you wish to change the timbre of the blocks, you analyse the sculpting surface with a sine wave sweep, and the instrument is automatically updated around four seconds later, confirmed by a clicking sound.

Setting Up the Sculpting Process

- There are four steps to making a Sculpture and I'm going to give you a demonstration of those now.
- To see the process we have a web page *show webpage* with some simple visual feedback, and to control it we have a touch device in front of you *show Sensel*.
- As you can see on the touch device, there are four numbers which refer to the four steps of creating a Sculpture.
- Step 1, we create a New Sculpture, go ahead and do that.
- Step 2, we select a starting timbre from four Presets. For this demo we are going to stay with Preset 1, and we can try the other presets later.
- Step 3, we Setup the Sculpting Surface.
- When you touch Setup, you will hear two sine wave sweeps as the surface is analysed and the webpage will say it is busy for a moment. Go ahead and touch Setup.
- *Touches Setup on Sensel*.
- *Wait for process to complete*.

Adding Sculpts

- Ok, now that the sculpting surface is setup, we are ready for Step 4 - Add Sculpt - where you can start adding materials and analysing them, and you can repeat this step as many times as you like.
- Take a piece of plasticine and place it onto the surface, pushing it down into place so it has a solid contact with the surface.
- *Fixes plasticine onto surface*.
- Now on the control device touch 'Add Sculpt' and you will hear the sine sweep again.
- *Touches Add Sculpt on Sensel*.
- *Wait for process to complete*.
- Now play the instrument again and listen to how the sound might be different to before.
- *Plays instrument*.
- What do you notice about the sound compared to before?
- *Responds*.

- An important idea is that the differences in sound come from the comparison of acoustic properties between the Step 3 - Setup, and Step 4 - the Sculpt you have added.
- Looking at the sculpt that you added with the plasticine, do any thoughts come to mind about how the material might have caused that change?
- *Responds.*
- *If P offers a hypothesis* How might you test that idea?
- *If P does not offer a hypothesis* Ok, what sculpt might you try next to learn more about the process?
- *Let P do 3-4 Sculpts.*

Recap

- To recap, first we added a New Sculpture, second we chose Preset 1, third we Setup the sculpting surface, and finally we Added Sculpts.
- Sculpts are always compared to the original Setup, and the touch device and web page allow us to navigate through different sculpts.
- Does everything make sense so far? Do you have any questions?

F.1.2.2 *Free Exploration of Sculpting (5 mins)*

Adding New Sculptures

- Now that you are familiar with the process, I am going to give you another five minutes to create a New Sculpture.
- This time, try the different Presets and choose one for your Sculpture.
- When you select a Preset, it will preview the sound on the Blocks.
- Each time you create a New Sculpture, you can select from these four Presets before beginning the Setup process.
- In the previous Sculpture we used Preset 1, so this time choose a different Preset.
- *Choose Preset.*
- Ok, now touch Setup.
- *Touches Setup on Sensel.*

Free Exploration

- Alright, now you are free for around five minutes to Add Sculpts to this Sculpture.
- *If they need reminding* Please remember to think out loud as you go.
- *Wait for P to do 5 sculpts.*
- *If P has not added a 'large' amount of material to dampen the model, then ask them to try this before moving on.*

F.1.2.3 *Demo 2: Advanced (5 mins)*

Ok, for the next five minutes I'm going to show you some more features of the Sculpting workflow.

Comparing and Locking Sculpts

- To assist the process, we can compare between different sculpts, by choosing which Sculpts are assigned to each Block.
- The Up and Down arrows will take you backwards and forwards within a Sculpture *Show Sculpt navigation on Sensel*.
- The Left and Right arrows will take you across different Sculptures *Use navigation functions on Sensel*.
- By default, when you Add a Sculpt the Blocks will update to the latest Sculpt.
- Sometimes however we want to Lock a Block to Sculpt, and you can do this using the Lock button in the middle of each Block *Lock a Block and Add a Sculpt*.

Subtractive sculpting method

- Ok, now I want to show you another approach to Sculpting.
- So far we have been Setting up Sculptures with no materials on the Sculpting Surface, and then adding materials as we sculpt.
- It is also possible to Setup the Surface with materials added, and then remove them while Adding Sculpts. Let's try this approach.
- First, please add a New Sculpture and select Preset 4.
- *Touches Add Sculpture and selects Preset 4*.
- Now take some plasticine and roll it flat using the rolling pin, and then add it to the surface.
- *Rolls plasticine and adds to surface*.
- Ok, now run Setup.
- *Touches Setup*.
- Now, take the scalpel and remove a small amount of material, touch Add Sculpt, and play the instrument.
- *Remove material and touch Add Sculpt*.
- What do you notice about the sound?
- *Responds*.
- Finally, I would like you to remove all of the material and touch Add Sculpt.
- *Remove material and touch Add Sculpt*.

