A Scale-Based Ontology of Digital Musical Instrument Design

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ABSTRACT

Subtlety and detail are fundamental to what makes musical instruments special, and worth dedicating a life's practice to, for designer, maker, player and listener alike. However, research into digital musical instrument (DMI) design tools and processes have so far mainly focused on high-level conceptual concerns and low-level technical abstractions, leaving subtlety and detail underexplored and undervalued. These nuances, and the processes they result from, cannot be fully articulated in words alone, yet they largely define an instrument's quality, and it is therefore important to understand how they come to be. We introduce a scale-based ontology that divides design details into three levels - macro, meso and micro - and we present a literature review of DMI design from the perspective of this ontology. Finally we extrapolate the ontology to consider its utility in broader contexts, and consider future directions.

Author Keywords

Digital Musical Instrument Design, Subtlety, Detail, Ontology

CCS Concepts

•**Applied computing → Sound and music computing;** Performing arts; •**Human-centered computing → HCI theory, concepts and models;**

1. INTRODUCTION

> Transistors which had been rejected as 'out of specification' were purchased by Roland and used as part of the TR-808's sound generating capability. Although they weren't faulty, they did exhibit some very particular qualities that helped give the 808 its distinctive sizzling sound. In fact, this tiny component, also known as an 2SC828-R, was so important to the final sound, that once supplies were used up, the TR-808 was discontinued." – Roland, *The TR-808 Story* [92]

When comparing two violins, the differences in quality will be stark if one is crafted by a master luthier, whilst the other by a student. Similar issues prevail with analogue electronic instruments; not only were the details of the *2SC828-R* precision manufactured, but they were also subtly different and uniquely suited to its task. Thus far, subtle details have been the Achilles heel of digital musical instruments (DMIs), with significant efforts in recent decades dedicated to defining, increasing, and evaluating their expressivity. Nonetheless, DMI design practitioners, technologists, and researchers continue to face complex issues when addressing subtlety and detail.

In a previous paper [10], we discussed violin luthiers' ability to concentrate on subtle details due to the ecological, cultural, and technical constraints on their practice. Following this, we conducted two studies where instrument makers focused on subtle details in one-hour activities [8, 9], but these did not produce subtle, detailed outcomes or what we refer to as micro design scale. In the first study, a simple, modular DMI design toolkit was paired with crafting materials, which produced what we refer to as macro scale outcomes [8] (Figure 2). In the first study, a modular DMI design toolkit was combined with crafting materials leading to macro scale outcomes [8] (Figure 2). In the second study, the same toolkit was integrated with a Pure Data patch, and meso scale outcomes became more apparent [9, 4]. In a third study [6, 5], we designed an apparatus and activity with more deliberate constraints at the macro and meso scales, allowing us to observe largely uninterrupted micro scale DMI design.

In this paper, we present an ontology of DMI design that was developed alongside our empirical studies of DMI design processes. Initially devised to guide our practical investigations towards subtlety and detail, we now offer it as a reflection on DMI design research, methods, tools, frameworks, and practices. We describe each scale in turn, comparing with existing literature as we progress. Finally, we discuss the general utility of the ontology and outline potential ways it could be further developed or adapted to support other researchers interested in similar topics.

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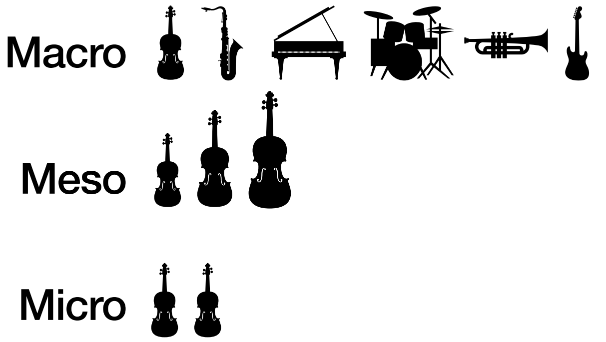
Where each scale considers digital musical instruments, and their underlying design processes:

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) The scale-based ontology of DMI design in textual form.



(b) Illustrated version of the ontology.

Figure 1: The scale-based ontology of DMI design, in textual (1a, left) and illustrated (1b, right) forms.

