Studying Subtle and Detailed Digital Lutherie: Motivational Contexts and Technical Needs

Jack Armitage
Intelligent Instruments Lab
Iceland University of the Arts
Reykjavík, Iceland
jack@lhi.is

Thor Magnusson
Intelligent Instruments Lab
Iceland University of the Arts
Reykjavík, Iceland
thor.magnusson@lhi.is

Andrew McPherson
Dyson School of Design Engineering
Imperical College London
London, United Kingdom
andrew.mcpherson@imperial.ac.uk

ABSTRACT

Subtlety and detail are fundamental to what makes musical instruments special, but accounts of their development in digital lutherie have been constrained to ethnographies, in-the-wild studies, and personal reflections. Though insightful, these accounts are imprecise, incomparable, and inefficient for understanding how fluency with the subtle details of digital musical instruments (DMIs) develops. We have been designing DMI design probes and activities for closed and constrained observation of subtle and detailed DMI design, but in two previous studies these failed to motivate subtle and detailed responses. In this paper we report on our third attempt, where we designed a tuned percussion DMI and a hybrid handcraft tool for sculpting its sound using clay, and a one hour activity. Among 26 study participants were digital luthiers, violin luthiers and musicians, who all engaged with what we define as micro scale DMI design. We observed technical desires and needs for experiencing and comparing subtle details systematically, and also widely varying, subjective emotional and artistic relationships with detail in participants' own practices. We reflect on the contexts that motivate subtle and detailed digital lutherie, and discuss the implications for DMI design researchers and technologists for studying and supporting this aspect of DMI design and craft practice in future.

Author Keywords

Digital Musical Instrument Design, Detail, Design Process, Craft Practice, Research Methods

CCS Concepts

•**Applied computing** → **Sound and music computing;** •**Human-centered computing** → **HCI theory, concepts and models;** *Empirical studies in interaction design;*

NIME'23, 31 May–2 June, 2023, Mexico City, Mexico.

1. INTRODUCTION

Digital luthiers [20] and musicians frequently refer to the subtle, rich, and nuanced details they observe in valued instruments or aspire to incorporate in their own creations. What do these terms imply in this context? *Subtlety* and *detail* offer an intriguing foundation to discuss the intricate qualities of musical instruments. Subtlety suggests delicate precision, understated complexity, and cunning craftsmanship; it reflects an appreciation for sophistication. For musical instruments, it aptly conveys their enigmatic presence, which is difficult to describe or reduce to words or formulas. "Detail," on the other hand, implies attentive consideration for every feature. For example, "down to the last detail" indicates thoroughness, while "go into detail" demonstrates a comprehensive account.

Digital luthiers exemplify a meticulous approach, focusing on instrumental nuances that might otherwise be overlooked. Craft researcher Kettley posits that when the perception of subtlety intersects with the technical mastery to create fine details, practitioners achieve an authentic process [21]. In this way, subtlety and detail can be viewed as interdependent elements of a perception-action cycle that ultimately yields excellent instrumental quality through time and efforts [28]. The question remains: how can we clearly define subtlety and detail to inspire practical investigation?

This paper tackles the task of defining and understanding the subtle and detailed elements of digital musical instrument (DMI) design at a foundational level, covering aspects that ethnographies [29], in-the-wild studies [17], and personal reflections [12] might not capture. We aim to explore questions such as: How do DMI designers initially react to new subtle details? What criteria lead them to regard some details as more important than others? How do they utilise their bodies and available materials to become well-versed in subtle details? In what forms is knowledge about these details presented and communicated? Are there any shared design principles or craft processes among makers?

We commence by establishing an operational definition for subtlety and detail based on our scale-based ontology of DMI design [5]. Subsequently, we discuss attempts to design study probes and activities [14, 16] for our research. We narrate the development of this research, detailing the outcomes of two failed studies and how they led to a revised set of constraints for study design. Finally, we present the findings from a third study and explore the resulting insights into this usually unseen domain.

2. BACKGROUND

2.1 Subtlety and Detail in DMI Design

In this paper, we propose defining micro scale details as the subtle and nuanced differences between seemingly identical instruments and their underlying design processes. This definition is adapted from Jordà's concept of a musical instrument's *micro-diversity*, which refers to the varying potential performances of the same piece [20]. Instead, we focus on instrument design processes rather than performances. For instance, when comparing inexpensive injection-molded objects with broad mechanical tolerances, their differences might be subtle or detailed. However, objects machined to tight tolerances exhibit a different level of subtlety, requiring a more discerning examination to identify their differences.

Additionally, Jordà described *macro* and *mid*-levels of musical diversity. To extend this analogy, we suggest considering *macro* and *meso* scale differences (our preferred term over mid) between digital musical instruments (DMIs) and their corresponding design processes. Where each scale considers digital musical instruments, and their underlying design processes:

- The macro scale defines forms and functions of instruments across ecologies.
- The meso scale defines configuration and mappings across taxonomically similar instruments.
- The micro scale defines subtle and detailed nuances between otherwise identical instruments.