- Earlier we added material and in some cases the sound overall was often quieter, whereas in this case we have removed material and the sound overall is louder.
- By removing material we are letting the surface resonate more freely, and by adding material we are absorbing some of that resonance.
- So, if we generally want to make a model louder like we just did with Base Model 4, we can Setup the sculpting process with some material added, and then remove it.
- If we generally want to make a model quieter like we did earlier, we can Setup the process with no material added, and add it.
- Any questions before we move on?

Creating a Sculpture based on an existing Sculpt

- In addition to creating Sculptures using the four Presets, we can also create a Sculpture based on a Sculpt.
- To do this, create a New Sculpture and select one of the Blocks.
- Again, the Blocks will preview the sound of your new instrument.
- The rest of the process remains the same: Setup and Add Sculpts.

Changing Block pitches

- Finally, you can also toggle the pitches of the Blocks using the Pitch button with the musical note.
- When you touch this button, the Block pitches will move between five possible states: spread out, Low, Low Mid, High Mid, and High.

F.1.3 *Matching task 1 script*

F.1.3.1 *Matching Task 1 (7-8 mins)*

Introduction (1 min)

- This first task is called the Matching Task.
- Imagine that a Percussionist has come to you as a master Sound Sculptor.
- They want an instrument that sounds like Preset 4 *create first Sculpture using Preset 4*.
- But what they have is an instrument that sounds like Preset 2 *create second Sculpture using Preset 2*.
- They want you to make their Preset 2 instrument sound as similar as possible to Preset 4.

- Unfortunately this Percussionist only has five minutes before they have to perform onstage with whatever you give them!

Practicalities (5 mins)

- So, your task is to make this starting model - Preset 2 - sound as similar as possible to this target model - Preset 4 - in the space of five minutes.
- To help you Compare, you can Lock Block 1 to Preset 4, and Lock Block 4 to Preset 2, and now Blocks 3 and 4 will update to the latest Sculpt so you can review your progress *Lock the Blocks appropriately*.
- You can also change the Blocks to a single pitch mode.
- During the five minutes you can create as many Sculptures as you like.
- Please remember to think out loud as you go.
- Are you ready for the task to begin?
- *Responds*.
- *Start timer*.
- *Three minutes pass*. You have two minutes left.
- *Four minutes pass*. You have one minute left.
- *Five minutes pass*. Ok, time's up.

F.1.3.2 *Post-task questions (2-3 mins)*

- How did you find the task?
- What sculpting techniques did you use or develop during this task?
- How effective were the techniques you tried?
- How close did your two closest Sculpts get to the target?
- How are your sculpts still different from the target?
- If you had one hour instead of five minutes, how would you spend that hour?
- How would you score yourself out of 10 on this task?

F.1.4 *Tuning task script*

F.1.4.1 *Instrument Tuning Task (30 mins)*

Introduction (1 min)

- This second task is called the Instrument Tuning Task and this time you are both the Percussionist and Sound Sculptor.

- Imagine you have a very informal, relaxed concert tomorrow evening, where you will perform a 3 minute piece using your instrument.
- You have 25 minutes to explore and tune your instrument Blocks before you will start composing and rehearsing.
- Do not worry, you will not be asked to perform, your task is just to prepare your instrument Blocks for the concert.
- Does that make sense?
- *Responds*.

Practicalities (25 mins)

- You are free to create as many Sculptures and Sculpts as you like for 25 minutes, and at the end you should have made your choices for each Block.
- Please begin when you're ready, and feel free to ask any questions as you go, *If they need reminding* and please remember to think out loud as you go.
- *Begins task*.
- *After 10 minutes* You have ten minutes of sculpting time left.
- *After 15 minutes* You have five minutes of sculpting time left.
- *After 19 minutes* You have one minute of sculpting time left.
- *After 20 minutes* Ok, stop sculpting. You now have five minutes to decide which Sculpts to use in your final instrument.
- *After 23 minutes* You have two minutes left.
- *After 24 minutes* You have one minute left.
- *After 25 minutes* Ok, time's up!

F.1.4.2 *Post-task questions (4 mins)*

Instrument

- Can you present your instrument?
- How would you describe the sounds of the four Blocks?
- How do you think you would play it for 3-5 minutes?
- What drove your decision making process for choosing these Sculpts for these Blocks?
- How satisfied are you with your instrument?