2. SCALE-BASED ONTOLOGY OVERVIEW

This section offers inductive and categorical definitions for the scale-based ontology of DMI design, whose absoluteness we will later challenge in Section 6. In 2005, Jordà sought to provide a means of comparing *performances* with DMIs at three levels of abstraction, referring to the *musical diversity* of an instrument [55]. He introduced the terms macro, mid, and micro-diversity; *macro-diversity* pertains to an instrument's ability to accommodate different styles, *mid-diversity* relates to an instrument's ability to support playing different pieces, and *micro-diversity* concerns the potential for performances of the same piece to differ. By repurposing the latter definition to focus on instrument design processes rather than performances, we can propose an operational definition for micro scale details: subtle and detailed nuances between otherwise identical instruments and their underlying design processes.

Consider constructing two DMIs of the same design while aiming to make them as similar as possible (or comparing the same DMI post-design revision); there would always be distinctions between them. The more similar these two DMIs are, the greater the level of subtlety and detail required to determine and evaluate their differences. Our definition assumes that the design processes behind these differences somehow produce them. In contrast, taxonomical frameworks compare high-level features like interactive paradigms [60] and features neither high nor low-level, such as mapping configurations or numbers of inputs and outputs [46]. Analogous to Jordà's levels of musical diversity, these frameworks could address *macro* and mid or *meso* scale differences between DMIs and their underlying design processes. While numerous frameworks address macro and meso scales, the micro scale has received far less attention. This scale-based ontology of DMI design is summarised in two ways in Figure 1, with a comprehensive account in [2]. 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)*.

The Reactable [56], Seaboard [57], and Svampolin [84] are innovative DMIs that emphasise different aspects of the scale-based ontology in their design and functionality. The Reactable, emphasising macro and meso scales, introduces a collaborative round table interface and a unique radial configuration of components. The Seaboard, focusing on meso and micro scales, implements MPE for responsiveness on a modified MIDI keyboard, enabling detailed gesture-based interactions. The Svampolin prioritises macro and micro scales by maintaining the traditional violin form while employing a hybrid acoustic-electric design with subtle differences in playing experience. Comparatively, the Reactable presents a novel form factor for collaboration, while the Seaboard and Svampolin enhance traditional instruments. Regarding meso scale designs, the Reactable employs tangible control, the Seaboard features a responsive surface, and the Svampolin integrates an electric violin with an acoustic body. In terms of micro scale differences, the Reactable's visual feedback, Seaboard's sensor responses, and the Svampolin's unique acoustic characteristics could impact the playing experience. However, the Svampolin's playing experience is most likely to be influenced by differences in resonance and timbre, due to inherent variations in wood density, grain patterns, and internal structure of the instrument.

To take another example, consider the grand piano. From this ontology's perspective, a prepared grand piano often represents a macro scale change in the instrument's form and function, involving a reconfiguration of its meso scale and introducing a new domain of micro scale details orthogonal to its previous idioms. In contrast, the *Magnetic Resonator Piano* (MRP), an electromagnetic augmentation of the grand piano, undertakes meso scale interventions while maintaining the existing macro, meso, and micro scale details of the original instrument [70, 71]. Both scenarios may involve underlying design processes that are subtle and detailed, but the MRP's context suggests that it would need to focus on considerable subtlety, whereas prepared pianos deliberately allow a broad space for high-level artistic exploration. Comparing two prepared pianos would not necessarily reveal comparable subtle details at the micro scale, since they may also be very different at the meso and macro scale, but comparing two MRPs would. This does not imply that DMI design always commences at the macro scale and progresses linearly and hierarchically towards the micro, as we discuss later in Section 6.

As the adage goes, *the map is not the territory*, but we find that this map has helped us gain clarity on subtlety and detail in DMI design, which we subsequently translated into practical enquiries providing further insights. We offer this ontology with a spirit of pragmatic curiosity, rather than being driven by a desire for an all-encompassing theory. As ontologies serve as models, and every model has its limitations, it is crucial to recognise that this ontology's primary objective is to assist in directing our subjective viewpoints on subtlety and detail in DMI design, rather than claiming to represent a fixed, external reality:

1. A great deal of DMI design research and practice addresses primarily high-level concerns, leaving subtlety and detail underexplored, and undervalued.

2. DMI design tools, frameworks and methods tend to mediate design processes in obfuscated and unacknowledged ways, through rigid high-level choices and low-level abstractions, rarely considering the needs of subtle and detailed design processes.

3. Addressing and understanding the subtleties and details of DMIs, and their underlying design processes, is both an important and tractable goal for the field.

