Haptic Experience Design

Tools, Techniques, and Process

by

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Abstract

Haptic technology, which engages the sense of touch, offers promising benefits for a variety of interactions including low-attention displays, emotional connections, and augmented media experiences. Despite these advantages and an increasing presence of physical devices in commercial and research applications, there is still little support for the *design* of engaging haptic sensations. Previous literature has focused on the significant challenges of technological capabilities or physical realism, with limited development on supporting experience design.

In this dissertation, I ask the following question: **how can we design, build, and evaluate interactive software to support haptic experience design (HaXD)?** I have two goals: 1) *describe* HaXD, including processes, strategies, and challenges, to understand requirements; and 2) *prescribe* guidelines on designing, building, and evaluating interactive software that facillitates HaXD. To accomplish these goals, I will iteratively design three vibrotactile authoring tools, each a case study covering a different user population, vibrotactile device, and design challenge, and use them to observed HaXD with their target users. I then plan to make these in-depth findings more robust in two ways: generalizing results to a breadth of use cases with side-projects, and grounding them with expert haptic designers through interviews and a workshop. By capturing haptic experience design and creating guidelines for supportive tools, I hope to make a first step towards establishing haptic experience design as its own field, akin to graphic and sound design.

Revision: r0.1

Preface

No creative work occurs by a lone individual; this dissertation is no exception. All of the projects described in this work are collaborative efforts in at least some capacity. Even where the author contributed all work, there was often informal feedback from friends, family, and lab mates. As such, this dissertation will use the first-person plural, “we”, throughout. In this preface, we clarify the author’s contribution to the work, much of which has been published.

In Chapter 1, **??**, and **??**, Oliver contributed writing and framing, with feedback provided by the supervisor (Dr. Karon MacLean) and supervisory committee (Drs. Ronald Garcia and Michiel van de Panne) throughout his PhD program. Some of this thinking is combined with a handbook chapter currently under review, developed with Dr. Karon MacLean and Hasti Seifi: TODO.

In **??**, Oliver contributed all work and ideas, with feedback and influence from supervisor Dr. Karon MacLean. This work has been published as .

in **??**, Oliver contributed all work and ideas, other than initial interviews with designers and haptic experts. This work was conducted while on internship at Disney Research Pittsburgh, with some supplementary work done at UBC, with feedback and influence from internship supervisor Dr. Ali Israr and PhD supervisor Dr. Karon MacLean, and has been published as .

In **??**, Oliver contributed all work and ideas, with feedback and influence from supervisor Dr. Karon MacLean, except for subsection TODO, where additional development work was done by TODO, TODO, and TODO. The majority of this work has been published as ; Section TODO is currently in development for a peer-reviewed submission.

In Chapter 2, Oliver was part of a collaborative team together with PhD student Hasti Seifi, undergraduate summer student Matthew Chun, and master’s student Salma Kashani, all supervised by Dr. Karon MacLean. Oliver and Hasti planned and managed the project, with Matthew and Salma doing proxy design, study design, and data collection for low-fidelity proxies and visual proxies respectively. Oliver lead paper writing and quantitative analysis, working closely with the other authors, and presented the work published as .

In **??**, Oliver played different roles depending on the focused design project.

Section TODO, FeelCraft Oliver worked closely with Siyan Zhao, supervised by Ali Israr. Oliver implemented the rendering system (which was co-developed with the engine described in **??**), developed the MineCraft plugin and connection architecture, and wrote the AsiaHaptics paper with feedback from Ali Israr. Oliver and Siyan together designed the implemented feel effects (Oliver lead implementation), planned, shot, and edited the video submissions (Siyan lead editing); each presented the demo once (Oliver at AsiaHaptics 2014, Siyan at UIST 2014). Artistic contributions to the video were made by Kyna McIntosh and Madeleine Varner. This work has been published as .

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Acknowledgments

Thank those people who helped you.

Don't forget your parents or loved ones.

You may wish to acknowledge your funding sources.

Chapter 1

Introduction

Human beings are physical, social creatures, and our technology has only just started to communicate on our terms. Over the years, computing has progressed from symbolic, machine-focused communication like punch cards, assembly languages, and terminal interfaces to physical and natural user interaction. Yet despite embracing new interaction techniques like touchscreens and voice control, the rich senses of touch have been relegated to buzzing alerts or limited to high-stakes expert systems like laparoscopic surgery.

Haptic technology involves the senses of touch; here we refer to both tactile (skin-based) and kinaesthetic (force- and position-based) perception. Between the resurgence of consumer virtual and augmented reality (VR & AR), rapid development of personal fabrication techniques, and recent additions of high-fidelity haptics to wearable products like the Apple Watch, we are poised to see haptic technology move from niche roles into mainstream adoption. This diverse field has been active in creating new devices and understanding human perception for decades, but the development of haptic media and design of haptic experiences remain a critical challenge. Haptic experiences are rich, diverse, multimodal entities which necessitate in-person interaction and have limited infrastructure. How can we enable creativity with these experiences? In this dissertation, I study the process of haptic experience design ("HaXD") and establish guidelines for building interactive software systems to support it.

1.1 Haptic Experience Design (HaXD)

We define "haptic experience design" (HaXD) as:

> *The design (planning, development, and evaluation) of user experiences intentionally involving both interactive technology and one or*

more perceived senses of touch, possibly as part of a multimodal or multisensory experience.