A full account of this ontology of DMI design can can be found in [5], but for now, comparing each definitions' attributes and contexts can help to reinforce their intended meaning:

- 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 form and function *(macro)*, and the same configuration and mappings *(meso)*, and are distinguished via their subtle and detailed nuances *(micro)*.

2.2 Challenges Faced in Previous Studies

In our previous paper [10], we explored how violin luthiers concentrate on micro scale details due to macro and meso scale cultural constraints on their practice. This focus enables them to improve their fluency with relevant micro scale details, accumulating experiential embodied expertise.

Intending to adopt a similar approach in DMI design, we conducted two studies where we tasked instrument makers with concentrating on subtle details during one hour activities [8, 9]. However, neither study yielded micro scale outcomes. In the first study, combining a simple, modular DMI design toolkit with crafting materials resulted in primarily macro scale outcomes [8]. We attribute this to the macro scale flexibility of the design environment and the absence of constraints on macro scale design compared to meso and micro scales.

The second study paired the same toolkit with a Pure Data patch and produced more noticeable meso scale outcomes [9]. A subsequent visual analysis of the design data confirmed that macro scale changes in the Pure Data patch were time-consuming and error-prone, while exploring alternative mappings was relatively easier [4]. We believe participants focused on meso scale features (mappings) due to the relative meso scale flexibility of the design environment compared to macro and micro scales. In both studies, participants quickly identified and exploited leverage points provided by the materials [8, 9, 4]. From a thematic analysis of participant interviews, we concluded that their focus on macro or meso scale features depended on the leverage provided by design materials, as well as individual backgrounds and motivations.

Findings from these two investigations highlight the significance of scale-based constraints in motivating micro scale design activity. Reflections on these studies led us to hypothesise that participants would only concentrate on micro scale details if macro and meso scale inflexibility of the design environment were externally imposed. To test this, we designed a study with more constrained apparatus and activities, and individual rather than group participation. We anticipated that these factors would increase the likelihood of participants focusing on micro scale details during their sessions. Having failed to motivate micro scale design previously, we reframed our inquiry to ask what *motivates* instrument makers and creatives to either concentrate on subtle design details or not in a one-hour, constrained activity?

3. SYSTEM & ACTIVITY DESIGN

3.1 Sculpting System

The system, depicted in Figure 1, is centred around a tuned percussion digital musical instrument (DMI) based on digital resonance models, which consist of a bank of second-order bandpass filters[1][1, 2]. Our study focuses on the design process of adjusting the resonators' behaviour, for which we developed a clay-based sound sculpting system.

The clay interface aims to shape a frequency response between an actuator and sensor, measured by a frequency sweep. It translates the frequency response features, which vary with different clay configurations, into parameters for the instrument's resonator model. The primary objective of this clay sculpting system is to allow users to handcraft digital resonance models through a subtle and repeatable interface, concentrating on the nuanced aspects of sound.

Figure 1 (top) illustrates the graphical user interface (GUI), while the physical interfaces are portrayed from the participant's perspective in Figure 1 (bottom). The tuned percussion instrument comprises four identical wooden blocks, each equipped with a piezoelectric vibration sensor underneath. Moreover, the resonance model sculpting tool comprises a hanging wooden panel, fitted with a piezoelectric vibration sensor and a vibration transducer mounted beneath it. The tangible user interface (TUI), based on a Sensel Morph device, manages the sculpting process and navigates previous sculptures, in conjunction with the GUI. The GUI showcases three panels of information: session state, instrument state, and sculpture state. Table 1 demonstrates the constraints we applied to these interfaces and materials to discourage macro and meso scale design while promoting micro scale design.

[1] `https://www.youtube.com/watch?v=EtJrk9LywWI`

Table 1: The main design features of the instrument, sculpting tool, mapping algorithm and comparison interfaces (GUI and TUI). Based on previous studies [8, 9], we constrained the macro and meso scales, and made the micro scale rich and open-ended.

Instrument	Sculpting Tool	Mapping	Comparison UI
• Four blocks with fixed pitches C3, A3, G4 and D5. • Physically identical blocks in a fixed horizonal row. • Block size same as human palm to constrain gestures. • Only four curated preset resonance models to play with.	• Only one material available for sculpting with. • Open-ended, continuous, sculptable material used. • Simple tools made from wood to encourage hands-on play. • All electronics underneath to prevent distraction/damage.	• Swept sine-wave freq. response for increased accuracy. • Measurement step decoupled design from performance. • Only the differences between *Sculpts* and *Setup* are mapped. • Magnitudes mapped to resonator gains, peaks/troughs to decays, freq. params not mapped.	• Automatically update instrument blocks to latest *Sculpt*. • 'Lock' UI for comparing old and new *Sculpts*. • 'Pitch Toggle' UI to compare *Sculpts* at different/same pitches. • Simple visualisation to prevent distraction from audiotactile focus.