4. Clearly defining the first two issues is a helpful first step towards addressing the third, but observation-inspired models of subtle and detailed DMI design processes, at first in isolation from other concerns, will ultimately be a greater incentive for future research.

3. THE MICRO SCALE: SUBTLETY & DETAIL

Longitudinal ethnographies [103] and reflections on practice [23] are a primary source for accounts of micro scale details [102]. Michel Waisvisz notably developed three distinct versions of his DMI *The Hands*, over a time span of more than twenty years [107, 28]. Torre and Andersen describe that Version 2 ("the customisation phase") spanned between 1990-2000, after which came Version 3:

> The differences between these two versions are minimal compared to Version 1 [...] After the finalisation of version 3 of The Hands, Waisvisz made the decision to stop developing and accept the physical layout as is. From this point onwards, he concentrated on refining [...] it became possible to focus on the musical intent beyond the novelty of the devices. [102]

Waisvisz was largely driven by personal musical needs, a common theme among digital luthiers who often design for themselves and require time to cultivate their musical practice. *The Hands* represented such a novel concept that Waiswisz, along with other practitioners developing glove-based instruments like Sonami [95, 33], initially had to investigate macro and meso scales of DMI design spaces, eventually narrowing down to the micro scale.

On the other hand, not all DMI design processes move from macro to micro, and McPherson's *Magnetic Resonator Piano* (MRP) [70] serves as a notable counterexample. Initially, he casually experimented with electromagnetic actuation of piano strings, inspired by the guitarists' EBow[1] rather than similar piano augmentations, of which he was unaware at the time. Much like Waiswisz, McPherson was driven by musical necessity; as a composer, he sought a means to introduce creative elements into his PhD compositions for solo piano, in which "the piece could exist without the technology":

> What I had in mind was the idea that you would have something that was still recognizable as a piano but had a sort of extraordinary range of tone color, especially the idea that you can kind of separate the timbre from the the dynamics.[2]

[1] `https://en.wikipedia.org/wiki/EBow`
[2] Personal correspondence, April 2021.

While practitioners had to invent macro and meso scales for *The Hands* and similar instruments, the MRP aimed to preserve the existing macro and meso scale aspects of the grand piano, extending its micro scale domains with minimal disruption. In recent years, there has been a growing interest in research regarding DMI design methods and practices that emphasise subtlety and detail. Jack et al. underscore the advantages of conducting in-the-wild research [91] by framing DMI research artefacts as polished products rather than functional prototypes.

> The differences in physical properties of what is considered a probe or product might be subtle, or even non-existent [...] Importantly, research products place an equal emphasis on non-technical design choices such as materiality, 'feel', and visual aesthetics.[50]

These subtleties become foregrounded further still when considering the issue of DMI replicability [19, 20]. Zayas et al. investigated this through the intimate lens of apprenticeship, where an apprentice aimed for exact replication of a DMI, under the supervision of the original designers [111]:

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

Practice-based accounts, such as these, raise intriguing questions about the development of expertise concerning subtle details and how it is reflected in design processes and tool usage. However, the resolution of these accounts is currently quite limited, and in our studies we have attempted to address this [6, 5]. In all of the above cases, though subtle and detailed DMI design issues are present, they are not visible in specifics. A crucial first step to uncovering micro scale details involves isolating them from other aspects of DMIs and their underlying design processes. The following section initiates this process by distinguishing between meso and micro scale DMI design.

4. THE MESO SCALE: CONFIGURATION & MAPPINGS

Practitioners undoubtedly use popular tools such as Arduino and Max/MSP for intricate DMI designs. However, despite toolmakers' claims of limitlessness, we believe based on our studies [9, 4] that these tools chiefly support meso scale configuration and mapping of DMIs. At the micro scale, details are often entirely abstracted away or inadequately facilitated. Additionally, we refer to existing literature that identifies these tools as embedding macro scale assumptions that users may accept either knowingly or otherwise. The meso scale sits between form and detail, a space demarcated by negating both macro and micro, and inhabited by explicit DMI design philosophy and expertise.