We use HaXD instead of the more general "haptic design", which can also refer to design practices related to haptics but not directly involving the user experience, e.g., mechanical design of a new actuator or software design of a new control method. Our definition also includes pseudo-haptics [**?**] and other illusions that trick the user into thinking haptic feedback is occurring without direct tactile or kinesthetic stimulation. For brevity, we will use "haptic designers" to refer to haptic *experience* designers.

Here, we also take a systems approach to design. Designers do not exist in a vacuum, but rather in in a physical, social, and cultural context, and are shaped by their personal experiences. As we will elaborate, diverse activities are involved in design, including *browsing* examples, *sketching*, *refining*, and *sharing*. Just as a user's physical, social, and cultural context must be considering in an interactive experience, so too must a designer's.

1.2 Approach

While many tools exist to support design in other modalities, such as graphic design, there are few for haptics. Part of this comes from immaturity of the field and lack of market penetration of highly expressive haptic devices. However, there are also intrinsic challenges to designing for the sense of touch. I approach this problem with three different strategies:

1. **Depth: Vibrotactile design tool case studies.** To understand design, I take a design perspective. In each of three case studies, I design, build, and evaluate a tool to support an aspect of haptic experience design, scoped to *vibrotactile* (VT) design. Each of these results in concrete implications for designing tools and a small window onto the larger HaXD process. Contributions include algorithms, data structures, interaction techniques, features, analytic techniques, and working software tools that have been employed by designers. **??**, **??**, and **??** outline these.

2. **Breadth: Focused haptic design projects.** While the case studies provide an in-depth investigation into vibrotactile sensation design, results may not generalize to other devices, and provide limited investigation into design activities like sharing. To generalize from vibrotactile effects, explore other aspects of haptic design, and gain personal experience as a haptic experience designer, I participate in several smaller side projects. These more focused

projects lend a broader context to our findings. Chapter 2 and **??** discuss these projects.

3. **Ground: Data from haptic experience designers.** Finally, despite the recent growth of the field, haptic designers remain relatively rare and difficult to recruit. To complement my primarily design-based approach and ground it with haptic experience designers in the field, I draw from other data sources: a workshop held at World Haptics 2015 and interviews with haptic designers. Described in **??**, this synthesized contribution provides additional concreteness to the characterization of haptic experience design.

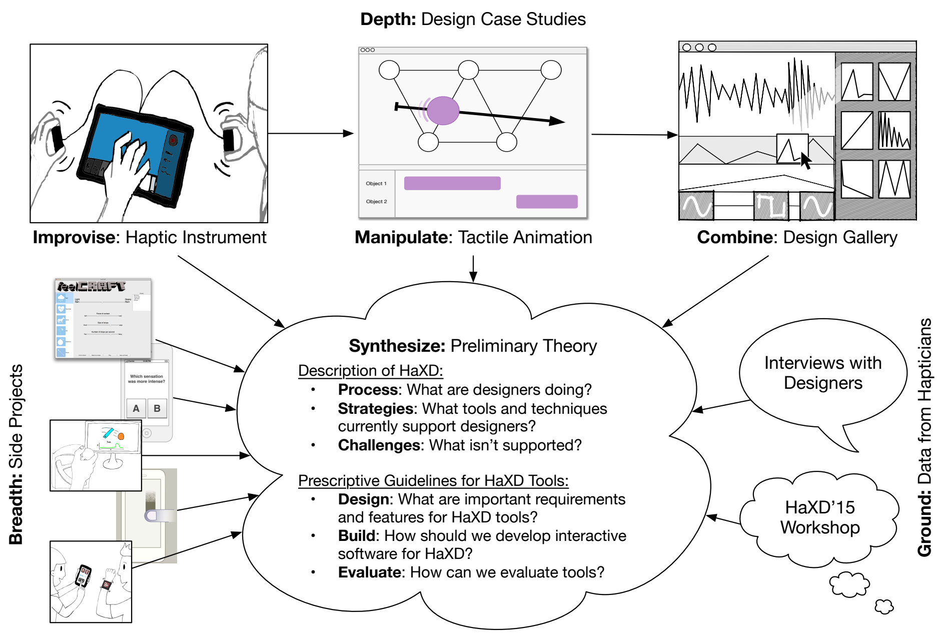


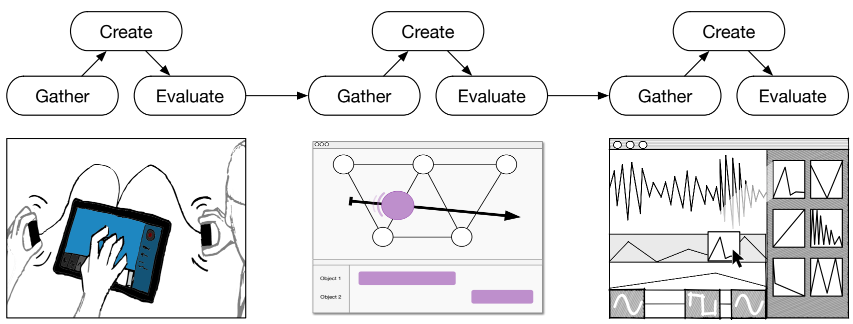
Figure 1.1: Approach overview. Three case studies investigate VT tools in-depth; findings are synthesized with side projects and grounded data into a preliminary theory.

