Studying How Digital Luthiers Choose Their Tools

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ABSTRACT

Digital lutherie is a sub-domain of digital craft focused on creating digital musical instruments: high-performance devices for musical expression. It represents a nuanced and challenging area of human-computer interaction that is well established and mature, offering the opportunity to observe designers' work on highly demanding human-computer interfaces. This paper explores how and why digital luthiers choose their tools and how these tools relate to the challenges they face. Findings from 27 standardised open-ended interviews with prominent digital luthiers from commercial, research, independent and artistic backgrounds are analysed through reflexive thematic analysis. Our discussion explores their perspectives, finding that a process of pragmatic rationalisation and environmental influences play a significant role in tool selection. We also present how challenges faced by digital luthiers relate to social creativity and meta-design. These findings build upon the existing literature that examines the designer-tool relationship.

CCS CONCEPTS

• **Human-centered computing** → **HCI theory, concepts and models**; **Interactive systems and tools**; • **Applied computing** → **Sound and music computing**;

KEYWORDS

Digital Musical Instruments, Digital Luthier, Design Tools, Design Practice, Qualitative, Thematic Analysis, Programming Languages

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1 INTRODUCTION

Digital lutherie, a term coined by Jorda [44], refers to the specalized domain [37] and diverse community that is concerned with the creation of technology for music. Creating digital instruments or interfaces, capable of expressing musical intention, is a process incorporating many disparate and specialist skills [69]. In the pursuit of this craft, the designer is required to use tools that extend beyond the traditional tools of a luthier (or any other traditional instrument builder), allowing the manipulation of digital technology as an additional medium [53]. Whilst the relationship between performer and their tools for performance is studied extensively, the relationship between the digital luthier and their tools is typically studied from the performer's perspective [9, 58] or otherwise focuses on the luthier's processes and intended outcomes [4, 22, 55, 65]. This is perhaps owing to the multifaceted role of the digital luthier, often performing the tasks of a designer, builder and performer [45]. It is then true that, as Cheatle and Jackson put it, artists "...act as creative and critical users of tools – both computational and otherwise – whose practice has the potential to reveal new insights and understandings about the world in which we live..." [17]. Whilst the artistic component of digital lutherie is apparent, there are of course many additional motivations for the design of digital musical instruments (DMIs) [40, 66, 79, 87]. The understanding and appreciation of musical context and culture and how they influence design are given due attention [52] and the open-source community around DMI design provides a unique and notable observation of social influences on design [74]. This work demonstrates the complex landscape of the designer-tool relationship and suggests many contributing factors at play. However, less work has been done to look at these relationships from the perspective of contemporary practitioners of digital lutherie, despite support for their apparent influence [65].

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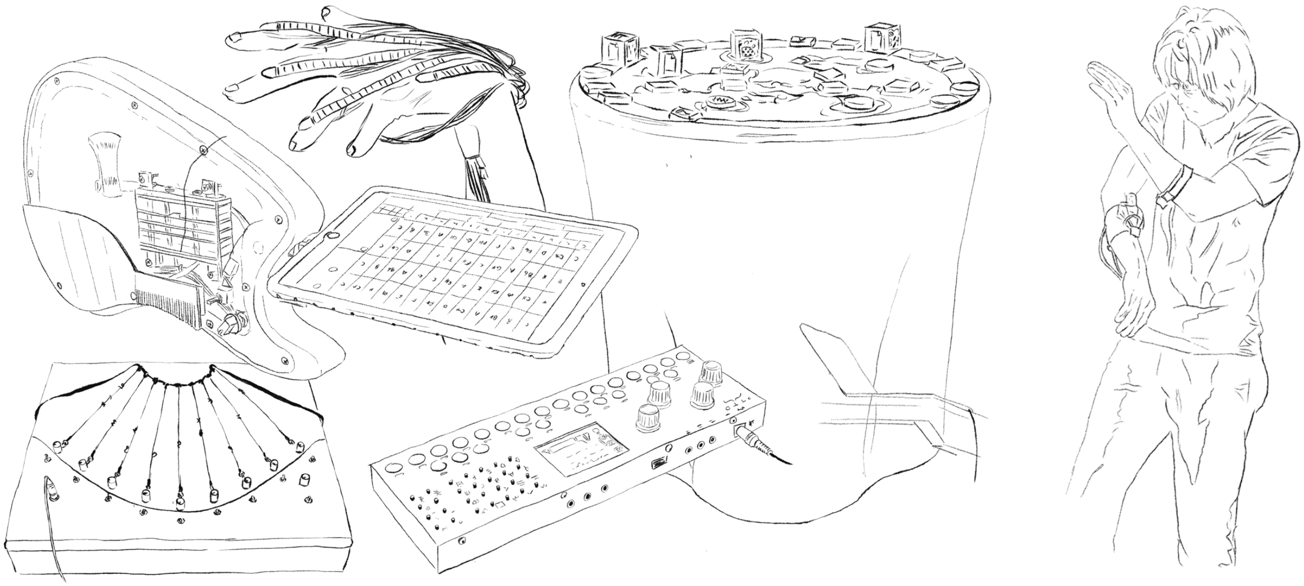

Figure 1: The Blade Axe, Electronic_Khipu_, The Ladies Glove, OTTO, Reactable, EMG based instrument

In the wider human computer interaction (HCI) community, we see Stolterman and Pierce examine the designer-tool relationship more directly [81]. They suggest that, in the HCI community, there is a tendency to focus on end-users (user-centred design). Similarly, in the digital lutherie community, considerable attention is given to the processes and use of tools [30, 39, 48]. Research on the motivations for choosing tools remains sparse. As such, this work looks to contribute to Stolterman and Pierce's suggestion that *"... there is a need for more developed understandings of how practicing designers use, understand, and interact with their tools"* by exploring this designer/tool relationship as a means to better understand the design practice [34]. This paper examines a group of digital luthiers, with differing perspectives, backgrounds and motivations and seeks to understand the challenges they face and the tools they use to overcome these challenges. This includes meeting the performance demands of real-time systems [41, 64] and the complex interaction goals [92] amongst many other individual challenges. We explore this relationship through three research questions:

Why and how do Instrument designers pick their tools?

What distinct problem spaces do instrument designers consider to be involved in instrument design?

How do instrument designers define a digital musical instrument?

We analyse 27 standardised open-ended interviews with prominent digital luthiers using reflexive thematic analysis, from which we generate three themes titled 'The Pragmatist', 'A Product of our Environment' and 'Intentions' (presented in Section 3). In Section 4 we discuss these generated themes and relate them to Stolterman and Pierce's previous work [81] as well as considering the implications of our findings in relation to the broader literature. This approach aims to build on existing work whilst drawing on the rich stream of research that has focused on digital lutherie, making observations that may generalise to other domains of design for digital systems. In particular, we consider the tools that facilitate the programmatic definition of instruments such as programming languages and graphical programming tools such as Max/MSP [77]. We provide our methodology in Section 2 and also in a prepublication [78], which provides a description and access to the data collected in this study in the hope it encourages further work in this area. We conclude with a summary of our findings and suggested directions for future work in Section 5. In the remainder of this section, we provide a background in support of our discussion and findings.

1.1 Situating Digital Lutherie as a Design Domain

Design is a field that naturally connects many domains, ranging from architecture to biology and beyond. Due to such complexity, it is no surprise that research tends towards domain-specific studies of design. While efforts toward a generalized definition of domain-independent design have been attempted [10, 82, 83], these failed to effectively incorporate aspects such as the creative and innovative components of design; a characteristic attempted to be captured by C-K theory [36]. Despite the attempts of C-K theory, much of the research design community have been more divided than unified by such theories, as highlighted by Dorst [90]. Dorst, too, looks to strategies to bring together independent fields of design with an approach that seeks to reconcile design practice and research. Rather than a single generalized framework, Dorst advocates for recognizing that design research exists as a discussion between dynamically interrelated fields and suggests that they should build bridges between them when appropriate to create a richer discussion.

The design process of creative technologists has primarily been researched in the context of digital craft, which focuses on expressivity, allowing individual mastery over the medium with which they work [42]. Much in line with Dorst's suggestions, combinations of craft and technology are being explored in considerable depth in areas such as DMI design and eTextiles [76]. This introduces a focus on the capacity for the craftsperson to achieve an ever more comprehensive and demanding set of engineering challenges whilst retaining the critical component of creativity described by Fischer [27]. Fischer describes the requirement for social and individual creativity in design as a spectrum that ideally depends on cross-pollination between the two, facilitated through the environment in which they interact.