4.1 Meso Versus Micro

DMI design toolkits serve as beneficial aids, streamlining implementation details into modular components that facilitate rapid exploration. These toolkits reflect specific musical cultures and knowledge [61], such as instrument classification systems [21] and synthesis approaches. Through abstraction, they achieve greater flexibility enabling innovative recombinations. Yet, as Perner-Wilson et al. remind

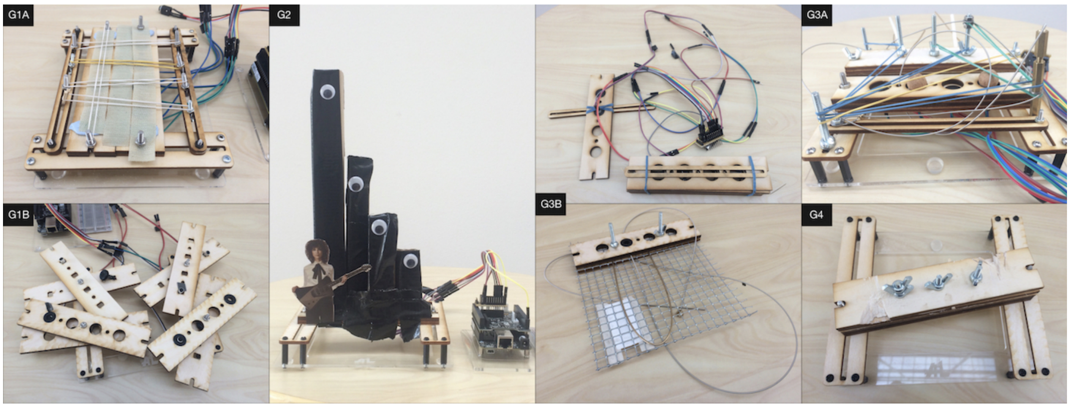


Figure 2: Outcomes from our first study combining a simple, modular DMI design toolkit with open-ended crafting materials, which we identified as producing predominantly macro scale outcomes, with the instruments diverging in their form and function [8].

us, "Modularity comes at the cost of constraint [...] They constrain what we build and how we think." [86]

Indeed, this approach often constrains the DMI design space to a predefined, combinatorial set of possible instruments, merely offering designers a curated selection of components. This resembles a simplified version of DMI design, akin to *GuitarHero* being a representation of playing guitar [11], or the notion that "everyone can play music" often associated with commercial DMIs [73]. While this approach holds value, it struggles to address micro scale details effectively.

Toolkit modularity tends to standardise micro scale details for compatibility, often sacrificing material subtlety. For instance, tangible media markers perform uniform functions irrespective of materiality [88], and recognition systems abstract those aspects away [43]. Although expert toolkit users can overcome such influences [13], beginners might inadvertently conflate a toolkit's perspective with the entire discipline [79].

While not all DMI design tools neglect micro scale details—platforms like Bela and Elk[3] promote subtle and detailed musical interactions [75, 80, 104]—there is still room for improvement. Although these platforms have facilitated closer examination of factors like latency and tangibility for DMI *performers* [49], DMI *designers*' haptic, tactile, and spatial abilities remain comparatively overlooked [16].

Considering the embodied craft process, DMI designers using these platforms may face constraints in displaying or manipulating micro scale details. The embodied expertise offered by existing DMI design tools and platforms often suffers from multiple levels of indirection [48], distancing designers from the behaviour they wish to create. As a result, designers may gain limited physical experience, hindering the development of their specialist tacit expertise.

To address these limitations, we suggest a deeper embrace of embodiment in digital lutherie, enabling luthiers to utilise their full bodily capabilities for creating and experiencing micro scale details. An efficient micro scale DMI design tool may benefit from a dedicated Bela-like device. Ideally, using DMI design tools should be as embodied as playing DMIs, as the machine that creates the machine often demands greater subtlety or sophistication—an idea evident in the meticulous tool-sharpening undertaken by violin luthiers.

4.2 Meso Versus Macro

Mapping is a well-cited DMI design topic and a staple of NIME publications over the years [31]. Established early in NIME's history [47, 45, 106], mapping has continuously gained attention, leading to numerous published frameworks, strategies, and tools. Much of the discourse around mapping toolkits is fundamentally meso in scale. These toolkits already assume a particular data flow architecture, usually consisting of temporally static relationships between features tied together with numerical weights and transformations. DMI designers leveraging these tools can explore numerous mapping possibilities but remain confined to the mapping mindset. Exceptions include those who master the tool, transcending its limitations or repurposing it [25]—though, in such cases, they could consider creating a new tool from scratch.