1.2.1 Depth: Vibrotactile Design Tool Case Studies

Each case study investigates a different set of design concepts with varying user populations, VT device, and design challenges (Figure 1.2), but restricts scope to

VT sensations. This offers a deep look into an expressive and increasingly common class of haptic devices, allowing us to explore critical features in a somewhat controlled fashion. An iterative approach allows us to refine ideas and methods, and so each case study follows three steps: *gather*, finding requirements and previous design elements; *create*, where we design and build the tool; and *evaluate*, where we test the tool with its target population and consolidate lessons learned.

In Study 1, the Haptic Instrument, we focus on real-time, rapid design of VT sensations with a first look into themes of real-time design and collaboration. When participants worked with our tool, mHIVE (a "mobile Haptic Instrument for Vibrotactile Exploration"), compositions couldn't be edited, suggesting mHIVE was suitable for exploration and improvised communication, but not as suited to refining ideas. This informed Study 2, Tactile Animation, where we developed a single abstracted animation object directly manipulated in both space and time. Animators found our tactile animation tool, Mango, easy-to-use, and confirmed our findings about the value of real-time exploration.



	Improvise: Haptic Instrument	**Manipulate:** Tactile Animation	**Combine:** Design Gallery
Who	Haptic Designer-Proxies *(researchers with some haptics experience)*	Animators *(visual designers who would be haptic designers)*	End-users *(people with and without basic media editor experience)*
What	Dual Haptuators	Spatial Vibrotactile Pad	Phone-mounted Haptuator
How	Real-time, collaborative parameter control	Direct space/time manipulation of animation object	Example-based interaction techniques, morphing
Discovery	Good for ad-hoc exploration, collaboration; bad for refinement	Real-time manipulation valuable; animators drew from examples	Hypothesis: *Designers rely heavily on examples early on, make final adjustments directly*
Platform	Mobile (Android)	Desktop (Python)	Web (JavaScript)

Figure 1.2: Vibrotactile design case studies. Each studies an aspect of vibrotactile design with a varied set of users, devices, platforms, and foci.

One stand-out result from both Mango and mHIVE is that designers drew from their experience or examples found in the world, and wanted to re-use what they had created (e.g., through copy and paste). In Study 3, I explore the role of examples in haptic design with a web-based tool, “Macaron”, a vibrotactile track-based editor with visible, incorporable examples directly embedded in the interface. We found examples were used primarily as templates to inform initial design, making each individual design easier but also scaffolding the user’s understanding of how to create VT effects.

1.2.2 Breadth: Focused Haptic Design Projects

Each case study provides concrete knowledge for building a vibrotactile authoring tool, and some insight into the vibrotactile design process. However, haptic technology consists of many devices and experiences beyond vibrotactile.

FeelCraft and Feel Messenger are collaborations with Disney Research members Ali Israr and Siyan Zhao, looking at distributing and customizing haptic effects in a consumer setting with low-fidelity rumble motor devices. I take a haptic designer role to gain a personal understanding of the process, and a software engineer role to understand relevant architectures.

CyberHap is a collaboration between UBC and Stanford looking at force-feedback devices in education; a large team is involved with undergraduate Gordon Minaker leading development of a teaching interface since February 2015, co-supervised by PI Dr. Karon MacLean and me.

CuddleBit is a project inspired by the Haptic Creature and CuddleBot project. A small, breathing and vibrating robot will be designed along with a behaviour prototyping tool in summer 2015. I supervise undergraduate Paul Bucci in this project exploring multiple modalities and potential for receiving input through a sensor.

HapTurk is a collaboration with PhD candidate Hasti Seifi on different techniques to crowdsource feedback on VT icons. Master’s student Salma Kashani and undergraduate Matthew Chun are developing visualizations and low-fidelity VT icons during summer 2015.

RoughSketch is a painting application for the TPad Phone, a variable-friction mobile device, for the World Haptics 2015 Student Innovation Challenge. Undergraduates Brenna Li, Paul Bucci, and Gordon Minaker are all fellow team members. Variable friction is a significant contrast to VT sensations as it is intrinsically connected to input: no sensation can be felt without active movement by the user.

1.2.3 Ground: Data from Haptic Experience Designers

I will synthesize findings from the three design case studies together with a number of side projects, the design literature, community feedback from a workshop on haptic experience design, and interviews with haptic designers into a preliminary design theory on how to support the creation of engaging, captivating haptic experiences. I expect to make progress on the following questions:

1. **Description of the Haptic Design Process.** What are the major **processes and tasks** conducted by haptic designers? What **strategies** do haptic designers employ, including existing tools? What are the **challenges** haptic designers face?

2. **Prescriptive Implications for HaXD Tools.** What are major **requirements** and **features** for designing HaXD tools? What are some considerations when **implementing** HaXD tools in software? How can we **evaluate** design tools effectively?

1.3 Outline and Contributions

This dissertation continues as follows. First, in **??**, I cover related work with an overview of haptic technology and applications, a presentation of existing haptic design tools, and a discussion of design theory from other fields.

Then, I outline each VT design tool case study in **??**, **??**, and **??**. In **??**, we present findings from our first vibrotactile design tool, the haptic instrument, which supported easy exploration and informal feedback, but identified a key problem: lack of refinement for designs. In **??**, we present findings from our second vibrotactile design tool, Mango, which established a generalized pipeline and was able to support both exploration and refinement for expert visual animators; it highlighted reuse as an important next step. In **??**, we present findings from our third vibrotactile design tool, Macaron, which implemented a browsing interface and analytics system; we found examples played a large part of the design process, and that a web-based tool allowed for easy deployment.