Frankjaer and Dalsgaard observe that craft-based practices can address many outputs and processes [29]. Examples given include the digitally assisted design of physical artefacts, computational physical artefacts and materials, digital artefacts such as code, merging digital and physical media and practices, and artefacts emerging from within Maker and DIY culture. They further observe that the ambiguity in defining a 'craft process' presents challenges in addressing knowledge creation that generalises to all craft processes. This ambiguity tends to also be prevalent within the specific domains in which we see digital craft, such as in providing a firm taxonomy of artefacts in the DMI community [85]. Ultimately, Frankjaer and Dalsgaard observe three approaches to the scientific inquiry of craft practices. They state these as "1. Combining, aligning, and integrating analogue and digital crafting techniques and processes; 2. Creating highly refined artefacts, defined by attention to detail and aesthetics; 3. Creating knowledge through deep, embodied engagement." They define these to encourage researchers to engage in craft processes in a tacit and embodied manner, engaging with the knowledge in a practice-based manner. This emphasis is due to the narrowing of experiential knowledge as it is transferred into the written form that constitutes typical scientific literature, a perspective shared by Dorst [90]. As such, the developing approach to analyse the design process of practitioners incorporates strategies such as workshops [52, 76], interviews with expert practitioners [81] and qualitative analysis of data derived from the first-hand experience.

The maker movement has profoundly lowered technological barriers, democratising and opening up access to technology [86]. Increased quality and availability of 3D modelling software and manufacturing methods drive the production and further development of more traditional instruments [23, 47, 95]. Entire hardware platforms dedicated to supporting the design intentions of digital luthiers also situate high performance embedded computing within the community [54, 64, 89]. This enables the realization of many forms of instrument design, from hybrid instruments [88], to entirely novel instruments.

1.2 Understanding the Designer-Tool Relationship

Given that its namesake is derived from the artisanal craft process of building stringed instruments, it is little surprise that digital lutherie, the process of building any form of DMI, has also been examined in the context of digital craft [5]. Digital luthiers often embrace a multifaceted role in their craft process, blurring the boundary between designer, builder and player. The building and design process both involve a range of technical cross-disciplinary skills. Nevertheless, the challenges of digital lutherie do not end there. There are considerations in the design of new DMI extending beyond the artefact itself and its use [43]. Numerous challenges related to the continued use and practice of the artefacts produced must also be considered [72]. Whilst this does raise the question concerning the importance of persistence in digital artefacts, all of these factors are important to consider in light of the intentions of the digital luthier (and further also the digital craftsperson more generally).

Stolterman and Pierce study the relationship between tool and designer concerning interaction design [81], noting the nearly infinite combination of tools that the designer may pick to support their approach. While superficially, characteristics such as 'efficiency' or 'ease of use' may motivate selecting a specific tool, they contend that the reality is more complicated and involves the social, cultural and material contexts in which design occurs. They look to Argyris' theory of action [3] as an explanation whereby the idealized way the designer wishes to approach the problem contrasts the reality.

In the context of digital lutherie, we see many interesting relationships between designers and their tools. If we look to the field of 'live coding', where performers use programming languages to manipulate audio and music in real-time [21], we can see a tendency of performers to write their own programming languages [57, 62, 63, 91]. Within this community this is recognised to the extent that work is actively exploring the facilitation of creating new languages [8]. We also see a similar niche fulfilled using machine learning [25], with both cases deferring some design component to the performer. We may also then consider that the design practice of digital luthiers sits at least partially at the level of meta-design, as described by Fischer and Scharff [28] as in many cases, for expressive musical interfaces, some component of the specification is deferred to the user. This deferred design component may be a controllers mapping to synthesizer parameters, for example, which can be approached in a variety of ways [51].

Ultimately, the role of a digital luthier provides a rich insight into digital craft, with well-established communities, research and technological ecosystem.

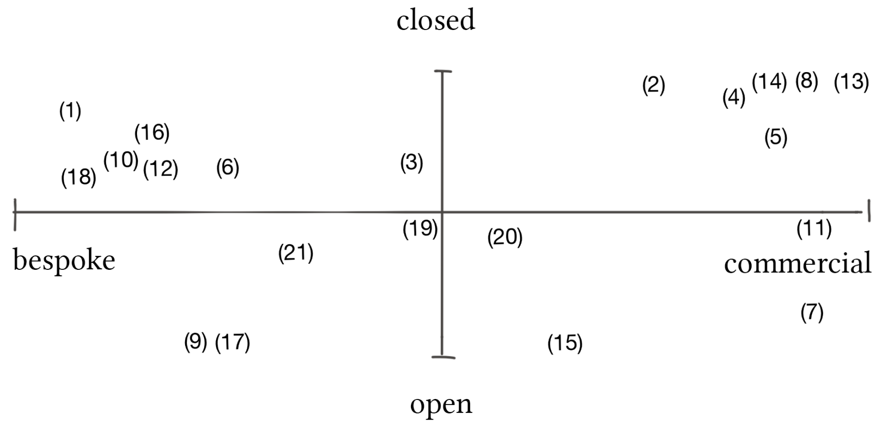

Figure 2: Plot representing an instruments characteristics, whether its motivation is commercial or bespoke (such as for a single art project) and whether it is closed source or open (where we incorporate surrounding publications and knowledge exchange as a form of openness). Numbers correlate to the instruments listed in Section 2.3.1.

2 METHODOLOGY

This study explores the perspectives of digital luthiers with a range of different motivations using reflexive thematic analysis as introduced by Braun and Clarke [11]. In order to best demonstrate rigour in our approach [20, 50] and to encourage further development of this work, we refer to a prepublication of our study, presented ahead of undertaking analysis [78]. Essential information is summarized below. Further details can be found in the related prepublication.

This methodology somewhat contrasts the approach typical of similar research based on grounded theory [12], omitting the need for peer validated coding for example. In this study, two primary coders familiarized themselves with and inductively coded the transcripts. Throughout the process, the research team met regularly to discuss and iterate around the analysis process (described below). This approach aimed to draw on the knowledge and experience of the research team to examine and generate themes [13], utilizing reflexive practice [2].

Based on Braun and Clarke's process for reflexive thematic analysis, the approach followed these steps:

1. Data familiarization period for reviewers
2. Data coding
3. Generation of themes
4. Discussion between researchers on themes, reflection and development
5. (Iteration around steps 2-4)
6. Refining and naming themes and development of themes
7. Writing paper; discussion of themes

In line with Braun and Clarke's [12] description of reflexive thematic analysis, we recognise that as researchers we play a role in the generation of qualitative information [35]. Researcher backgrounds and more information to contextualise our stance can be found in the prepublication [78]. Ethical approval for this study was granted by the authors' Faculty Research Ethics Committee. Participants provided written consent for the information provided to be used in this work and provided in a raw format for future works. Prior to publication of the data, participants were offered the opportunity to make amendments or redact any part of their transcripts.

2.1 Motivations

This work is motivated to explore the relationship between tools and the designers of high-performance devices for human-computer interaction. Digital lutherie represents a well-developed example of such a community, typically centred around the NIME conference [60]. In particular, we seek to explore how digital luthiers choose the tools that facilitate the digital components of their craft, with a primary interest in how the interactions of programming instruments occur. We recognise that digital lutherie has become a rich opportunity for the development of new programming languages [67]. In particular, domain-specific languages [38] such as those that underpin the live-coding community [21]. However, this area of research is missing an extensive analysis of how people come to settle on the programming languages (and other tools) that allow them to build complex systems. We provide further context to our motivations in our prepublication [78].

2.2 Participants

Participants were directly invited according to a purposeful sampling strategy based on their contributions to a range of novel digital musical instruments or association with an organisation that produces novel DMIs. Participants were approached online and invited to participate or recommend a suitable participant. A subset of these instruments are listed in Section 2.3.1, and a selection is illustrated in Figures 1, 3 and 4.