Not all DMIs require a mapping-centric design approach; exploring alternative paradigms reveals a landscape of truly macro scale differences. Magnusson elaborates on these conceptual features as epistemic dimensions inadvertently encoded into tools by designers [61]. Imagine a hypothetical pianist, unfamiliar with any other instrument—how limited would their understanding of non-pianistic music be [40]? DMI design tools similarly encode worldviews that remain hidden unless one has experienced others and adopts a well-traveled paradigmatic outlook.

Borrowing expressions like "can't see the wood for the trees" and "if all you have is a hammer, everything looks like a nail" helps illustrate this concept. Abstracting this sentiment, meso scale frameworks or tools, if considered in isolation, appear to possess macro scale characteristics; if all you know is a specific meso scale framework or tool, the space you are in will appear to be macro in character.

Sound and music computing (SMC) languages, such as [69, 109, 89], also perpetuate a meso scale illusion of universality [74, 72, 94]. This claim stems from two sources: the technical computational universality of Turing-complete SMC languages and the similarities between programming and natural language relative to most other tools [24]. Beware the "Turing tar-pit", where although "everything is possible—nothing of interest is easy" [85]. Expecting monkeys to create Shakespeare by randomly typing may not appeal to audiences desiring results within their lifetimes! Tools like Max/MSP pose various difficulties due to these unrealistic expectations, as Snape and Born discuss [94].

[3] https://elk.audio

5. THE MACRO SCALE: FORM & FUNCTION

At the macro scale of DMI design, designers concentrate on the overall form and function of digital musical instruments, aiming to create innovative and expressive tools that either expand on existing concepts or introduce entirely new paradigms for music making. In this domain, designers usually emphasise broader conceptual aspects, such as interface metaphors, instrument ecologies, and interactions with other musicians or external systems. To operate effectively at the macro scale, designers must consider factors like user experience, ergonomics, accessibility, and cultural resonance, frequently utilising various design methodologies, such as participatory design, user-centred design, or ethnomethodological considerations. Figure 2 illustrates some of these concerns in the outcomes of one of our workshop-studies [8]. As Bates elucidates, a DMI's role can be contextually equivocal, with the same instrument suggesting different relations in various sociohistorical settings [12].

Since NIME began, the field of DMI design has experienced considerable advancements in technology, leading to a growing emphasis on macro and meso scale aspects, as more instruments investigate the potential of novel interface designs and configurations. In turn, this has undoubtedly resulted in experimental aesthetics playing a dominant role in DMI performances [22, 78, 83, 110, 82]. Numerous taxonomical analyses and evaluation frameworks have also been developed, similarly focusing on high-level concerns [53, 52]. However, the importance of micro scale factors should not be overlooked, as they significantly contribute to defining the character and unique appeal of a particular instrument. Whilst many DMIs build upon proven design concepts, it is arguably the integration of macro, meso, and micro scale elements that often results in a well-balanced, expressive, and engaging instrument that appeals to a wide range of users. Anderson and Gibson, adopting this holistic perspective, frame the meaning of "new" in NIME:

> A new instrument provides an intuitive interface between gesture and sound; it allows for the development of virtuosity [...] can provide long-lasting and fulfilling interactions that exceed the novelty of its modifications and extensions [...] capable of surprising the performer and allowing the continual renewal of musical possibilities. [1]

In recent years, discussions surrounding politics, equity, inclusivity, diversity, and environmental issues have substantially influenced critical discourse and decision-making within macro-scale DMI design. DMI design communities are embracing various stances, including practice-based [39, 54, 100], ecological [96, 37, 30], and anti-solutionist [59, 81], with analogous patterns observed in related fields such as organology [27, 26, 63]. Designers are becoming more attentive to fostering diversity in musical expression, accessibility for individuals with disabilities, and cultural inclusivity, aiming to develop tools that cater to broader audiences and promote social, cultural, and ecological awareness. Moreover, sustainable design practices are gaining prominence, with designers focusing on reducing waste and environmental impact, using eco-friendly materials, and enhancing energy efficiency. This evolving discourse has expanded the landscape of DMI design, making it more conscious of socio-political and cultural contexts, as well as ecological responsibilities, and these macro scale concerns continue to impact DMI design at the meso and micro scales.

6. EXTRAPOLATING THE ONTOLOGY

Thus far, the scale-based ontology of DMI design has been introduced, serving to accentuate and scrutinise the intricacies of detailed DMI design. Three distinctive scales have been proposed: the micro scale, which encompasses the nuances, and the meso and macro scales, which do not. By isolating the micro scale, it has become possible to initiate an understanding of its practical investigation. Now, we shall broaden our focus, moving away from the micro scale to explore the full expanse of the ontology, and its limitations.