Sculpting

- What sculpting techniques did you use or develop to create these sounds?
- How effective were the techniques you tried?
- What drew your attention in terms of the physical sculpting?
- What drew your attention in terms of the sonic outcomes?
- How interested were you in the variety of sounds you were creating?
- How interested were you in the finer details of the sounds you were creating?

F.1.5 *Matching task 2 script*

F.1.5.1 *Matching Task 2 (7-8 mins)*

Introduction (1 min)

- This is your final task and it is another Matching Task.
- This time we are going to do the exact same task but in reverse.
- Instead of going from Preset 2 to Preset 4, we are going to go from Preset 4 to Preset 2.
- *First create target Sculpture with Preset 2.*
- *Second create starting Sculpture with Preset 4.*
- Again you will have 5 minutes.

Practicalities (5 mins)

- So, your task is to make this starting model - Preset 4 - sound as similar as possible to this target model - Preset 2 - in the space of five minutes.
- To help you Compare, you can Lock Block 1 to Preset 2, and Lock Block 4 to Preset 4, and now Blocks 3 and 4 will update to the latest Sculpt so you can review your progress *Lock the Blocks appropriately*.
- You can also change the Blocks to a single pitch mode.
- During the five minutes you can create as many Sculptures as you like.
- Please remember to think out loud as you go.
- Are you ready for the task to begin?
- *Responds*.
- *Start timer*.
- *Three minutes pass*. You have two minutes left.
- *Four minutes pass*. You have one minute left.
- *Five minutes pass*. Ok, time's up.

F.1.5.2 *Post-task questions (2-3 mins)*

- How did you find the task?
- What sculpting techniques did you use or develop during this task?
- How effective were the techniques you tried?
- How close did your two closest Sculpts get to the target?
- How are your sculpts still different from the target?
- If you had one hour instead of five minutes, how would you spend that hour?
- How would you score yourself out of 10 on this task?

F.1.6 *Post-activity interview script*

Interview Discussion Topics/Questions (20-25 mins)

Activity clarifications (3-5 mins)

- *Review motifs, methods, gestures from session*
- During the activity, you did / said ____. I'd just like to clarify what your intentions were / what you were thinking / what you meant.
- During the activity you developed / used the technique of ____ when sculpting. Why do you think this came about?
- During the activity you came back to the idea of ____. What motivated this decision?

Activity reflections (3-5 mins)

- What are your general reflections about the activity?
- Was there anything particularly motivating about this activity or process for you?
- What were the pain points of this process for you?
- How else would you imagine working with these sound models using other interfaces, and what do you think would be the relative advantages/disadvantages?
- What would you do with this system if you could use it for a day?
- How about for a month?

Participation survey follow up (3-5 mins)

- I've got a copy of your participation survey here and I'd just like to ask you a few questions about your responses.
- You mentioned ____, can you tell me a bit more about that?

- In your creative practices, are you very focused on details and nuances of your work and the work of others?
- When you are doing ____, can you give any examples of small details or nuances that you spend a lot of time with, and why you care about them?
- Why do you think some people take a lot of care over small details while others don't?

Comparing personal practices to activity (3-5 mins)

- How do you think your personal experiences and practice shaped your response in this activity?
- How did the aspect of ____ in this activity compare to your own experience of doing ____?
- You mentioned that the details of ____ matter to you in your practice. Even though this activity was brief, can you identify what details and nuances stood out to you the most?
- What do you think this process was asking you to care about?
- Would you be interested in using a system like this in the longer term in your own work? If so, how could you see it fitting in or what do you think it could be useful for?

Any other questions (3-5 mins)

- Do you have any questions about the study?

F.2 ONBOARDING INSTRUMENTS

F.2.1 *Call for participation*

Call for Participation - Study on Digital Handcraft for Musical Instrument Making

You are invited to join a study about digital handcrafting in the context of musical instrument design, hosted by researchers in the Augmented Instruments Lab (http://instrumentslab.org).

In the study you will be introduced to a set of digital handcrafting tools and asked to use them to carry out a set of tasks. The activity will last for one hour and will be followed by a 25 minute discussion, so overall the session is expected to last for up to around 90 minutes.

Participants should have at least some experience making and/or playing any kind of musical instrument. Please fill in this form to let us know about your experience, creative practices and availability: https://forms.gle/g6frFKA8NBjgf2Dg6

Sessions will take place at Queen Mary University of London between Friday 24th January and Sunday 2nd February 2020.