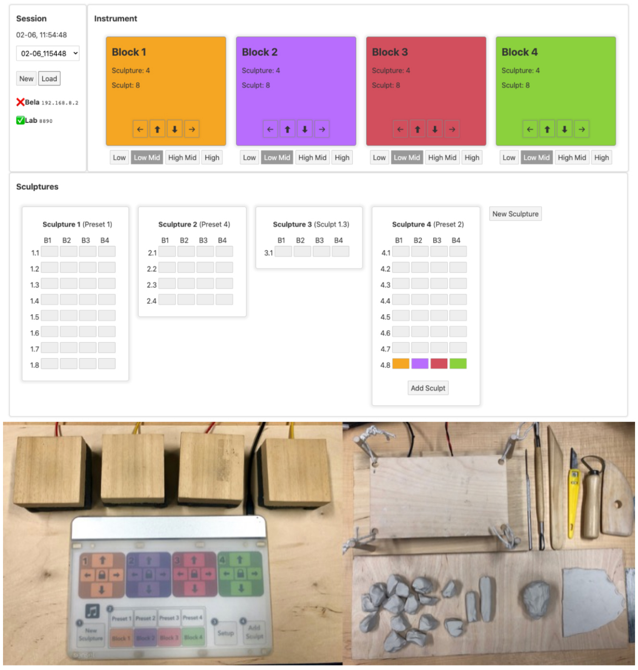

Figure 1: The sculpting system from the user's perspective. **Top**: graphical user interface (GUI). *Top left*: the Session panel displayed admin features. *Top middle*: the Instrument panel displayed the state of the four tuned percussion blocks. *Bottom*: the Sculptures panel displayed each Sculpture as a table, and each individual Sculpt as a row.
Bottom: photos of the physical interfaces. *Left*: digital tuned percussion instrument (above) with four playable blocks, and tangible user interface (TUI) (below) for navigating the GUI. *Right*: sculpting surface (above left), sculpting tools (above right) and sculpting clay (below).

3.2 Sculpting Workflow

In this activity, sculpting refers to employing the sculpting surface, clay, and tools to manipulate digital resonance models which are excited using tuned percussion blocks. This process is divided into *Sculptures*, comprised of sequential *Sculpts*.

A *Sculpture* utilises an existing resonance model, calibrating it to the sculpting surface, and then allows the participant to modify the model based on further alterations to the sculpting surface, recorded as separate *Sculpts*. Every *Sculpt* is composed of a frequency response measurement of the sculpting surface, along with a newly-created resonance model, which is produced by associating differences in frequency response to model parameters.

For every *Sculpt*, the mapping algorithm compares the current frequency response with the calibration frequency response and maps variations between them to the parameters of the selected preset resonance model, ultimately creating a new resonance model. Consequently, each *Sculpture* signifies a collection of variations on a specific preset resonance model, linked by the physical *Sculpts* introduced during the process.

The interaction loop can be summarised as follows: utilise the TUI to establish a new *Sculpture*; choose a resonance model preset; prepare the sculpting surface; modify the chosen model by sculpting with clay; and compare the results via the TUI and GUI.

3.3 Sculpting Activity

We guided 26 instrument makers and musicians through an hour-long session of short creative and technical briefs, followed by 30 minutes of semi-structured interviews. The activity aimed to constrain macro and meso-scale design by delivering briefs that contextualised the otherwise unfamiliar micro-scale details. At a technical level, it also swiftly enabled participants to manage the sculpting workflow and process independently and immerse themselves in specific contexts that necessitated engaging with the subtle characteristics of the materials.

The one-hour activity comprised four tasks: Demo (15 mins), Matching Task 1 (5 mins), Tuning Task (20 mins), and Matching Task 2 (5 mins). The Demo involved a hands-on guided exploration of the interface features, incorporating some free exploration time. The Matching Task, a succinct technical task, was repeated to facilitate a comparison of outcomes before and after a lengthier, creative task called the Tuning Task.

In the Matching Task, participants assumed the role of a sound sculptor, tasked with creating a sound for a musician that closely resembled another provided example. During the Tuning Task, participants took on the role of a musician and were asked to curate or 'tune' their own sounds in preparation for an imaginary improvised concert.

Following the completion of these tasks, semi-structured interviews took place, spanning 20-25 minutes. The topics covered included: clarifications (3-5 mins), reflections (3-5 mins), participation survey follow-up (3-5 mins), comparisons between personal practices and the activity (3-5 mins), and any additional questions (3-5 mins).

4. OUTCOMES

Thematic analysis was conducted on the participant session videos, surveys, and interviews, viewed through the lens of the previously described scale-based ontology. As anticipated, both motivating and demotivating factors emerged, some of which were specifically related to participants' backgrounds.