6.1 Ambiguity of DMIs as Design Objects

Over 100 NIME papers, approximately 5% of the total literature, feature "controller" in the title, and likely many more discuss controllers without mentioning them in the title. Whilst acoustic and electronic musical instruments have long exhibited decoupled mechanisms [66], decoupling is almost an overt idiomatic feature of numerous DMIs, given current technology allows for it so arbitrarily and discretely. The benefits of separating sound from the source are manifold, including pedagogical [84] and aesthetic [68] advantages, but this gives rise to the "problem" of mapping, as DMI design decisions must be made where no choice previously existed. Entire practices are established around this notion, such as modular synthesis [35] and gestural music controllers, which have become a specialised sub-field in the NIME community [108, 17, 51, 97, 76]. How do these scenarios challenge the ontology?

Regarding familiar instruments, like the guitar, the applicability of scale-based ontology may be debatable. Guitars have seen significant decoupling and reconfiguration exploration. Harrison et al. discuss performances featuring various guitar-like instruments, questioning when the essence of the guitar may become uncertain, causing identity crises and disintegration [42]. Answers to such questions are subjective and context-dependent, and understanding this ambiguity is crucial for DMI designers, particularly in Accesible DMIs (ADMIs) [41]. From an ontological perspective, investigating the scales contrasting these guitar variations is vital for deeper exploration and comprehension.

If a controller is examined in isolation, should it be considered a meso scale device, as it cannot produce music without pairing with a sound source? Controllers possess their own forms and functions, which can be compared across, seemingly contradicting this notion, yet both positions appear valid. What is the ontological status of DMI practices focused on evolving assemblages [15, 98, 112, 87]? Similarly, how should networked and distributed DMIs' scales be characterised [18, 58, 77]? Are instruments created with meta instruments considered meso scale [34, 32, 14]? Is it feasible to interpret composed instruments [93] in terms of Jordà's scales of musical diversity and the scale-based ontology of DMIs? What about instruments as scores [99, 101], and live coding as both instrument [90] and score [62]? In all these cases, identifying the macro, meso, or micro scale becomes challenging, and the ontology does not always offer additional clarity or insight. However, when comparing two similar artefacts, subtle details once again become discernible. Sensor calibration and processing in controllers, latency and jitter characteristics in networked music systems, and domain-specific syntax in live coding are all subtle, but significant.

6.2 Non-Linear DMI Design Processes

Prototypes serve to isolate specific design issues and demarcate phases, as Houde and Hill (Figure 3) describe in a case study:

> Three prototypes were developed almost in paral-

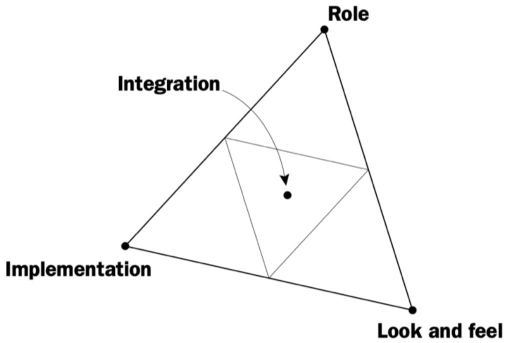


Figure 3: "Four principal categories of prototypes" described by Houde and Hill [44].

> lel. They were built by different design team members during the early stages of the project. No single prototype could have represented the design of the future artifact at that time. Making separate prototypes enabled specific design questions to be addressed with as much clarity as possible. The solutions found became inputs to an integrated design. [44]

Although DMI designers often work individually, they frequently employ similar iterative prototyping methods [103, 36, 105]. This characteristic extends the scale-based ontology in intriguing ways. The separation of concerns, utilised by designers, might be viewed as a temporal equivalent of the decoupling depicted in the previous section.