Please share this study invitation using the following link: https://twitter.com/jdkarmitage/status/1220304905619083264

If you have any questions please contact Jack Armitage at j.d.k.armitage@qmul.ac.uk.

Thank you for your interest in this research!

F.2.2 *Pre-activity survey*

Please tell us about your experience levels with each of the following activities (options: No experience, Up to one year, Between one and five years, Between six and ten years, Over ten years)

- *Building or designing any kind of musical instrument.*
- *Practicing a handcraft (e.g. carpentry, ceramics).*
- *Playing an acoustic musical instrument.*
- *Playing an electronic or digital musical instrument.*
- *Performing live music.*
- *Recording and/or producing music.*
- *Using a programming language.*
- *Any other form of engineering or technical background.*

If you answered up to one year or greater in the previous question, please give a brief description about your experience and/or creative practice.

Is there anything else you would like to tell us about your experience or creative practices?

F.2.3 *Activity brief*

Digital handcrafting activity

In this study we are interested in the idea of digital handcrafting in the context of digital musical instrument design. This study presents a digital musical instrument along with some tools for modifying its sound characteristics.

First you will complete a brief tutorial for using the tools (around 15 minutes). This will be followed by a series of tasks (around 45 minutes). Once the tasks are complete, there will be a discussion (around 20 *minutes). The researcher will be on hand at all times throughout the activity should you have any questions.*

The activity is being recorded, and we encourage you to share your thoughts out loud as you go. The camera will be focused on your hands and not your face. Data privacy and protection rights apply to all data collected in this study. Any data we wish in future to make public will require your approval.

F.3 final study feedback from chris egerton

After the study described in Chapter 8 was completed, I emailed the participants with a final thanks, and to request for any additional feedback or reflections if they had any. A number of participants responded, among them Chris Egerton, a stringed-instrument maker, restorer, and conservator, who generously took the time to elaborate on a variety of issues. His comments were so useful to me in confirming and correcting some of my assumptions, and so thought-provoking in the breadth of their extrapolations, that I have with his permission reproduced them in full below.

F.3.1 *My comments on the session*

The craft interface although simple and quite crude produced surprising results that seemed usefully connected to intuitive skills and acquired technical practices. It was an interesting novel experience. The interface(s) could be redesigned, enlarged or developed to take advantage of particular applied activities such as the 'barring' of an instrument soundboard, shaping of a resonant sound cavity, etc. Selection of craft materials could be expanded to include a wider range of substances, components. Craft practitioners often use dozens or hundreds of different tools and materials to produce their works. New interfaces could incorporate specific or various tools to suit the user. It seems logical that user-practice would develop familiarity with parameters and possibilities of any given craft interface. Children or other learners using the interface could develop simultaneous personal motor skills and audio awareness capabilities. The PhD researcher, although concentrating on fulfilling current research, should imagine and asks questions about wider applications, implications and possible distant future developments of his ideas.

F.3.2 *New haptic tools – we want 'em*

Virtual objects or materials – using virtual haptic modelling materials (eg clay, paint, brush..) to shape sounds or to perform in real time. Artists of various types would thereby have direct access to the digital creation process using their own skills. Using haptics, blind or partially sighted or otherwise differently abled may be advantaged or facilitated beyond their immediate physical or sensory abilities. Virtual haptic instruments. Accidental glitching or unconventional playing techniques may surprise. Dancers movement in a responsive (haptic?) field to generate sound performance. Tai chi, martial arts. Animals, creature's natural or trained movements captured as digital sound patterns.

F.3.3 *My own practice and work*

I became more conciously aware of the potential results and effects of my applied craft interventions on the behaviour and sound of instruments I create or restore. For example applying a small patch, surface coating, material graft or replaced part. For a conservator this is a good thing as it's important to objectively and actively assess any treatment consequences on cultural objects before, during and after, as well as allowing free application of tacit and acquired skills and intuitive knowledge. A refined craft interface perhaps connected with 3-D virtual objects might allow testing or assessment of real world interventions before application, but that's about 25 years in the future I would guess. At the moment we rely on empirical scientific testing of materials and methods in proxy, which gives a good guess at what might happen, but it's far from speedy or human focused.

Chris Egerton
Stringed-instrument maker, restorer, conservator.
27 Feb 2020

Some other research works of possible interest:

- https://www.cam.ac.uk/research/news/virtual-violins
- Laser vibrometry of instruments generally.
- http://www.stoppani.co.uk/Technical.htm

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