Overall, the apparatus utilised in this activity proved rewarding enough to encourage continued exploration at sub-

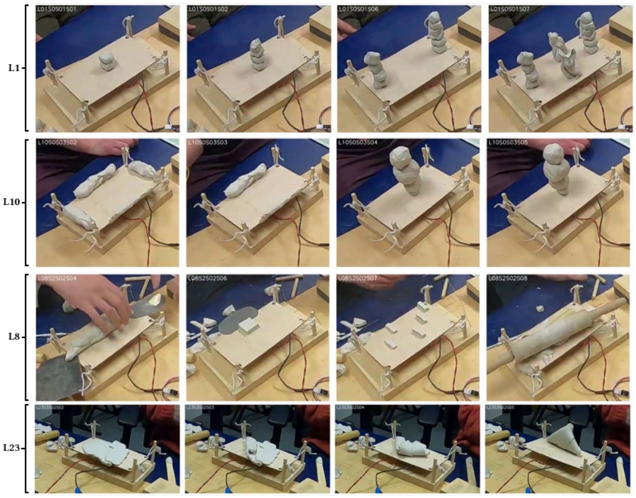

Figure 2: Attempts to sculpt extreme sounds and find the limits of the system. 1st row: **L1** gradually added more and more mass. 2nd: **L10** focused stacked mass onto a fine point. 3rd: **L8** explored multiple kinds of extremes. 4th: **L23** manipulated one large piece of clay.

tle and detailed levels, keeping participants positively engaged throughout. The sub-activities directed participants' attention to various facets of detail, preventing boredom or straying off-task. Notably, some participants opted to disregard the sculpting tools and used their hands instead, while others discovered alternative uses for the tools.

Table 2 offers examples of exceptions where, despite the restrictions, participants were drawn towards macro and meso-scale design ideas.

4.1 Systematic Activity in Responses

Despite the system's absence of features to visually revisit Sculpts, participants managed to create sequences of Sculpts that exhibited unique patterns. We identified these patterns by constructing matrices of video stills from every session (Figures 2 and 3).

Figure 2 presents various attempts by participants to systematically explore the limits of timbre space, using large amounts of clay and probing the edges of the surface: **L1** explained their attempt to "find out the logic by putting extremes, to bring mass into the extremes." **L10** shared similar thoughts, stating "because I was struggling to see the patterns, I was trying to do the extremes." **L8** also ventured "into extremes to see if that would help me to work out what was doing what [...] it sort of feels like it's very subtle, some of the changes."

Figure 3 showcases **L20**'s disciplined approach to sculpting, highlighted by their sculpture of 38 steps, the longest in the dataset. This sequence, when viewed visually, appears almost like frames of a stop-motion animation or snapshots of a choreographed dance[2]. **L3** commented: "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."

[2]See this YouTube video `https://youtu.be/uR95X0iW7Oo` for an animated version.

4.2 Participant Reflections on Detail

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. Refer to [2] for more on how the participants' responses to the activity relate to their backgrounds, and [6] regarding the *proto-algorithmic* aspect of the sculpting patterns.

Becoming aware of infinite detail.

L25 gave a relatable description of the experience of learning how to perceive and manipulate micro scale details: "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 [...] as you step through each step in the process, you learn a bit about the causal chain." **L16** related their experience as focusing attention inwards towards the inherent detail of the sounds: "I was trying to pick sounds that could last a long time. If I'd have seen some piece [of music] 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]."

Emotional and psychological relationship to detail.

L14, **L15** and **L30** conveyed that conflict, struggle and contradiction were also part of the experience of working with fine details: **L14** mentioned that "the more you think about the details, the less peace you will have in your soul [...] I'm not sure thinking about more details is essentially making me happier." Similarly, **L15** claimed "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." **L30** had a different dilemma, saying "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 [details]."

Time and cultural memory of details.

L7 highlighted that the sculpting system's details did not possess any "cultural memory" of its own and that the difficulty of engaging with this activity was the lack of context through which to find meaning in the detail. **L7** noted "when you have an instrument that has no cultural memory of it, then I would benefit from a little bit more information [...] I was browsing so many things that I didn't really understand entirely the difference [...] 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." This sentiment was somewhat shared by **L18**, who claimed "I'm somewhat of a perfectionist" and that they "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", but "eventually I want the thing to be the exact way I want it to be, so I would go into detail."

Lack of interest in details.

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** was interested in finding timbral limits (Figure 2) and used sculpting tools as materials (Table 2), confirming that the system and activity "seemed much more nuanced than I would normally go". **L26** agreed; "Many times when I look for small differences, they don't matter too much. And I