Categories of Commercial, Research, Community and Artist backgrounds were defined as a basis to select participants. Commercial and Research categories describe instruments for either commercial production or coupled to a research process, respectively. Community instruments broadly encompass open source projects, small teams or individuals, independently making instruments in low volumes. The Artist category represents instrument designers who build instruments to support their artistic endeavours. Of course, there is significant overlap with these definitions; however, drawing evenly from these groups helped to vary the sample of the community.

Purposeful sampling was also selected to more deliberately distribute perspectives across genders in search of a more gender diverse representation [61, 71, 94]. We acknowledge a lack of cultural diversity in this study, another important facet of diverse study populations that should be accounted for in future work [93]. These factors could be improved with a broader call in conjunction with the selection process used here, such that selection is not limited to the networking capacity of the researchers.

For this study, 27 participants were interviewed. A demographic of the population is provided in Table 1, and a selection of the participant's self described roles can be seen in Section 2.2.1. Further, information gathered on the participants includes their familiarity with HCI literature or the NIME community [60], the programming languages they use and the tools they use. We also capture a rudimentary metric of experience in the form of years spent in the field and the number of instruments they have designed. We emphasise that this is a metric of limited insight that can poorly characterise experience. However, attention was given to incorporating a range of experience levels when sampling participants in the selection process. For further details on the data set used (including the published dataset), see the prepublication [78].

2.2.1 *Participant Roles.*

- Music Technology Researcher and Professor.
- Digital Artist/Performer/Composer
- Artist
- Software Engineer
- Software Engineering Manager
- CEO
- Composer
- Founder
- Researcher and Lecturer
- Assistant Professor of Music Technology
- Composer & Instrument Builder
- Audio Developer
- Researcher, Designer, Performer
- Software Developer
- Professor
- Electronic musician
- DSP Engineer
- Professor of Media Computing
- Hardware and Software Engineer
- Lead Designer
- Composer and Interactive Hardware Developer
- Creative Director

2.3 Instruments

The instruments created by this group of designers represent a range of novel devices with a significant digital component. The sampling strategy aimed to incorporate many modes of interaction and motivations for instrument development. Instruments include open source and proprietary instruments, with some instruments representing a hybrid of the two (for example, open-source software only). Instruments also vary from bespoke instruments designed for a limited project to instruments intended for commercial mass-market production. This is often reflected in the designer's role; however, it is notable that many designers themselves work on multiple instruments that have very different use cases, decoupling the role of any one instrument and the designer. The instruments included in this study are intended to generally represent the work of the digital luthier and may include instruments that were developed with others or individually. It should be noted that the interviews were conducted around the holistic experience of the participants and not focused on the design of single instruments for the most part. The instruments listed are shared to help to represent the motivations and context in which the participants operate and therefore the kind of perspectives they may share.

2.3.1 *Participant Designed Instruments.*

(1) Soft Revolvers
(2) Alpha Sphere
(3) Knurl
(4) Artiphon Orba
(5) Reactable
(6) The Blade Axe
(7) Mutable Instruments Beads
(8) Claravox
(9) Polaron
(10) The Ladies Glove
(11) Linnstrument
(12) Concertronica
(13) Abelton Push
(14) Roli Seaboard Grand
(15) OTTO
(16) Electronic_Khipu_
(17) The Daïs
(18) EMG instruments
(19) Gechologic Loopsynth
(20) Bastl Kastle Drum
(21) The D-Box

2.4 Interviews

Following an internal pilot study with peers with DMI design experience, standardised open-ended interviews were conducted with 22 participants engaging with an interviewer via video call and five via email. Interviews had a duration of 20 - 60 minutes at the discretion of the participant. Interviews took place between 25th January 2021 and 1st April 2021. Participants were provided with a copy of the questions to use as a reference during the interview. The lead author carried out all interviews.

Gender		**Ethnicity**		**Age**	
Male	14	White	21	18 - 24	1
Female	8	Asian	1	25 - 34	12
Non Binary	1	Lantinx	1	35 - 44	6
Prefer not to say	4	Brazilian	1	45 - 54	2
		Prefer not to say	3	55 - 64	4
				Prefer not to say	2

Table 1: Participant demographics (N = 27)

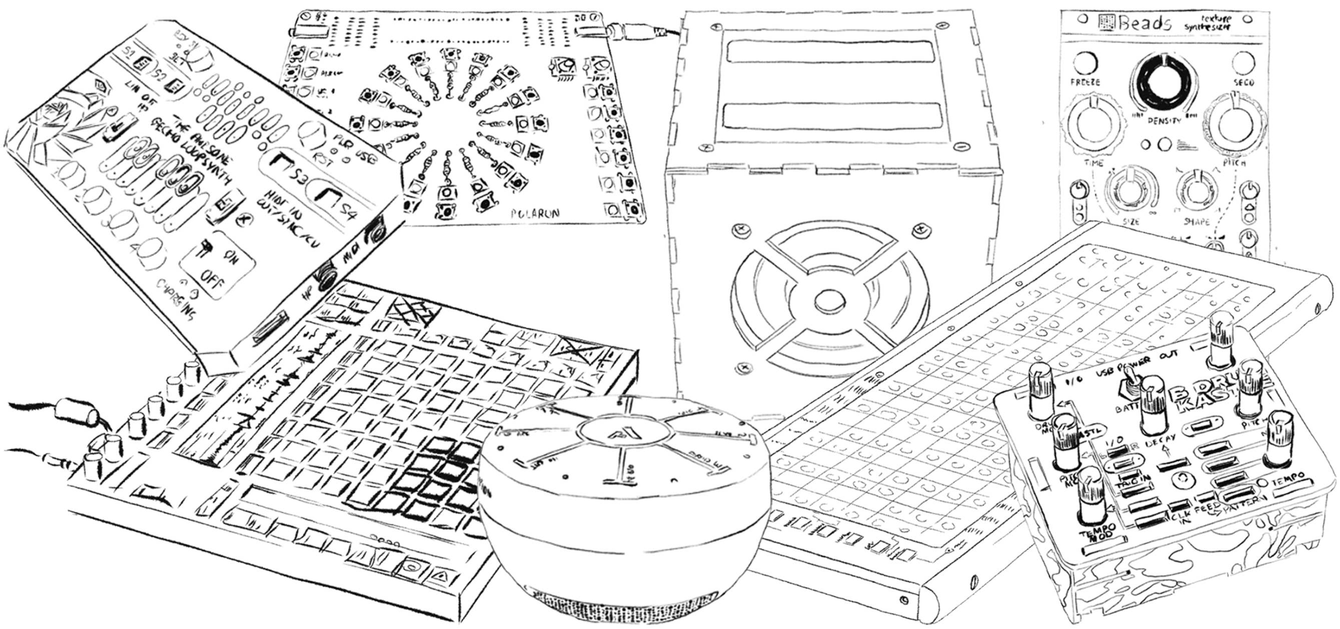

Figure 3: Gechologic Loopsynth, Push, Polaron, Orba, The D-Box, Linnstrument, Mutable Instruments Beads, Bastl Kastle Drum

Interviews were recorded (audio only) and transcribed verbatim, then processed to ensure appropriate confidentiality and IP protection. In the case of email interviews, emails were formatted to match transcripts.

3 RESULTS

From the 27 participants interviewed, three themes were generated that provided narratives to perspectives of the digital luthiers that address the research questions of this study. To contextualise quotes, we reference the participant ID found in the transcripts (e.g P7 for participant 7). Where relevant, we will mention data provided by the participant that is accessible as metadata in the transcripts or within the data repository[1]. For more details on the published data and metadata, see the prepublication. Excerpts from transcripts may be edited from the verbatim transcripts for ease of reading (whilst maintaining meaning), with square brackets indicating notable edited words.

[1] https://github.com/muses-dmi/dmi-design-study

3.1 'The Pragmatist'

'The Pragmatist', captures the prevalent tool selection approach conveyed by many participants. Participants tended to see themselves as having pragmatic motivations for tool selection, such as choosing the tool or programming language best supported on their target platform. In contrast, the pragmatic choice for others is using a language in which they are proficient, which may be less suitable for the platform but saves time overall. This theme portrays the shared experience that designers tend toward making decisions with a cost-benefit analysis based on their own experience and the technology they interact with.

The theme takes its title from P1, who referred to being pragmatic throughout the interview:

> "So I would say I'm very pragmatic with that. If the question is why, I mean, it depends [on] so many things, on what's available and what you can do." (P1)

P23 also shares this terminology, describing their pragmatic decision-making process.