I then describe focused haptic design projects in Chapter 2 and **??**, and the results from our grounded data collection in **??**. In Chapter 2, we document findings from HapTurk, a technique for getting feedback on vibrotactile designs at scale: from the crowd using proxy vibrations distributed over Mechanical Turk; we also comment on uses for haptic broadcasting. In **??**, we synthesize together findings from our side projects, showing generality by applying our understanding of haptic design explicitly in several domains and gaining practical experience designing haptic experience. In **??**, we complement our design-based inquiry through interviews with professional haptic designers and a workshop run to elicit feedback from the community; this captures a description of haptic design, reinforcing our findings for important support tools, and identifies more systematic challenges.

Finally, in **??**, we conclude with a summary of our final results and directions for future research.

Chapter 2

Share: HapTurk

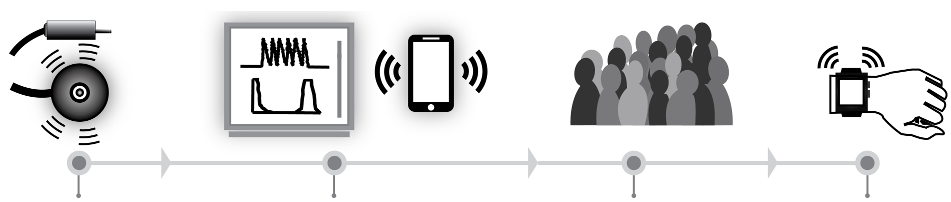
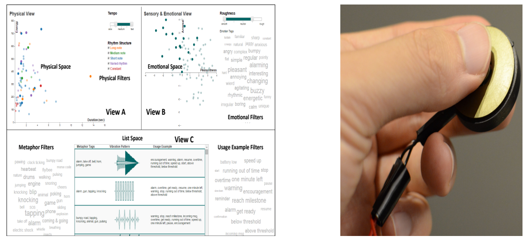


Figure 2.1: In HapTurk, we access large-scale feedback on informational effectiveness of high-fidelity vibrations after translating them into proxies of various modalities, rendering important characteristics in a crowdsource-friendly way.

While Chapters 3-5 document iterative development of VT tools, in Chapter 2 we recount a designed *technique* to support large scale feedback high-fidelity VT effects: HapTurk. As we have shown, tactile design relies heavily on iteration and user feedback [71]. In **??** we found utility in informal, collocated user feedback, but were unable to reach conclusions about haptic language due to small sample size.

In other design domains, crowdsourcing enables collecting feedback at scale. Researchers and designers use platforms like Amazon's Mechanical Turk[1] to deploy user studies with large samples, receiving extremely rapid feedback in, e.g., creative text production [**?**], graphic design [**?**] and sonic imitations [**?**]. The problem with crowdsourcing tactile feedback is that the "crowd" can't feel the stimuli. Even when consumer devices have tactors, output quality and intensity

[1]Also known as "MTurk", `www.mturk.com`



(a) VibViz interface [75] **(b)** C2 tactor

Figure 2.2: Source of high-fidelity vibrations and perceptual rating scales.

is unpredictable and uncontrollable. Our approach is to instead send more easily-shared stimuli: *proxies*, which are sent to the crowd instead of the source stimuli. In this chapter, we design and evaluate the potential of two proxy methods for high-fidelity vibrations: visualizations and low-fidelity phone vibrations.

2.1 Approach - Proxy Vibrations

We define a *proxy vibration* as a sensation that communicates key characteristics of a source stimulus within a bounded error; a *proxy modality* is the perceptual channel and representation employed. In the new evaluation process thus enabled, the designer translates a sensation of interest into a proxy modality, receives rapid feedback from a crowd-sourcing platform, then interprets that feedback using known error bounds. In this way, designers can receive high-volume, rapid feedback to use in tandem with costly in-lab studies, for example, to guide initial designs or to generalize findings from smaller studies with a larger sample.

To this end, we must first establish feasibility of this approach, with specific goals: **(G1)** Do proxy modalities work? Can they effectively communicate both physical VT properties (e.g., duration), and high-level affective properties (roughness, pleasantness)? **(G2)** Can proxies be deployed remotely? **(G3)** What modalities work, and **(G4)** what obstacles must be overcome to make this approach practical? In this chapter, we describe and assess two proxy modalities' development, translation process, validation with a test set translation, and MTurk deployment. To our knowledge, this is the first attempt to run a haptic study on a crowdsource site and characterize its feasibility and challenges for haptics.

2.2 Design

We required a set of exemplar source vibrations on which to base our proxy modalities. This set needed to 1) vary in physical, perceptual, and emotional character-

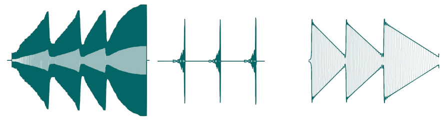


Figure 2.3: VIS$_{\text{DIR}}$ Visualization, based on VibViz

istics, 2) represent the variation in a larger source library, and 3) be small enough for experimental feasibility.

2.2.1 Affective properties and rating scales

To evaluate our proxies, we adapted six rating scales from the tactile literature and new studies. Seifi *et al* [75] proposed five taxonomies for describing vibrations including physical, sensory, emotional, metaphors, and use examples. Three taxonomies comprise quantitative metrics and adjectives; two use descriptive words.

We chose six quantitative metrics from [75] that capture important affective (physical, perceptual, and emotional) VT qualities: 1) *duration* [low-high], 2) *energy* [low-high], 3) *speed* [slow-fast], 4) *roughness* [smooth-rough], 5) *urgency* [relaxed-alarming], and 6) *pleasantness* [unpleasant-pleasant]. A large scale (0-100) allowed us to treat the ratings as continuous variables. To keep trials quick and MTurk-suitable, we did not request open-ended responses or tagging.