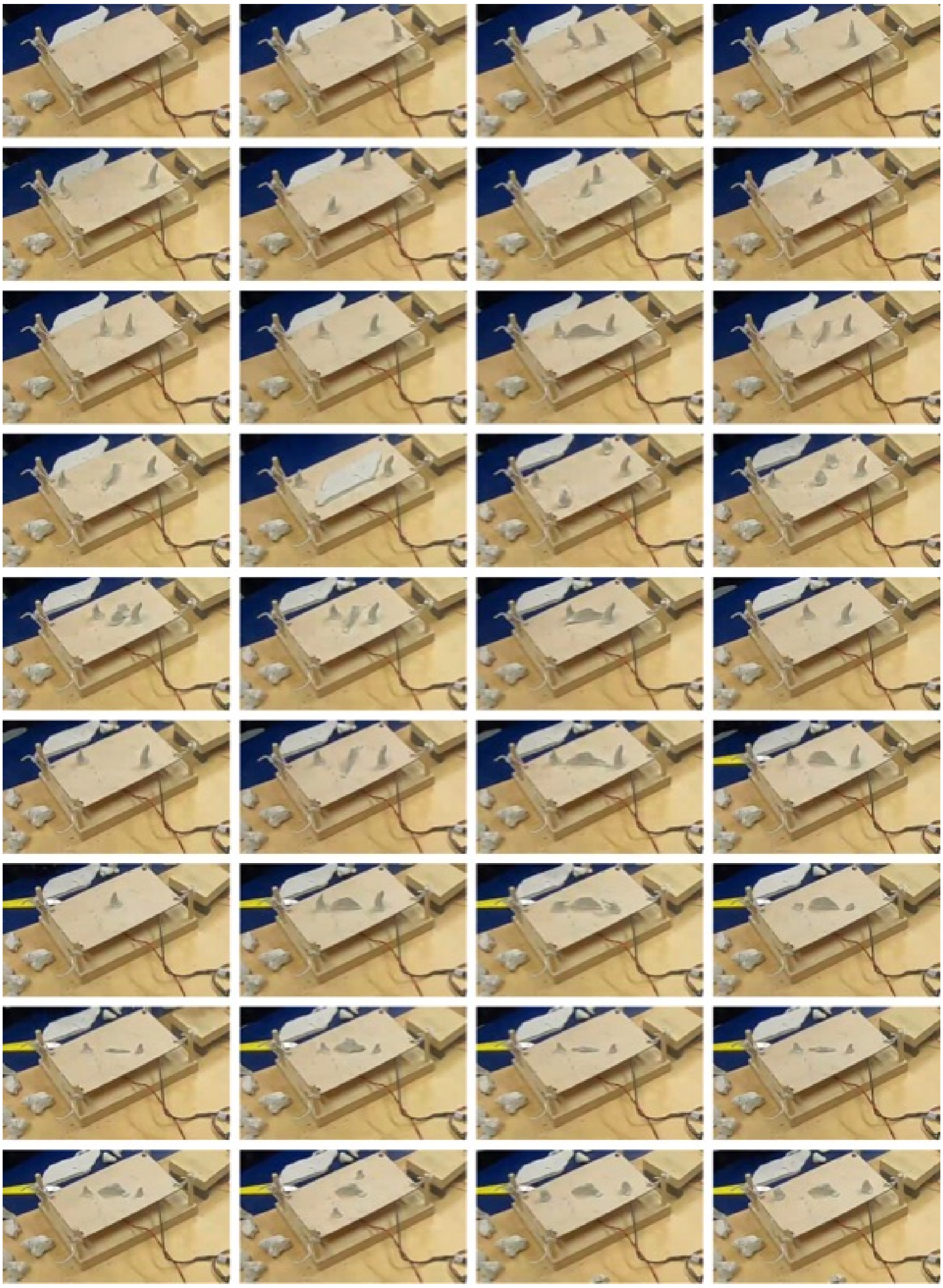

Figure 3: **L20** session's video stills display a sculpture comprised of 36 individual pieces (arranged from right to left in rows one to nine), showcasing remarkable attention to detail. Upon closer examination, one can discern a recurring motif within the pattern: a fingertip-diameter mound at the base, tapering to a pointed tip. This mound serves as the foundational element in the pattern, as its base diameter, height, and mass vary across the sculptures.

L20 surmised that the sculpting surface functioned as an "asymmetrical soundboard" possessing a "diagonal effect"; nevertheless, they expressed dissatisfaction with the GUI's lack of visual memory, stating, "I've gone through a series of sequences, I've not remembered which one was which". Moreover, they elaborated on their employment of symmetrical spatial motifs, explaining, "I've been playing around using symmetrically placed pieces because that seemed to be easier to manipulate and think about what you're doing [...] So the approach was logical, but [...] there were gaps in the logic."

Table 2: Examples and quotes from the outlier non-micro scale episodes in the study outcomes, where participants engaged in what we describe as macro and meso scale activity. Full details of these episodes can be found in [2].

	Inductive Definition	Deductive Examples	Luthier Quotes
Macro	*roles, forms and functions of instruments across ecologies.*	• Using the sculpting tool as a performance interface or pedagogical aid. • Storytelling with clay figurines, where each sculpt/sound is a 'frame'.	**L9**: This is ready for some storytelling [...] it is like a boxing ring [...] you can explain to people what is a sine sweep. **L27**: I created a very simple story: these are two animals, and they have a tea party, and after they have cake...
Meso	*configuration and mappings across taxonomically similar instruments.*	• "Hacking" the sculpting system to create clipped/distorted resonance models. • Using sculpting tools (e.g. knife, rolling pin) as sculpting materials.	**L5**: No more optimisation, let's kick it, introduce some variations [...] almost a reset, like a mutation, evolutionarily. **L8**: Because of the tools there, I wondered how subtle it would be able to detect [...] how shape would affect the sound.

look at them instead of looking at things that are more drastic, usually [...] 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."