Considering Figure 3, a straightforward analogy could be drawn between *Role*, *Implementation*, and *Look and feel* prototypes and the ontology's macro, meso, and micro scales, respectively. However, another approach would consider the areas surrounding the four points as highly subtle and detailed, with the areas farthest from the points exhibiting lower subtlety and detail. A prototype focusing solely on implementation will necessarily delve deeper into details than one exploring both implementation and role. Designers prototype distinct issues in parallel to streamline intricate resolutions within their designs and accumulate tacit knowledge about micro scale aspects long before finalising the design. This outlook might offer enhanced flexibility when comparing two prototypes of the same type, such as two implementation prototypes with comparable micro scale details. In contrast, the macro, meso, and micro scales of an *integrated* prototype might be more fittingly analogous to role, implementation, and look and feel. Indeed, Houde and Hill emphasise that prototypes convey different information to various design stakeholders at distinct stages of the design process, generating potential ambiguities and challenges.

Recalling Waiswisz's Hands instrument, tracing the level of detail over time might, from a distance, resemble a smooth line transitioning from macro to micro. Nonetheless, closer inspection would likely reveal fluctuating oscillations among different levels of detail, each conveying a unique narrative. In reality, there is no prescribed level of detail for an initial prototype, nor are there rules dictating the level of detail a specific prototype should exhibit at any given stage of the design process. These factors depend on the designer's requirements and the design space's shape at any point in the process. Moving beyond an idealised concept, the idea of a progression from macro to micro is likely only applicable to designs created "from scratch." In practice, designs can begin and end at any scale, and may not necessarily have a definitive conclusion.

6.3 Heterarchical DMI Design Spaces

Although we have previously implied a hierarchical view of the ontology, in this section, we explore it from a heterarchical perspective. Magnusson introduces the concepts of ergomimesis and ergophor [66, 64, 65] to describe the migratory patterns of musical instruments across cultures over time [67]. These terms usefully emphasise that, on an ecological level, instruments with different macro scales borrow or imitate meso and micro scale details from each other, rendering the idea that they suddenly become incomparable too radical.

Additionally, manufacturers specialising in multiple instruments presumably share trade secrets among their products. Moreover, substantial alteration of an instrument's micro scale details will inevitably trigger meso or macro scale changes at some point, particularly when the levels are tightly coupled, and the instrument's form or function is inextricably linked to its most subtle features. Engelbart encapsulates this concept with his notion of a capability hierarchy:

> A change can propagate up through the capability hierarchy; higher-order capabilities that can utilize the initially changed capability can now reorganize to take special advantage of this change and of the intermediate higher-capability changes. A change can propagate down through the hierarchy as a result of new capabilities at the high level and modification possibilities latent in lower levels. [29]

Similarly, Gero's function-behaviour-structure ontology of design and design processes [38] also allows for heterarchical changes to the design state space through processes he terms "reformulations," where any aspect of the design can instigate a transformation of another. Despite the inherently hierarchical nature of the proposed scale-based ontology, changes to the hierarchy can occur heterarchically in practice. Furthermore, with the increasing integration of artificial intelligence into DMIs [7, 3], we anticipate that self-modifying or evolving instruments will soon start making heterarchical changes semi-autonomously.

7. CONCLUSION

In this paper, we have introduced a novel ontology of DMI design comprising macro, meso, and micro scale details. This ontology is specifically designed to reveal and isolate design processes that focus on subtle nuances at the micro scale. We outlined our empirical efforts to investigate this domain, which led us to examine the meso and macro scales more closely, culminating in a critical literature review.

The meso scale is where we identify a considerable amount of DMI design research, primarily focusing on tools and frameworks. However, we note that while this domain often claims to support both micro and macro scale DMI design, it frequently falls short of achieving either. We intend for this observation to serve as a call to action for DMI design technologists to reassess how their tools foster digital lutherie at the most subtle and intricate levels.

To support this discussion, we also examined various areas of DMI design where our proposed scale-based ontology can be either challenged or enhanced. We highlighted potential connections with other concepts, ideas, and methodologies, and emphasised that in practice, changes to the hierarchical ontology can occur heterarchically.

In conclusion, the scale-based ontology presented in this paper not only facilitates better understanding of the micro scale nuances in DMI design, but also demonstrates its potential utility as a robust thinking tool for designers working in the field. We hope that the insights gleaned from this exploration can contribute to the development of more effective design tools, techniques, and frameworks that address the needs of DMI designers at every level. By scrutinising and addressing the challenges within the DMI design landscape, it is our aim to inspire innovation and creativity while supporting a more comprehensive approach to digital instrument design in the future.

8. ACKNOWLEDGMENTS

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9. ETHICAL STANDARDS

All of the studies mentioned in this paper as having been carried out by the authors were at their time of being carried out subject to ethical approval. All study participants gave informed consent to participate.

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