2.2.2 High-fidelity references

We chose 10 vibrations from a large, freely available library of 120 vibrations (VibViz, [75]), browsable through five descriptive taxonomies, and ratings of taxonomic properties. Vibrations were designed for an Engineering Acoustics C2 tactor, a high-fidelity, wearable-suitable voice coil, commonly used in haptic research [75]. We employed VibViz's filtering tools to sample, ensuring variety and coverage by selecting vibrations at high and low ends of energy / duration dimensions, and filtering by ratings of temporal structure/rhythm, roughness, pleasantness, and urgency. To reduce bias, two researchers independently and iteratively selected a set of 10 items each, which were then merged.

Because VibViz was designed for a C2 tactor, we used a handheld C2 in the present study (Figure 2.2b).

2.2.3 Proxy Choice and Design

The proxies' purpose was to capture high-level traits of source signals. We investigated two proxy channels and approaches, to efficiently establish viability

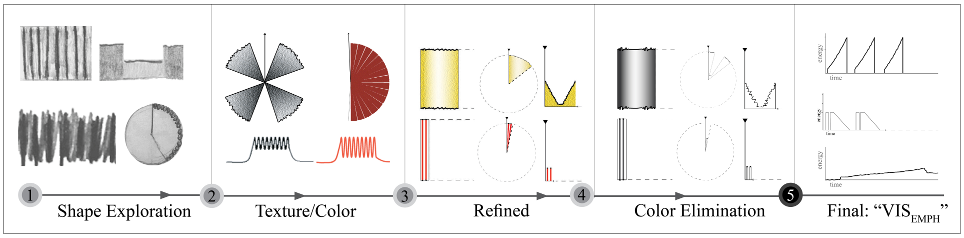


Figure 2.4: Visualization design process. Iterative development and piloting results in the VIS_{EMPH} visualization pattern.

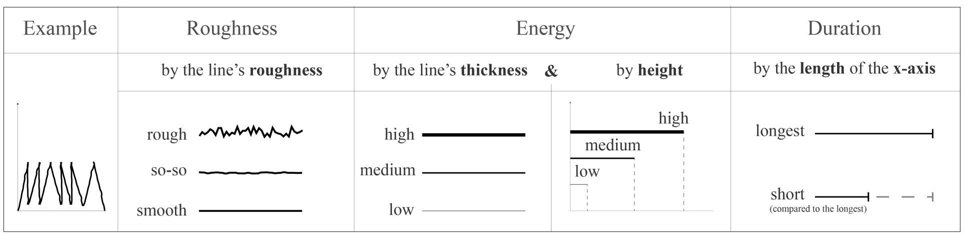


Figure 2.5: Final VIS_{EMPH} visualization guide, used by researchers to create VIS_{EMPH} proxy vibrations and provided to participants during VIS_{EMPH} study conditions.

and search for triangulated perspectives on what will work. The most obvious starting points are to 1) visually augment the current standard of a direct trace of $amplitude = f(time)$, and 2) reconstruct vibrations for common-denominator, low-fidelity actuators.

We considered other possibilities (e.g., auditory stimuli, for which MTurk has been used [**?**], or animations). However, our selected modalities balance a) directness of translation (low fidelity could not be excluded); b) signal control (hard to ensure consistent audio quality/volume/ambient masking); and c) development progression (visualization underlies animation, and is simpler to design, implement, display). We avoided multisensory combinations at this early stage for clarity of results. Once the key modalities are tested, combinations can be investigated in future work.

“REF” denotes high-fidelity source renderings (C2 tactor).

(1) Visual proxies – Norms in published works (e.g. [11]) directed [75] to confirm that users rely on graphical $f(time)$ plots to skim and choose from large libraries. We tested the direct plot, VIS_{DIR}, as the status-quo representation.

However, these unmodified time-series emphasize or mask traits differently than felt vibrations, in particular for higher-level or “meta” responses. We considered many other means of visualizing vibration characteristics, pruned candidates and refined design via piloting to produce a new scheme which explicitly *emphasizes* affective features, VIS_{EMPH}.

(2) Low-fidelity vibration proxy: – Commodity device (e.g. smartphone) actuators usually have low output capability compared to the C2, in terms of frequency response, loudness range, distortion and parameter independence. Encouraged by expressive rendering of VT sensations with commodity actuation (from early constraints [11] to deliberate design-for-lofi [40]), we altered stimuli to convey high-level parameters under these conditions, hereafter referred to as LOFIVIB.

Translation: Below, we detail first-pass proxy development. In this feasibility stage, we translated proxy vibrations manually and iteratively, as we sought generalizable mappings of the parametric vibration definition to the perceptual quality we wished to highlight in the proxy. We frequently relied on a cycle of user feedback, e.g., to establish the perceived roughness of the original stimuli and proxy candidate.

Automatic translation is an exciting goal. Without it, HapTurk is still useful for gathering large samples; but automation will enable a very rapid create-test cycle. It should be attainable, bootstrapped by the up-scaling of crowdsourcing itself. With a basic process in place, we can use MTurk studies to identify these mappings relatively quickly.