> "No, I think, my choice of language at that moment, I must say, it's very pragmatic. And it's, it perhaps isn't for the elegance of the coding act, but for interoperability, platform independence. And so there's a natural tendency to go towards just tried and true languages like C or C++. It's been very interesting to see how a slightly higher level language like Python has really evolved in the past few years to become a kind of standard for signal processing." (P23)

P1 and P23 both use the term 'pragmatic' to identify their motivations but focus on different technical requirements demonstrating that each project requires the weighing of specific characteristics rather than a common path of least resistance for all instruments. For example, P23, a researcher, notes that platform independence is valued in their tools. P1 is also a professor but notes that due to the time in which they worked on their instruments, the primary consideration was what technology was available and could meet the required goal at all. In their interview, P1 goes on to suggest that there is much more choice for tools now. P15 builds on this, also referencing interoperability, this time in the context of the now rich existing ecosystem of technologies that already exist. When asked why they chose their tools, p15 mentions:

> "But also because of how it integrates with other tools like Max, for instance, because you can write your own externals in C or C++, like, audio plugin API's and so on. Right. So this would be the main reason why I, or people I work with continue using C++, I believe." (P15)

Aside from performance reasons, P15 suggests that C and C++ are pervasive in digital musical technology in large part due to interoperability. They also provide more personal insight, suggesting that fluency is highly valued.

> "The other one would be Python. Because first of all, I think this is still the most relevant reason, I am fluent in it." (P15)

This suggests two sides to the pragmatic designer. One that accounts for technical requirements of the system they are working with, such as those introduced by P1 and P23, and one that considers the individual capabilities of the designer (or designers), such as existing skills and knowledge. We look at these as the ideas of technical and individual pragmatism, respectively, representing two sides to the pragmatic designer described in this theme. Participant 15 emphasises the point that this fluency is a powerful motivation in choosing a tool that speaks to the capacity of being able to express ideas using the tools available efficiently, a principle that resonates with many other participants:

> "...the properties of the language lead you to be able to be expressive and create an instrument of different expressivivity more directly and so I think the choices are deeply related." (P19)

> "I think I've talked about my main goals in digital musical instrument design are to be immediately expressive and is the reason i choose to make digital musical instruments as opposed to analogue." (P26)

> "As I said, a language or something for C++ or something that is [performant], but still plug and play and very expressive for audio would be would be great." (P17)

> "...not much profound to say here, it is kind of familiarity causes productivity." (P16)

Across a number of participants, expressivity resonates as a strong motivation for their tool choice. P16 phrases this as a capacity to be more productive, whilst P19 emphasises that this capacity leads to a deeper intimacy with the instrument that is produced, even implying that the expressive power of these tools can directly impact the instrument's expressivity.

We see these two sides of pragmatic decision making weighed up by P26, who considers the investment learning a new system takes against the potential returns.

> "...but they call them programming languages for a reason and learning each new language or each new interface takes more time and so if the i guess the main thing is if the promise of the efficiency of the new device or platform is worth the time and energy it takes to learn it..." (P26)

Many participants couple their expressivity with efficiency, ultimately suggesting that they benefit from better productivity when familiar with their tools. This implies an apprehension to use tools that feel less familiar due to potential loss of productivity. We see P16 grapple with this when working with the programming language Faust, which offered value; however, due to less familiarity, it ultimately lost productivity when working with the predominantly C++ codebase of their instrument OTTO.

> "But like I mentioned Faust, like, yes, it would be it's great to prototype. prototype. But at the end of the day, when I then have to translate that to C++, and it's not just it can't be, it can never be a one to one translation, having to redo a bunch of things, makes it so that I don't really end up saving any time compared to just making it in C++ from the beginning. " (P16)

Participants tendency to make pragmatic choices appears to be primarily driven by one major perceived constraint on their design process. Whether the limitation is a deadline for a commercial release or is the desire to be rewarded by a sense of rapid expressivity as described above, participants across backgrounds appear to make practical choices that improve their efficiency. Therefore, a significant component driving pragmatic decision-making is the limitations of time.

> "But ultimately, the biggest challenge of making an instrument is, is time. Everything else follows after that, like building something good enough

that someone else wants to play it again is a function of time." (P16)

> "Another important point in the approach to a new project is the time. This is the first time I'm working without deadlines.
> In the past I'm just working by the deadline. " (P21)

> ". . . and therefore, in the biggest challenge is usually time you have a lot of ideas, but then when you need to, make both mechanics and electronics and software, all that stuff takes a long time. . . " (P22)

Interestingly, this core constraint is shared across the backgrounds of participants. It therefore becomes a pragmatic choice to employ tools that offer efficiency in use. Participants such as P16 demonstrate the relationship between the individual pragmatism of utilising their skills and time. They present a view on how the maturity of documentation and learning resources can actively be a barrier to tool selection:

> ". . . if Faust was as developed as it is now when I started doing my PhD, I probably would have like, played around more with domain specific languages ."(P16)

Expertise is a limitation relating to time mentioned by many participants in that it takes considerable time to learn new skills relevant to DMI design. Accessible and well-documented technology provides a well-represented solution for this to the participants in the study:

> "I use Bela and Arduino because they are very well documented" (P18)

> "[On documentation] Yeah, yeah. It has to be also very elementary, like, really basic level so that, because even when you understand stuff, oh, what's a sample rate. All right. I know that in another context that you are in a flow or, you know, it's it can be a bit too much sometimes." (P27)

> "Beyond that, well-typed and well-documented APIs are really important. That's one reason I love Rust; it has great documentation tooling and a culture of aggressive documentation. . . " (P20)

In summary, 'The Pragmatist' provides a narrative shared across backgrounds in which the participants pick their tools according to a cost-benefit analysis of what practically impacts the project. We describe two distinct sides to this: one that prioritises technical choices, typical in more commercial settings, and one that prioritises the individual's practical limitations. For all backgrounds, we see that both sides are factored in and considered, and the exact criteria for the pragmatic choice are motivated to address the perceived constraints. This theme indicates there is a clear appreciation that participants choose tools to support these practical considerations and address the predominant constraint of time.

3.2 'A Product of our Environment'

This theme examines how environments such as schools, communities or industry practices influence designers' tool choices. Irrespective of background, participants were very aware of their environment's influence on their choices, and many attributed their educational institution to be a significant factor in the tools they use, particularly in the context of their education.

> "I've learned C and C++ at the university around the year 1996 and thankfully it's still the most widely used language in embedded systems." (P24, Hardware & Software Engineer)

> I'm finishing a second master program in Electronic Arts and we must learn about all these tools, so this is the handiest world I have right now. And of course, this is a discussion and influence in how I form my work (P21, Artist)

For P11, the influence of their educational institution leads to their early adoption of the programming language Faust. Whilst two other participants also mention Faust, P11 is the only one that mentioned Faust being taught at their educational institution. Faust is a language based on the functional programming paradigm and a domain-specific language for audio processing. The functional paradigm is a departure from many more common languages digital luthiers use, which are more general-purpose, imperative languages. Whilst this does not suggest much about the suitability of these paradigms, the use of a tool that contrasts the tools others use helps to make the influence of education quite distinct.

> "So I think I started using Faust for geographical reasons. Because I did my undergrad in France, at the birthplace where Faust was created." (P11)

P16 and P17 both mention using Faust. However, neither adopted it long term, despite speaking highly of it. Ultimately, P11 developed into a role as a language developer for Faust. As such, the environmental pressures for using that tool have led to them using it extensively.

A reluctance to change their tools from the ones they learned initially seems common. Having been introduced to tools through education, P26 found little motivation to change the tools as the current tools serve their needs, though they do allude to the curiosity of other technologies. We see across these participants an exploration of affordances and constraints similar to those described by Magnusson [55], largely presented in this context by the environment.