Handcraft versus machined details.

L11 and **L13** appeared to display completely opposing relationships to precision achieved through handcraft versus digital fabrication: **L11** "A couple of people from software engineering backgrounds 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? 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** "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."

Violin luthiers' relationship to details.

L3, an experienced string-instrument maker and conservator, said that their experience made them "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." **L10** and **L11** were also both involved in acoustic instrument making. **L10** described that in their work they "always aim for perfection, sometimes that's more achievable than others." About the system, **L11** commented "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", adding "having to do it over and over and over again, that's just that what we do every day". Comparing with their own practice, **L11** said they would "never get bored" with violin making, which to them is "an endless problem, but in an interesting way".

5. DISCUSSION

5.1 Motivation to Focus on Subtle Details

These findings corroborate the DMI design literature on the efficacy of constraints in shaping musical activity [19, 22]. In this particular instance, it demonstrates that dedication to subtle and intricate design can be enhanced by limiting the macro and meso scale elements of an apparatus and activity while providing a simple, yet engaging, micro scale domain to work with.

Motivation for micro scale design seems to be bolstered by intimate interactions [18] with open materials [24]. Furthermore, the two role-playing scenarios within the activity altered participants' relationships with micro scale details, suggesting that the ecological context of a DMI [26, 13], even if fictitious, can not only encourage but actively steer micro scale design activity.

Section 4.1 highlighted a strong inclination towards systematic approaches to nuanced and detailed design, but due to time constraints and other limitations, this was feasible only to a certain extent. Regardless of whether this approach was ideal for the participant, it seems practical that study apparatus for micro scale design in less than an hour should endeavour to facilitate swift, systematic exploration (we explore this further in [6]). According to these results, in addition to the factors previously mentioned, affordances that might best support this include real-time, automated documentation, annotation, and visualisation of the experimentation process.

Another positive aspect of this apparatus was that any physical sculpture was valid and a sound would always be produced; thus, there were no potential errors and no 'aesthetics of frustration' typically associated with digital sound programming experiences [11]. Considering these findings and interpretations, it appears that technical advancement in micro scale design with an unfamiliar apparatus is directly related to both the rapidity and sophistication of systematic exploration affordances and the relevance of preexisting knowledge and abilities.

As for creative engagement with micro scale design, Section 4.2 posited that it is heavily influenced by participants' inherent motivation to work with subtle details generally. In this study, the activity briefs did not explicitly outline much context surrounding the micro scale particulars of the musical instrument, leaving this aspect unfamiliar and open-ended. For certain participants, their motivation would have been enhanced had there been a more unambiguous briefing about this element of the activity. Lastly, despite meso and macro scale constraints, participants whose practices predominantly involve meso [9, 4] and macro [8] scale design were likely to explore the upper extremes of the micro scale domain and potentially subvert the apparatus or activity to investigate meso and macro scale reinterpretations.

5.2 Implications for DMI design

DMI design technologists aiming to facilitate subtlety and detail in DMI design, or reflect on the effects of current tools, may find it helpful to examine the affordances provided by the apparatus in this study and consider which existing tools, if any, support this type of design. Although this apparatus is not proposed as a blueprint for all successful subtlety and detail-oriented DMI design tools, the underlying principles and approach might prove beneficial. These principles entail leveraging existing physical crafting skills, fostering tactile intimacy and open-ended material play, minimising disruptive errors, and developing DMI design tools that are as real-time as possible.

Technologists might also question how particular tools constrain macro, meso, and micro scale design, along with their impact on user motivation. If certain biases are discovered, were they designed accidentally, intentionally, or after an unforeseen event? Supporting rapid systematic exploration of micro scale details presents an intriguing area to investigate, as affordances enabling this may differ significantly from current DMI design tools, being perhaps more process-oriented. This study indicates that rapid systematic exploration is enhanced when design moves are navigable and comparable through automated documentation and visualisation. We delve further into this idea from an algorithmic pattern perspective in [6]. Existing reified tools may resist interventions with this effect, necessitating novel tools with fewer or different assumptions about the user's relationship with micro scale details.

This research was relatively high-level and exploratory, prompting many issues and questions among DMI design researchers that may only be addressed through more detailed and controlled studies. Yet, the overall conclusion seems plausible: it is possible to motivate micro scale design within a one-hour activity using an unfamiliar apparatus, a previously unproven accomplishment with specific implications. Primarily, this means that studying subtle and detailed DMI design doesn't rely solely on longitudinal, in-the-wild studies [27] limited to small cohorts. "In vitro" study then becomes a viable, complementary alternative with favourable factors of frugality, specificity, and unfamiliarity [30]. The latter has been constructively employed in numerous DMI design studies [23, 15, 31], rendering certain types of questions more manageable. One significant avenue of interest concerns the physiological and sensorimotor processes underlying the acquisition and application of tacit and embodied knowledge of subtle DMI design details. Studies could further explore how this knowledge is transferred and co-developed between makers in various community settings, from individual and in-person workshops to group and online contexts [32].