2.2.4 Visualization Design (VIS_{DIR} and VIS_{EMPH})

VIS_{DIR} was based on the original waveform visualization used in VibViz (Figure 2.3). In Matlab, vibration frequency and envelope were encoded to highlight its pattern over time. Since VIS_{DIR} patterns were detailed, technical and often inscrutable for users without an engineering background, we also developed a more interpretive visual representation, VIS_{EMPH}; and included VIS_{DIR} as a status-quo baseline.

We took many approaches to depicting vibration high-level properties, with visual elements such as line thickness, shape, texture and colour (Figure 2.4). We first focused on line sharpness, colour intensity, length and texture: graphical waveform smoothness and roughness were mapped to perceived roughness; colour intensity highlighted perceived energy. Duration mapped to length of the graphic, while colour and texture encoded the original's invoked emotion.

Four participants were informally interviewed and asked to feel REF vibrations, describe their reactions, and compare them to several visualization candidates. Participants differed in their responses, and had difficulties in understanding VT emotional characteristics from the graphic (i.e. pleasantness, urgency), and in reading the circular patterns. We simplified the designs, eliminating representation of emotional characteristics (color, texture), while retaining more objective mappings for physical and sensory characteristics.

VIS$_{\text{EMPH}}$ won an informal evaluation of final proxy candidates (n=7), and was captured in a translation guideline (Figure 2.5).

2.2.5 Low Fidelity Vibration Design

For our second proxy modality, we translated REF vibrations into LOFIVIB vibrations. We used a smartphone platform for their built-in commodity-level VT displays, their ubiquity amongst users, and low security concerns for vibration imports to personal devices [**?**]. To distribute vibrations remotely, we used HTML5 Vibration API, implemented on Android phones running compatible web browsers (Google Chrome or Mozilla Firefox).

As with VIS$_{\text{EMPH}}$, we focused on physical properties when developing LOFIVIB(our single low-fi proxy exemplar). We emphasized rhythm structure, an important design parameter [79] and the only direct control parameter of the HTML5 API, which issues vibrations using a series of on/off durations. Simultaneously, we manipulated perceived energy level by adjusting the actuator pulse train on/off ratio, up to the point where the rhythm presentation was compromised. Shorter durations represented a weak-feeling hi-fi signal, while longer durations conveyed intensity in the original. This was most challenging for dynamic intensities or frequencies, such as increasing or decreasing ramps, and long, low-intensity sensations. Here we used a duty-cycle inspired technique, similar to [40], illustrated in Figure 2.6.

To mitigate the effect of different actuators found in smartphones, we limited our investigation to Android OS. While this restricted our participant pool, there was nevertheless no difficulty in quickly collecting data for either study. We designed for two phones representing the largest classes of smartphone actuators: Samsung Galaxy Nexus, which contains a coin-style actuator, and a Sony Xperia Z3 Compact, which uses a pager motor resulting in more subdued, smooth sensations. Though perceptually different, control of both actuator styles are limited to on/off durations. As with VIS$_{\text{EMPH}}$, we developed LOFIVIB vibrations iteratively, first with team feedback, then informal interviews (n=6).

2.3 Studies

We ran two user studies to evaluate our proxy methods. Study 1 was an in-lab comparison between our high-fidelity reference vibrations and our proxies. Study 2 was an MTurk-deployed comparison of our proxies compared with both in-lab high-fidelity references and in-lab proxies. In both cases we use equivalence testing for statistical analysis.

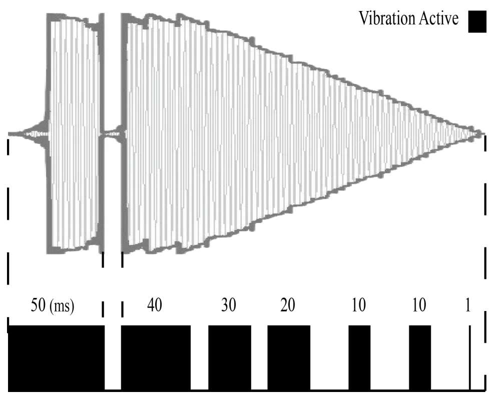


Figure 2.6: Example of LOFIVIB proxy design. Pulse duration was hand-tuned to represent length and intensity, using duty cycle to express dynamics such as ramps and oscillations.

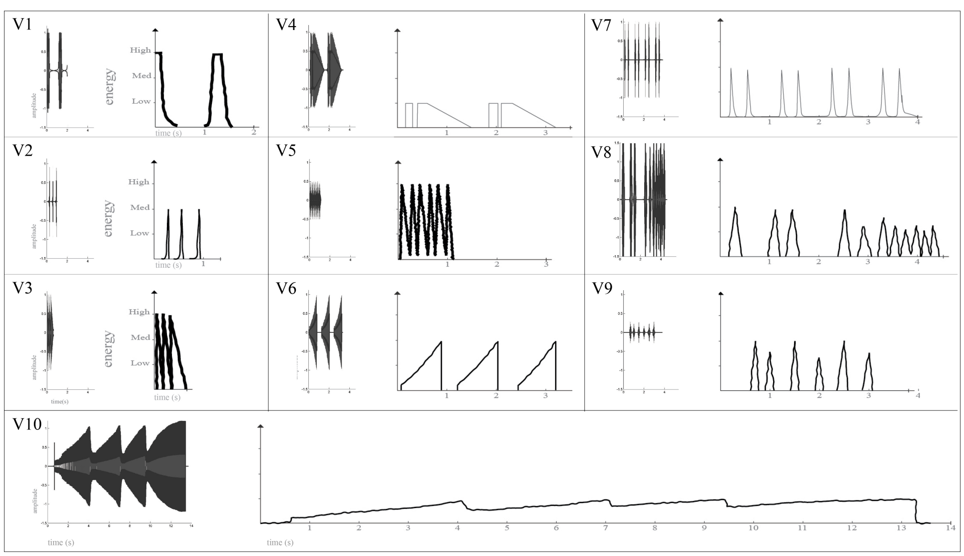


Figure 2.7: Vibrations visualized as both VIS_{DIR} (left of each pair) and VIS_{EMPH}.