> ". . . I haven't used Bela because the tools that I learned, particularly when I was an undergrad just continue to work for me, but I am curious about other platforms. . . " (P26)

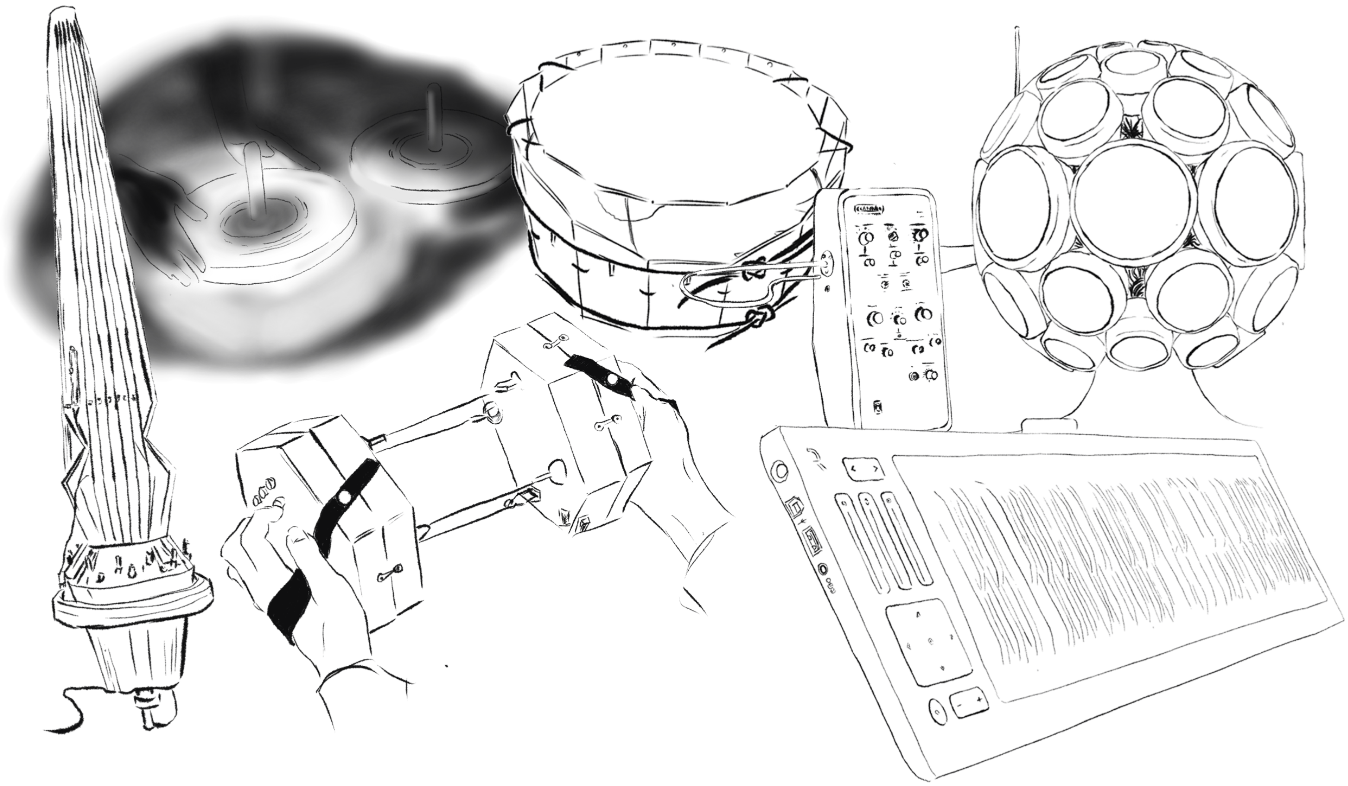

Figure 4: Knurl, Soft Revolvers, Concertronica, The Daïs, Claravox, Alpha Sphere, Roli Seaboard

Much like educational communities, the open-source community represents a highly influential environment that impacts participants. We see that open source tools represent an ideology with which participants identify. Both P11 and P27 share their preferences for open source tools.

> "...And it's just like something that needs to be 3d printed, for example, then I will use [it] and, I am an open source person, you know, like so. So I prefer to to use open source tools. ..." (P11)

> "I choose because it's open source mostly. It's also what's my education has given to me in the conservatoire." (P27)

We see that the open-source community's influence and surrounding ideology plays into the environmental influence to which the individual is exposed. P27 is very aware of how their particular environment influences their tool choice. They observe that their environment is made up of various influences, implying that it can be challenging to move from the initial tool introduced through education, even balanced against an ideology to use open source tools.

> "Relating to hardware, you may [say] it was a consequence of environments mostly. I am aware [that] Fusion [360] is not an open source thing, although I said in the beginning I want to use open source. So it's more emotionally about my environments right now as I say..." (P27)

It is clear then that there is a complex interplay between many factors of an individual's environment that have a significant hold on the tools participants might use. We see that for participants such as P26, the ability of open-source culture to facilitate knowledge exchange is the most important aspect, further blurring the boundaries between educational communities and open source.

> "...I think open source culture is really important and I have the career that I do because of google, like hands down, I wouldn't know anything that I know if it wasn't for the internet... ..." (P26)

Participant 3 describes two external influences on tool choice, community and University, respectively. This further demonstrates that the environment is, of course, not a homogenous entity, but a blend of the environments to which the designer is exposed.

> "And also, I went to university in Ohio, and there were classes in Python and in pure data. So I guess, like, the fact that I was exposed to those things at school, like made it easy for me to use them in my projects as well...

> ...And yeah, like the Fab Labs, in Montreal, were sort of my way in. And then like, from getting into those communities. And also with like, people around me there, were also interested in like, doing 3d stuff and whatnot. I learned about different software." (P3)

Participants often make decisions based on the availability of technology. Particularly in the case of participants who were working early in the history of DMIs, the idea that *'it was what was available'* was a common sentiment, meaning designers used whatever the most suitable, available tool for the job was at the time.

> "However, in the 80s I was using C because that's the only computer I had. And the only compiler I had was a floppy of the C language." (P1)

> "In fact, in the early days of my early machines, I used only assembly language. But then C finally became barely fast enough around for embedded processors around the 1990s. So I would say that, pretty much everybody just uses C, with a lot of optimization of loops and things like that." (P9)

However, availability remains relevant in more recent examples too. Notably, P2 qualifies that they chose the 'only mature' language, combining their environmental challenges with those of pragmatism and a need for reliability that participants refer to in Section 3.1.

> "C/C++ was the only mature programming language available on STM32F when I started developing the Eurorack line" (P2)

Despite the developments and richer ecosystem now available, this suggests that even today, the range of tools is quite heavily constrained by the technology the designer works with, necessitating the selection of tools from a suitable range. For P19, this relates to their workflow; beginning their process by considering the technology available to them, they immediately impose a set of constraints on the available tools.

> "And so I look at the environment in which that instrument has to sit, you know, it's got to be able to deal with MIDI, and it's got to be able to do this, and it's got to have and the constructs of like, well, what position does it take in the musicians Arsenal? Do I have the luxury of building like a two by four box made out of steel, that's gonna be the centrepiece or is this, like, you know, something that's guitar pedal size, I mean, these things have an influence on your hardware. And then working back your hardware generally dictates a very limited choice of software environments in which to work in." (P19)

The sense of availability described by participants appears to relate to the environment of the digital luthier rather than to the global availability of technology. But for some participants the tools and technology available are more than adequate:

> "I think the tools available nowadays are very solid and well designed, both from the users' and developers' perspective." (P18, Professor)

> "I don't feel that anything is seriously lacking among the tools we have. For each task there are multiple choices / providers so it is easy to replace what is not working." (P24, Hardware & Software Engineer)

> "I'm just pretty satisfied with what I have. I mean, I could complain for hours with how are you using it?" (P4, Artist)

> " I think it's the best time so far in the whole world to do this stuff as an individual." (P5, Software Engineer (open source))

Artistically, P8 notes that this itself can be distracting. As they discuss setting out with a clear intention in mind, they see tools tending to cloud artistic intention, causing them to get lost due to the available options.

> ". . . there's all these new advances endlessly. And technology's fascinating. So you end up going down endless streams. . .
> . . . I already think all in their nature, all the software tools probably lie on the negative side of the previous point that was made there. There's that whole idea of artistic limitations being a sort of thing that we should embrace." (P8)

Another substantial environmental influence on tool choice is industry. 'Industry standard' is a prevalent term indicative of the impact industry has on digital luthiers, particularly those with commercial backgrounds such as P7, P12 and P10. We see that these participants look to industry practices to support their decisions around tool choice.