Moreover, future research might combine "in vitro" and "in vivo" approaches by utilising an "in vitro" study as the foundation for a more detailed "in vivo" study or vice versa. We envision a spectrum of methods and approaches for investigating subtle and detailed DMI design, with the "in vitro" approach offering a valuable addition to existing methodologies. Our approach could also supplement micro-phenomenology, recently utilised in NIME [25], to examine the experience of micro scale details with agential and intelligent instruments [7, 3].

6. CONCLUSION

In this paper, we have detailed our exploration into subtlety and detail in digital lutherie, which we characterise as the nuances between taxonomically similar instruments or the same instrument at different moments. Our study demonstrated how employing DMI design probes and activities with constrained high-level functions, features, and briefs alongside open-ended subtle details can foster subtle and detailed responses, even within a one-hour activity. We suggest that this approach presents a frugal and complementary alternative to longitudinal, ethnographic, and in-the-wild studies, enabling more comprehensive comparisons across participants.

The outcomes of our study indicate that DMI design technologists can more effectively support subtle and detailed design and craft by capitalising on existing physical crafting knowledge and skills, encouraging tactile intimacy and open-ended material play, eliminating disruptive runtime errors, and developing DMI design tools that are as real-time as possible. Moreover, we propose that DMI design researchers interested in tacit and embodied knowledge in digital lutherie will find that concentrating on micro scale details and devising study probes and activities yielding design and craft process data at this level unveils an untapped domain for empirical investigation.

This new area of study could provide valuable insights into the physiological and sensorimotor processes underlying the acquisition and application of tacit and embodied knowledge about subtle design details of DMIs. Additionally, it may shed light on the collaborative aspect of digital lutherie, addressing how this knowledge is transferred and co-developed within various settings like individual, in-person workshops or online community platforms.

Furthermore, as part of future research, a hybrid approach combining this "in vitro" method with "in vivo" analysis could be employed, encompassing various methodologies to enhance our understanding of subtle and detailed DMI design. This approach may offer a more holistic perspective, fostering innovation and advancements in digital musical instrument design, and perhaps, the overall experience of digital lutherie.

In conclusion, our investigation has opened up new avenues for exploring the subtleties and details that make digital musical instruments engaging and satisfying to create and perform with. Through continuing this research, we hope to contribute to the development of more impactful, expressive, and nuanced DMIs for artists, musicians, and designers alike.

7. ACKNOWLEDGMENTS

Thanks to Victor Shepardson, Nicola Privato, Andrea Martelloni and Rodrigo Diaz for feedback. Thanks to the anonymous reviewers for their helpful comments and suggestions.

This research is supported by the European Research Council (ERC) as part of the Intelligent Instruments project (INTENT), under the European Union's Horizon 2020 research and innovation programme (Grant agreement No. 101001848). This research was also supported by EPSRC in the UK, under the grants EP/L01632X/1 (Centre for Doctoral Training in Media and Arts Technology) and EP/N005112/1 (Design for Virtuosity).

8. ETHICAL STANDARDS

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 handcrafting tools and asked to use them to carry out a set of tasks" 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. On arriving for their session, participants reviewed a proforma consent form, which contained a description of the activity.

9. REFERENCES

[1] J. 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*, <Programming> '20, pages 225–226, New York, NY, USA, Mar. 2020. Association for Computing Machinery.

[2] J. Armitage. *Subtlety and Detail in Digital Musical Instrument Design.* Thesis, Queen Mary University of London, Apr. 2022.

[3] J. Armitage and T. Magnusson. Agential Scores: Artificial Life for Emergent, Self-Organising and Entangled Music Notation. In *Proceedings of the 8th International Conference on Technologies for Music Notation and Representation.*

[4] J. Armitage, T. Magnusson, and A. McPherson. Design Process in Visual Programming: Methods for Visual and Temporal Analysis. In *Proc. Sound and Music Computing Conference.*

[5] J. Armitage, T. Magnusson, and A. McPherson. A Scale-Based Ontology of Digital Musical Instrument Design. In *Proc. New Interfaces for Musical Expression.*

[6] J. Armitage, T. Magnusson, and A. McPherson. Sculpting Algorithmic Pattern: Informal and Visuospatial Interaction in Musical Instrument Design. In *Proc. Sound and Music Computing Conference.*

[7] J. Armitage, T. Magnusson, V. Shepardson, and H. Ulfarsson. The Proto-Langspil: Launching an Icelandic NIME Research Lab with the Help of a Marginalised Instrument. In *Proc. New Interfaces for Musical Expression.*

[8] J. Armitage and A. McPherson. Crafting Digital Musical Instruments: An Exploratory Workshop Study. In *Proc. New Interfaces for Musical Expression*, Blacksburg, Virginia, USA, 2018.

[9] J. Armitage and A. McPherson. Bricolage in a hybrid digital lutherie context: A workshop study. In *Proceedings of the 14th International Audio Mostly Conference: A Journey in Sound*, pages 82–89, Nottingham United Kingdom, Sept. 2019. ACM.