2.3.1 Comparison Metric: Equivalence Threshold

To assess whether a proxy modalities were rated similarly to their targets, we employed *equivalence testing*, which tests the hypothesis that sample means are within a threshold δ, against the null of being outside it [**?**]. This tests if two samples are equivalent with a known error bound; it corresponds to creating confidence intervals of means, and examining whether they lie entirely within the range $(-\delta, \delta)$.

We first computed least-squares means for the 6 rating scales for each proxy modality and vibration. 95% confidence intervals (CI) for REF rating means ranged from 14.23 points (Duration ratings) to 20.33 (Speed). Because estimates of the REF "gold standard" mean could not be more precise than these bounds, we set equivalence thresholds for each rating equal to CI width. For example, given the CI for Duration of 14.23, we considered proxy Duration ratings equivalent if the CI for a difference fell completely in the range $(-14.23, 14.23)$. With pooled standard error, this corresponded to the case where two CIs overlap by more than 50%. We also report when a *difference* was detected, through typical hypothesis testing (i.e., where CIs do not overlap).

Thus, each rating set pair could be *equivalent*, *uncertain*, or *different*. Figure 2.9 offers insight into how these levels are reflected in the data given the high rating variance. This approach gives a useful error bound, quantifying the precision tradeoff in using vibration proxies to crowdsource feedback.

2.3.2 Study 1: In-lab Proxy Vibration Validation (G1)

We obtained user ratings for the hi-fi source vibrations REFand three proxies (VIS$_{\text{DIR}}$, VIS$_{\text{EMPH}}$, and LOFIVIB). An in-lab format avoided confounds and unknowns due to remote MTurk deployment, addressed in Study 2. Study 1 had two versions: in one, participants rated visual proxies VIS$_{\text{DIR}}$ and VIS$_{\text{EMPH}}$ next to REF; and in the other, LOFIVIB next to REF. REF$_{\text{VIS}}$ and REF$_{\text{LOFIVIB}}$ denote these two references, each compared with its respective proxy(ies) and thus with its own data. In each substudy, participants rated each REF vibration on 6 scales [0-100] in a computer survey, and again for the proxies. Participants in the visual substudy did this for both VIS$_{\text{DIR}}$ and VIS$_{\text{EMPH}}$, then indicated preference for one. Participants in the lo-fi study completed the LOFIVIB survey on a phone, which also played vibrations using Javascript and HTML5; other survey elements employed a laptop. 40 participants aged 18-50 were recruited via university undergraduate mailing lists. 20 (8F) participated in the visual substudy, and a different 20 (10F) in the low-fi vibration substudy.

Reference and proxies were presented in different random orders. Pilots confirmed that participants did not notice proxy/target linkages, and thus were unlikely to consciously match their ratings between pair elements. REF/proxy presentation order was counterbalanced, as was VIS_{DIR}/VIS_{EMPH}.

2.3.3 Proxy Validation (Study 1) Results and Discussion

Overview of Results – Study 1 results appear graphically in Figure 2.8. To interpret this plot, look for (1) equivalence indicated by bar color, and CI size by bar height (dark green/small are good); (2) rating richness: how much spread, vibration to vibration, within a cell indicates how well that parameter captures the differences users perceived; (3) modality consistency: the degree to which the bars' up/down pattern translates vertically across rows. When similar (and not flat), the proxy translations are being interpreted by users in the same way, providing another level of validation. We structure our discussion around how the three modalities represent the different rating scales. We refer to the number of *equivalents* and *differents* in a given cell as [x:z], with y = number of *uncertains*, and $x+y+z=10$.

Duration and Pleasantness were translatable – Duration was comparably translatable for LOFIVIB [5:1] and VIS_{EMPH} [6:1]; VIS_{DIR} was less consistent [7:3] (two differences very large). Between the three modalities, 9/10 vibrations achieved equivalence with at least one modality. For Duration, this is unsurprising. It is a physical property that is controllable through the Android vibration API, and both visualization methods explicitly present Duration as their x-axis. This information was apparently not lost in translation.

More surprisingly, Pleasantness fared only slightly worse for LOFIVIB [4:2] and VIS_{EMPH} [4:1]; 8 / 10 vibrations had at least one modality that provided equivalence. Pleasantness is a higher-level affective feature than Duration. Although not an absolute victory, this result gives evidence that, with improvement, crowdsourcing may be a viable method of feedback for at least one affective parameter.

***Speed and Urgency translated better with* LOFIVIB** – LOFIVIB was effective at representing Urgency [6:2]; VIS_{EMPH} attained only [4:5], and VIS_{DIR} [3:5]. Speed was less translatable. LOFIVIB did best at [4:2]; VIS_{DIR} reached only [1:6], and VIS_{EMPH} [3:5]. However, the modalities again complemented each other. Of the three, 9/10 vibrations were equivalent at least once for Urgency (V8 was not). Speed had less coverage: 6/10 had equivalencies (V3,4,6,10 did not).