> "It mostly comes down to accessibility, familiarity, and cost. We look for tools that would be considered the standard for that task, within our specific industry.
> . . . Due to the above mentioned options, STM32 has become somewhat of an industry standard for DMI, further perpetuating itself as the ideal solution due to devs familiarity with the platform, and the plethora of example projects." (P7, CEO)

> "I've continued to use like, different IDE's, because, like, you know, the industry standards for the various use cases that we're looking at. Right." (P12, CEO & Founder)

> "In members of the team who were used to, you know, who are doing aerospace or, or other even industrial kind of firmware, and so C was a shared language there on the on the app side. . .

> ... it was honestly just about the personnel, the people in our network or on the team and their familiarity.(P10, CEO & Founder)"

> "C++ has also been the language I used the most previously in my career." (P2, Company Owner)

When specific features of technology such as performance is highly valued, there tends to be a convergence on tools within the industry. This has formed a consistent image of what tools are appropriate across participants. We suggest this common focus may contribute to a feedback loop where more adoption leads to more development and support, further entrenching the sense that a tool is industry standard.

This is suggested by P6, who indicates how only given considerable development can a new tool become viable when discussing their delayed adoption of the programming language Swift. For P6, a designer with a commercial background, reliability is critical in the tools used in a software engineering role at a large instrument company.

> "I've gravitated towards maintainability. Because whenever you create any type of product that is software based, you will spend way more time dealing with the life cycle of the product and with the initial creation spike. So even though I have a natural affinity to cool stuff, and like emerging languages and new new ideas, I've been bitten quite a bit in my early career by choosing tools that weren't completely safe, stabilised, and then having to spend a lot of time dealing with problems that are introduced just to to evolve in programming languages or programming platforms." (P6)

Clearly, support for tools also factors into this sense of industry-standard, whether that be from hardware vendors or the open-source community. This support directly influences the industry standards:

> "Software tools are usually supplied by chip manufacturer, in my case all necessary compilers and IDE were freely available from STMicroelectronics & Atollic, Espressif, or as a free open-source software from 3rd party (Eclipse)." (P24)

In summary, we see that participants have unique social and cultural environments in which they work. Some of the clear examples of these include education, open-source communities and industry. The environment presents a set of pressures that have a significant influence on tool selection and we suggest that these environments also act as a buffer that preserves an intuition of the affordances and constraints of a tool, giving rise to notions such as *industry standard*.

3.3 'Intentions'

Inevitably, there are unique pressures on tool selection related to the intention of the digital instrument being designed. This theme, titled 'Intentions', reflects how each designer also makes special considerations in tool choice related to the purpose for which the instrument is being designed. Here we see the stories of designers converge on the requirements dictated by how they intend to use the instrument they are creating. In this theme, we see that some of the ideas presented are outside the design problem space and focus on more peripheral issues with creating digital instruments.

P12 describes their goal to have a "mastery of production", explaining how tool choice extends beyond the design space and facilitates more typical manufacturing and collaborative design processes through communication.

> "And I want to do is like to have mastery of like, production, right, like, but production, I mean, like mass production. So, some of the tools are even like that communication with the people that run the factories ... I consider that as part of the, that's part of the instrument, that you're ultimately putting into people's hands." (P12)

We see others from commercial backgrounds build on this using a large variety of tools to coordinate and collaborate even in remote settings, emphasising the importance of selecting tools that facilitate their specific requirements for long-distance collaboration that operate in real time.

> "we are pretty much always on video, and in collaborative documents as we're doing the design. So it is a very real time design and development process for the team. Compared to just handing over documents, you know, as explicit files, these are usually collaborative real time documents. I think it makes a big difference." (P10)

> "These challenges together comprise the project management aspect of designing something. Tools vary, but it is important to use some sort of task management system(Trello, Asana, etc.) and a calendar." (P7)

In team settings, to meet an instrument's goals, additional communication and collaboration tools supplement more specialised design tools to enable operation that allows more people to work together more quickly.

Typically, for individual digital luthiers, their role tends to be less clearly defined. As an artist, P4 describes the challenge of managing the time spent between designing and working on the instrument and performing with the instrument. This is particularly relevant to those designers who are both performers and inventors of the instrument, an attribute that is common in the digital lutherie community [44].

> "So it's really hard because you have to really focus on what you want to do. You know, I cannot, you know, I have to really be very careful. Do I spend more time in design and writing software? Or do I spend more time in actually applications of the software for performance?" (P4)

In particular, we see that the boundaries between the design tools they choose and the instrument itself are often blurred. For artists, tools are often part of the process, as P3 notes, where the idiosyncrasies of tools can help to guide the design.

> "So and I like that process of going through the difficulties of and also like, each platform has his idiosyncrasies that direct a bit, how are you going to use it, and I like that aspect of like, working with the code or working with a programming platform, and then like, it co constitutes to kind of work that you're going to be doing on those platforms." (P3)

This relationship can make it challenging to provide a taxonomy of roles for the tool designer, instrument designer and performer. However, it does imply interesting considerations of meta-design in this relationship whereby design choices are deferred between roles, allowing more multidisciplinary roles as discussed in the context of Armitage and McPherson's work [5]. This is well exemplified in the context of P23's research and instrument design, who works to expose low-level features at a high level, such as "signal processing, feature extraction, [and] some machine learning".

> "...we're working with people who create tools, and we try to design those tools so that they're available to the musician in the high level environments." (P23)

In particular, we see those with artistic motivations to be leveraging this deferred capacity for design the most, utilising visual patching languages that act like musical ecosystems [67] and also machine learning such as in the work of P3. These tools allow the performer to take charge of design elements of the instrument, blurring the capacity of where the tools stop and the instrument begins.

> "I think that the neural net thing is, is a great improvement for me, I can feel. I feel like I react to what is there. " (P3)

P11's research work directly involves the design of tools for creating DMI, in their case, working on the audio digital signal processing language Faust. This supports the image of the multifaceted roles digital luthiers have, and P11's deep adoption of the tool they work on demonstrates how many digital luthiers develop a deep understanding of their tools and the musical intentions of their work, but also how other designers might work.

> "But like, mostly I write things and Faust because, it's quicker for me to write them in Faust than in C++" (P11)

We see many other participants reflect this component of tool design and instrument design as they work on their software libraries. For many, the intent of their work becomes not only producing instruments for performance but also as a means of developing and sharing tools. This likely relates to the way participants identified regarding open-source culture.

> "So I have this, this library that I use, which is actually my own prototyping library that I made in C++. And [...] gives you like, real time audio, in one line of code pretty much, and then a super simple UI library, so that I can quickly prototype my audio algorithms. " (P22)

While for some artists or researchers, the instrument they designed served a singular or personal role, the broader adoption of an instrument was the intention for many instrument designers. Participants describe this as a significant challenge for digital instrument designers.

> "The reception by the public of anything that is not directly
> recognizable as a Moog/Buchla adaptation. The weight of the tradition,
> and 'groupthink' embedded in clichés and concepts such as 'menu
> diving', 'digital coldness', 'presets'." (P2)

As such, participants emphasize incorporating user feedback into the design process.

> "Third step is to make an early demo, share it around, and get feedback from potential users, which often makes us to rethink it - add or remove a thing or two. They often ask questions that show us what is exciting, what nobody cares about and what is missing - at this stage there us usually enough time to improve and fix most of these things." (P24)

P15 describes how this requirement factors into tool choice and describes how a means for easily exporting their work into a common and widely supported format would be desirable in their tools.

> "Could be like, I don't know, like, maybe even something that quickly enables me to export my prototypes to like a plugin in a known format is already useful, right? So because also, for me, it's like, then it can be distributed to many users quickly for testing with users. Getting frequent user feedback is super important to me. " (P15)

This is motivated by a desire to be able to "drop the idea when it's not good early". This user-focused design is an important motivation recognised by many participants who intend to create an instrument to be used and adopted more widely. In order to get feedback on their open-source development, P17 has leveraged social media platforms as a tool to help with both feedback and the future adoption of their project.

> "That that the the open source has been a joy. Yeah, for sure. Yeah, yeah. It's also the like, we've been mentioned a bunch of times on Reddit, like on the synthesisers subreddits and stuff and which has gotten us some attention." (P17)

For a researcher such as P16, instrument design can be a process for explorations in the instruments' craft. They describe their tools as facilitating different capacities to explore the design space from a more abstract perspective.