[10] J. Armitage, F. Morreale, and A. McPherson. The finer the musician, the smaller the details: NIMEcraft under the microscope. In *Proc. New Interfaces for Musical Expression*, pages 393–398, Copenhagen, Denmark, 2017. Aalborg University Copenhagen.

[11] A. Basman. Building Software is Not a Craft. *Proceedings of the Psychology of Programming Interest Group*, 2016.

[12] P. Cook. Principles for designing computer music controllers. In *Proc. NIME*, 2001.

[13] C. Erkut and S. Serafin. From Ecological Sounding Artifacts Towards Sonic Artifact Ecologies. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, pages 560–570. ACM, 2016.

[14] B. Gaver, T. Dunne, and E. Pacenti. Design: Cultural probes. *interactions*, 6(1):21–29, 1999.

[15] M. Gurevich, P. Stapleton, and A. Marquez-Borbon. Style and Constraint in Electronic Musical Instruments. In *Proceedings of the International Conference on New Interfaces for Musical Expression*, pages 106–111, Sydney, Australia, 2010.

[16] H. Hutchinson, W. Mackay, B. Westerlund, B. B. Bederson, A. Druin, C. Plaisant, M. Beaudouin-Lafon, S. Conversy, H. Evans, and H. Hansen. Technology probes: Inspiring design for and with families. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 17–24, 2003.

[17] R. Jack, J. Harrison, and A. McPherson. Digital musical instruments as research products. In R. Michon and F. Schroeder, editors, *Proceedings of the International Conference on New Interfaces for Musical Expression*, pages 446–451, Birmingham, UK, July 2020. Birmingham City University.

[18] R. H. Jack, A. Mehrabi, T. Stockman, and A. P. McPherson. Action-sound Latency and the Perceived Quality of Digital Musical Instruments: Comparing Professional Percussionists and Amateur Musicians. *Music Perception*, 36(1):21, 2018.

[19] R. H. Jack, T. Stockman, and A. McPherson. Maintaining and Constraining Performer Touch in the Design of Digital Musical Instruments. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '17, pages 717–720, New York, NY, USA, 2017. ACM.

[20] S. Jordà. *Digital Lutherie: Crafting Musical Computers for New Musics' Performance and Improvisation.* PhD thesis, Universitat Pompeu Fabra, 2005.

[21] S. Kettley. 'You've got to keep looking, looking, looking': Craft thinking and authenticity. *Craft Research*, 7(2):165–185, Sept. 2016.

[22] T. Magnusson. Designing constraints: Composing and performing with digital musical systems. *Computer Music Journal*, 34(4):62–73, 2010.

[23] A. P. McPherson, A. Chamberlain, A. Hazzard, S. McGrath, and S. Benford. Designing for exploratory play with a hackable digital musical instrument. In *Proc. ACM Designing Interactive Systems*, pages 1233–1245. ACM, 2016.

[24] C. Nordmoen, A. McPherson, J. Armitage, F. Morreale, and R. Stewart. Making Sense of Sensors: Discovery through craft practice with an open-ended sensor material. In *Proc. Designing Interactive Systems*, page 10, 2019.

[25] C. N. Reed, C. Nordmoen, A. Martelloni, G. Lepri, N. Robson, E. Zayas-Garin, K. Cotton, L. Mice, and A. McPherson. Exploring Experiences with New Musical Instruments through Micro-phenomenology. In *NIME 2022*, jun 16 2022. https://nime.pubpub.org/pub/o7sza3sq.

[26] M. Rodger, P. Stapleton, M. van Walstijn, M. Ortiz, and L. S. Pardue. What makes a good musical instrument? A matter of processes, ecologies and specificities. In R. Michon and F. Schroeder, editors, *Proceedings of the International Conference on New Interfaces for Musical Expression*, pages 405–410, Birmingham, UK, July 2020. Birmingham City University.

[27] Y. Rogers and P. Marshall. Research in the Wild. *Synthesis Lectures on Human-Centered Informatics*, 10(3):i–97, 2017.

[28] G. Torre and K. Andersen. Instrumentality, Time and Perseverance. In T. Bovermann, A. de Campo, H. Egermann, S.-I. Hardjowirogo, and S. Weinzierl, editors, *Musical Instruments in the 21st Century*, pages 127–136. Springer, 2017.

[29] G. Torre, K. Andersen, and F. Baldé. The Hands: The Making of a Digital Musical Instrument. *Computer Music Journal*, 40(2):22–34, May 2016.

[30] D. Wilde, A. Vallgårda, and O. Tomico. Embodied design ideation methods: Analysing the Power of estrangement. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 5158–5170. ACM, 2017.

[31] V. Zappi and A. McPherson. Dimensionality and Appropriation in Digital Musical Instrument Design. In *Proceedings of the International Conference on New Interfaces for Musical Expression*, pages 455–460, 2014.

[32] L. Zayas-Garin, J. Harrison, R. Jack, and A. McPherson. DMI Apprenticeship: Sharing and Replicating Musical Artefacts. In *International Conference on New Interfaces for Musical Expression*. PubPub, Apr. 2021.