> " What does that mean in a, in a digital lutherie context. So you know, you need, you really need tools that can access that level of resolution that

> you're interested in. So and the majority of research and platforms have all been at a higher level, at a lower level of fidelity than that, until recently, I would say in the main, you know, Arduino, and Teensy, and whatever they are low resolution platforms, but they're cheap and quick and dirty, and they allow you to explore like, the breadth of the design space as opposed to the depth of the design space" (P16)

As a researcher, participant 23 also reflects on an intention for their work that relates to the digital component of their work. As with other digital technologies, digital instruments are susceptible to so-called *bit rot* [49]. P23 recognises that to achieve their goals, their work should be reproducible "in another era by other people." This provides an essential motivation for tool choice that relates to making pragmatic decisions for interoperability described in Section 3.1.

> "...that's why the tools. [...] Why is that? That they're nice, I can describe the kind of interoperability over time, in that I have to perform a concert programme, sometimes with works that are over a decade old, alongside a piece that I've just written the other day, and they and they have to load up and don't have accounts to work with more than one system. " (P23)

This theme describes the participants' unique tool choice requirements that serve the long term goals of the instrument they are designing. For commercial development, extra attention is given to more generally used tools that aid the realisation of 'products' capable of production at scale. These strategies are also employed to a lesser extent in their group work scenarios, where the skills of a team can be effectively employed and integrated through the use of tools that support collaboration. Other goals such as exploration of instruments in research and realisation of artistic intentions can lead to influences on tool choice that runs counter to productive outcomes, where limitations can become part of the workflow. Motivations for the instrument a participant is working on range from the development of digital lutherie tools themselves to many other forms of music-making [80]. These narratives represent motivations for tool choice that track directly with the motivation for creating the instrument.

4 DISCUSSION

Through an iterative and reflexive approach, we took transcripts from 27 interviews and provide a discussion and interpretation of the perspectives shared by the participants. Working inductively, we found many compelling observations that generalised from different participant backgrounds. We focused on the perspectives shared across participants with different motivations for design, aiming to address our research questions.

In summary, we see in Section 3.1 'The Pragmatist', a narrative is described whereby designers make their decisions based on analysis and their experience with a problem space [33], selecting tools with attributes that solve the most significant challenges to them. These challenges are often problem-specific, so the value of attributes such as performance or maintainability is skewed according to the designer's requirements. For example, we see that those in commercial settings place explicit value on tools that support easily maintainable products, particularly when discussing code. Alternatively, those with limited technical expertise, such as an artist exploring instrument design, may prioritise well-documented tools as this facilitates an accessible form of support to help them achieve their goals. Across the study, we see that these pragmatic choices hinge around some of the following points:

- Performance
- Interoperability
- Ease of use
- Accessibility
- Availability
- Familiarity/efficiency of use

We also present the theme 'A Product of our Environment', where we interpret that external cultural, societal and institutional influences all impact on a designer's choice of tool. We see how notions such as 'industry standard' impact tool choice for those managing a team in an industry setting, but also in other contexts. There are examples where industry standards influence the choice of programming language at educational establishments, and ultimately, this popularity influences the available support from a mature community. We also see how open source as a community and shared ideology (although complex and open to interpretation) provide an environmental influence that is drawn on and used across design motivations. All of these environmental factors provide a push and pull influence that substantially impacts the tools used by the participants in this study. Ultimately, it is apparent that the tools provided by a university or endorsed by a community tend to affect tool selection significantly, and we suggest that this may be the overruling factor.

Our final theme, 'Intention' accounts for the salient challenges presented in the domain of digital musical instrument design. Despite the focus on addressing technical challenges through pragmatic tool choice, very few suggested these domain-specific problems constituted the most relevant challenge in DMI design. While considering the latent meaning of some interviews suggests there are prevalent challenges and demands of DMI design related to the interaction of controlling the instrument, we focus on the more explicit semantics presented in this study. This suggests that the most significant challenges digital luthiers face are related to how the instrument is intended to be used. This can motivate tool selection in a project-specific capacity. For those working in teams, tools may need to either support collaborative features or be supplemented by other tools that do. For those looking for widespread adoption of their instrument, tools that allow for integrated user testing become critical, and intentions for artistic output can require tools that can facilitate the reproducibility of technology in the distant future. For many, the capacity for some component of the instrument's design to be deferred to the user are also desirable. 'Intention' describes the pressures on tool selection that are unique to each project and driven by the motivations of the digital luthier to build an instrument.

4.1 Why and how do Instrument designers pick their tools?

Our themes show that across different contexts, the motivation for tool selection can be described with three shared narratives. Much like Stolterman and Pierce [81], our study finds that a primary factor reported for tool selection is a rationalised selection process. They describe this as following a model "*in which one selects an appropriate tool based on a clear understanding of the design situation, the desired outcome of the situation, the types of activity needed to reach that outcome, and the types of tools that can satisfy the desired outcomes of the situation.*"

Our narrative around pragmatism very much corroborates this finding, where terms such as *interoperability*, *performance*, *accessibility* and *efficiency* highlight the rationalised decisions made by the designer concerning their problem. In addition to this, we find a second narrative comparable to Stolterman and Pierces findings. Stolterman and Pierce discuss environmental factors in a more specific capacity, considering community, culture and branding in relation to the designer's identity. Our interpretation frames the environment as external influences that incorporate the cultural and personal identity, but also includes more overt external influences. A strong example found in this study is the impact that educational institutions have on tool choice. Whether due to simple availability or increased accessibility due to pedagogical support, educational institutions' presentation of tools accounted for the initial use of tools and continued use of the tool in many cases. We see some scenarios where the tool is not expressive enough and is therefore outgrown (for example, using graphical programming environments for programming). However, the consensus demonstrated by participants is that designers tend to stick with a tool offered up by environmental factors as long as it meets their pragmatic requirements.

Together we see these pressures form a set of both affordances and constraints, a concept well established in HCI literature, based on work by Gibson [32] but reformed for use in design by Norman [19]. Whilst in HCI, this term has mostly been used to explore the affordances objects offer to users; considering affordances as it evolved from ecological psychology, we see that the theory of affordances has been discussed in the context of properties and environments before. Chemoro's definition of affordances demonstrates the relationship between the features offered by the environment and a person [18]. In light of our themes, we suggest that affordances are a valid way to analyse the tool choice of participants. The work of Magnusson has extended this potential and examined DMI design in the context of its limitations [56], which was a more prevalent topic in our study. Magnusson suggests that whilst learning a new DMI, people explore affordances. However, the majority of the time, learning the instrument "involves building a habituated mental model of its constraints." We suggest that whilst most digital luthiers in this study were likely experienced beyond the stage of initially exploring their tools affordances, the constraints of tools are preserved and shared by communities in the form of tacit knowledge. As such, we suggest that how digital luthiers (designers of DMIs) select their tools can also be considered in a similar capacity to how performers select their instruments.

A digital luthier may explore the affordances and constraints of their tools, evaluating them in order to meet the practical criteria that the instrument requires. Where the tool is widely understood to have a set of affordances or constraints, the community preserves and shares this knowledge, influencing tool choice for other digital luthiers in turn. For example, the idea that C++ is good for performance. It is not new to see this kind of application of the affordances moved to a different level of the design process as DeNora examines it in the case of music sociology, considering what is afforded to the listener [24]. We see that both affordances and constraints should also be relevant for considering the designer-tool relationship of digital luthiers.

Stolterman and Pierce interpret designers' tool choices using the concepts of espoused theory and theory in use [6]. The manner in which we see environmental factors 'complicating' designers' espoused theory of 'pragmatism' may add support to this interpretation. The self-reporting nature of this study allows participants to inaccurately reflect their motivations, offering the potential for developing espoused theories of the designer-tool relationship, that do not fully reflect the reality of why they choose them. This study does indicate that digital luthiers do reflect on their tool choices and, due to their relation to projects they currently work on, do describe scenarios that suggest theory in use:

> "And because I'm working in an embedded environment for my instruments, it's their C/C++. Not because I really like them or not, not even that I'm really strong at them. But I think it's just more or less the only way I can get the results that I want." (P5)

Our observations show that digital luthiers tend to be particularly aware of the environmental influences that affect their tool selection, implying less disparity between their espoused theory and theory-in-use. We see an example of this when P27 reflects that they currently use a tool that goes against their ideology of using only open-source software (as discussed in Section 3.2). This self-awareness and reflection only complicates the relationship between designer and tool and is essential to consider in future work.

4.2 What distinct problem spaces do instrument designers consider to be involved in instrument design?

In answer to this research question, we have focused on the challenges faced by participants and how they related to their tool choices, a first step in building a model of the problem spaces that digital luthiers face [33] when designing DMI. Despite the differences between participants and the instruments they design, we have primarily presented shared narratives that are developed from this study. Of course, each instrument and the context in which it is developed has many unique factors affecting tool choice. We found that where these focuses differ, they are mostly tailored by the major challenges they face outside the domain or designing the instrument itself. Many participants use tools for support outside of collocated settings, typically finding additional tools to fill this role. For example, commercial teams and research teams discuss needing tools for collaboration. We see this observation reflected in wider HCI literature across disciplines, showing that the importance of social design should be reflected in a designer's tools [1, 46]. Tools could therefore benefit by better supporting this workflow or integrating with other tools that do.

This need for remote collaboration extends beyond structured 'team members', however. Due to the importance of meeting the demands of the performer, user-focused design is vital for any instrument, a perspective clearly shared by participants. Of course, co-design, participatory design, and user experience are well-explored facets of DMI literature [14, 31]. The importance of these considerations leads digital luthiers to call on their tools to facilitate the interaction between the user and themselves. Much like working in an industry team, those looking to engage with their instruments end-user require a seamless collaborative process. For participants designing instruments intended to be played by others, they clearly indicate a need to support social creativity [27] in their tools in order to realise those instruments effectively. Fischer et al. recognise that individual and social creativity represents a continuum that should be integrated for solving complex design problems. The combination of challenges in user experience and facilitation of social creativity culminates in digital lutherie situating itself as an ideal candidate for meta-design [28]. Due to the way digital luthiers tend to take many roles as designer and performer, Fischer's description of meta-design as a "coadaptive process between users and a system" seems an ideal fit. Meta-design allows for components of a systems design to be deferred to the user. P9 approaches this by making parts of their instrument open source to support this relationship.

> "One of the problems is it's such a new idea and so flexible, but a lot of people want to make it into the ideal instrument. So early on, I decided to make the software open source. And I wanted to make open source development as easy as possible." (P9)

DMI tools are often developed to encourage and facilitate meta-design [16]. For some participants, graphical patching tools such as Max/MSP and Pure Data can be considered a part of the instrument rather than just a tool, exposing the capacity for the instrument to be redesigned continually. This is particularly common for artists, such as P4 and P26, who are challenged by continually finding ways to express their artistic intent for new ideas and works. It is common in DMI literature to represent a DMI abstractly as a controller and sound generator with a mapping between the two. Many projects look to expose this relationship, constituting a meta-design relationship between the tool and digital luthier, who, as Jorda describes, typically embodies the instrument maker and the performer [44]. We consider that the field of digital lutherie might be one of the most developed examples of meta-design and that it naturally addresses some of the most significant issues faced by digital luthiers. Fischer's work on meta-design sees it as a tenet of end-user development which is described as a "society-changing invention" [26]. This is clearly paralleled in the DMI community, and we suggest these two areas of research support each other and would do well to cross-pollinate.

Participants also indicate that limitations of time, resources and expertise are also some of the most limiting factors they face. We see that these challenges are largely coupled to the practical motivations in tool choice set out in Section 3.1. Participants search for tools that offer efficiency and accessibility in response to these limitations.

Finally, for some participants, the greatest challenge represents the steps beyond the creation of the instrument. The adoption of new DMI is something already considered in the literature [40, 59, 72]. In commercial settings, this can involve marketing, communication with a community, and even breaking down preconceptions of the user base (as in the case of P2). As this study focuses on the designer-tool relationship grounded in digital lutherie, these aspects are difficult to build upon. However, participants introduced these as prominent issues, which could be further investigated in future work.

4.3 How do instrument designers define a digital musical instrument?

Of course, the challenges in defining a digital musical instrument are well considered in the literature [73], and this ambiguity is well reflected in the participants of this study. Participants tended to create an ad hoc definition that they often recognized as contrived or quickly contradicted. There was a strong tendency to note that providing a definition does not matter. Any boundaries are quickly blurred by the continuum that represents controllers, interfaces, and instruments. A deep dive into this topic is beyond this paper; however, drawing on the analysis from this study, we note some interesting and related points. Many participants value the observation that DMIs are not bound by physical properties, with P6 suggesting there is no limit to their potential.

Some participants view the digital component of DMI to be just another material used to create an instrument. Participants also considered aspects such as *idiomaticity*, *expressivity*, *feedback* and *virtuosity*, of importance in DMI, which are well explored in literature [7, 15, 68, 70, 75, 84].

We also see many participants make a comparison of DMI to a mathematical function. P2 provides us with the notion of $y = f(x)$:

> *"So in the end, it is just about evaluating a big outputs = f (inputs) function. (P2)".*

This is possibly expanded by comments that suggest that DMIs are more than simply the combination of controller and sound generator (P1, P6), suggesting there is importance to the process of mapping between input and output. In this paper we have focused on the designer-tool relationship where this question was formed to help understand what digital luthiers were motivated to create. We see through this analysis that not only is the taxonomy of DMI difficult to define but also, the taxonomy of digital luthier itself is not clearly seperated between tool designer, instrument designer and performer, with some participants spanning all of these roles.

Ultimately, this question does little to provide a taxonomy of digital musical artefacts, but we suggest these transcripts offer useful perspectives that would be well explored in future works that explore this question more deeply.

5 CONCLUSION AND FUTURE WORK

The relationship between digital designers and their tool choice is complex and continues to call for more attention to be better understood. Despite the different settings in which digital instruments are developed, we find that digital luthiers share many motivations for choosing tools. Through our inductive approach, we come to a set of narratives that supports the work of Stolterman and Pierce who observe similar themes of 'rationalised reasoning' and 'the social, material, and cultural context in which the design process takes place'. We see these as pragmatic decision making and the influence of the environment, respectively. Stolerman and Pierce consider Argyris' theory of action [3] and relates the pragmatic process to espoused theories and the environmental aspects to relate to theories in use. We suggest this is a good opportunity for future work to explore through observational study as our findings further complicate this relationship. We find the digital luthiers in this study to demonstrate an awareness of how their espoused theories and theories in use interact, understanding that the environmental influences often override their espoused theories of tools. We also consider these influences in the context of affordances offered by both the tools and the environment in which they exist [32]. Much as Magnusson has found in the use of DMIs, we find that participants focused on the constraints of the tools they use to design DMIs [56]. Therefore, we find that in analysing the designer-tool relationship, designers engage with a tool's affordances and constraints. In light of the environmental context in which tools exist, our study suggests that the community preserves and shares knowledge where a tool is widely understood to have a particular set of affordances or constraints.

Where we do see specialisation in tools, our findings imply these relate most notably to the instrument's intentions. For a majority, DMI design is socially collaborative. This may be in the case of a team of digital luthiers, but often this is directly the users (performers) providing feedback or further developing a design themselves. For those instruments, Fischer's recommendation of integrating social creativity and individual creativity is demonstrated in the tool choices digital luthiers make [27]. This included using domain-specific tools that supported social creativity as well as supplementing them with more general-purpose collaborative tools. Those focused on individual creativity specialised their tools towards efficiency and accessibility. This, too, engages social creativity less directly, engaging with quality documentation and mature tools provided by communities such as industry or the opensource community.

Finally, through understanding the challenges designers face and how this influences their tool choice, we recognise digital lutherie as a rich example of meta-design [28]. The literature surrounding digital lutherie and DMIs describes the fluid nature of the roles digital luthiers and DMIs have [44, 73]. For many, the ability to defer components of an instrument's design to the performer is a defining feature of a DMI. This has seen the use of many of the principles that Fischer [26] describes as EUD (End User Design) being applied in this craft [16, 25]. This study suggests that these features are important considerations for designing new tools for digital lutherie.

Much like Stolterman and Pierce, we continue to show the complexity of the designer-tool relationship and continue the trend of prompting more questions. However, we see that the perspectives shared by digital luthiers present many directions for enquiry relating to how we interact and design digital systems. We emphasise that this work presents a foundation for further enquiry into the designer-tool relationship for digital luthiers and encourage others to utilise the transcripts available to supplement other methods that explore these ideas.

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