***Roughness had mixed results; best with* $\textbf{VIS}_{\textbf{EMPH}}$** – Roughness ratings varied heavily by vibration. 7 vibrations had at least one equivalence (V2,4,10 did not). All modalities had 4 equivalencies each: VIS_{EMPH} [4:3], VIS_{DIR} [4:4], and LOFIVIB [4:5].

Energy was most challenging – Like Roughness, 7 vibrations had at least one equivalence between modalities (V1,4,10 did not). LOFIVIB [4:5] did best with

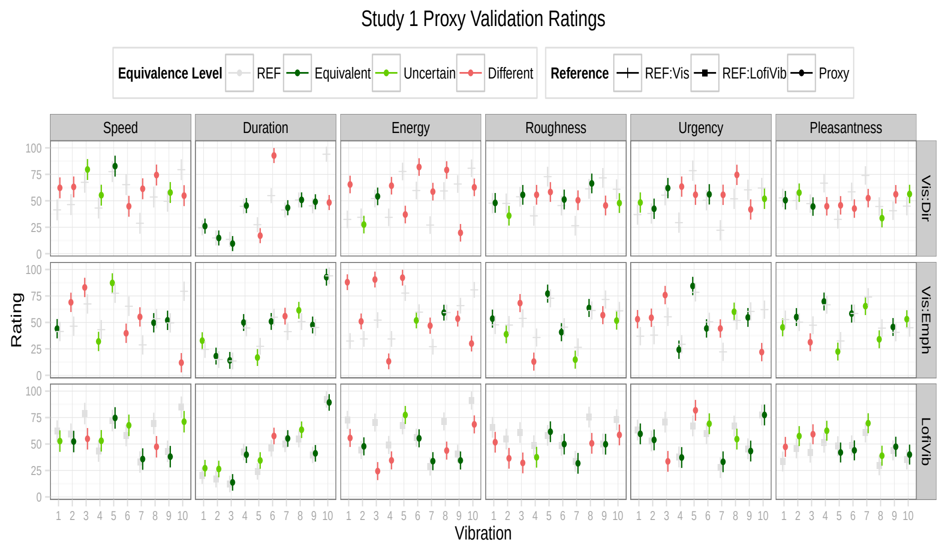


Figure 2.8: 95% confidence intervals and equivalence test results for Study 1 - Proxy Validation. Grey represents REF ratings. Dark green maps equivalence within our defined threshold, and red a statistical difference indicating an introduced bias; light green results are inconclusive. Within each cell, variation of REF ratings means vibrations were rated differently compared to each other, suggesting they have different perceptual features and represent a varied set of source stimuli.

Energy; VIS_{EMPH} and VIS_{DIR} struggled at [1:8].

Emphasized visualization outperformed direct plot – Though it depended on the vibration, VIS_{EMPH} outperformed VIS_{DIR} for most metrics, having the same or better equivalencies/differences for Speed, Energy, Roughness, Urgency, and Pleasantness. Duration was the only mixed result, as VIS_{DIR} had both more equivalencies and more differences [7:3] versus [6:1] In addition, 16/20 participants (80%) preferred VIS_{EMPH} to VIS_{DIR}. Although not always clear-cut, these comparisons overall indicate that our VIS_{EMPH} visualization method communicated these affective qualities more effectively than the status quo. This supports our approach to emphasized visualization, and motivates the future pursuit of other visualizations.

V4,V10 difficult, V9 easy to translate – While most vibrations had at least one equivalency for 5 rating scales, V4 and V10 only had 3. V4 and V10 had no equivalences at all for Speed, Roughness, and Energy, making them some of

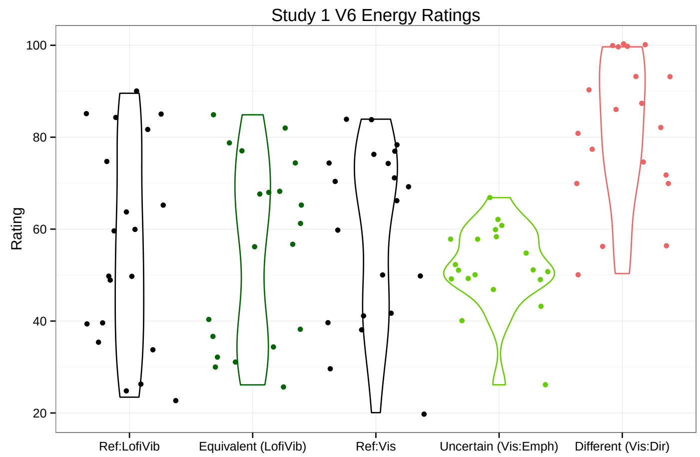


Figure 2.9: Rating distributions from Study 1, using V6 Energy as an example. These violin plots illustrate 1) the large variance in participant ratings, and 2) how equivalence thresholds reflect the data. When equivalent, proxy ratings are visibly similar to REF. When uncertain, ratings follow a distribution with unclear differences. When different, there is a clear shift.

the most difficult vibrations to translate. V4's visualization had very straight lines, perhaps downplaying its texture. V10 was by far the longest vibration, at 13.5s (next longest was V8 with 4.4s). Its length may have similarly masked textural features.

V8 was not found to be equivalent for Urgency and Pleasantness. V8 is an extremely irregular vibration, with a varied rhythm and amplitude, and the second longest. This may have made it difficult to glean more intentional qualities like Urgency and Pleasantness. However, it was only found to be different for VIS_{DIR}/Urgency, so we cannot conclude that significant biases exist.

By contrast, V9 was the only vibration that had an equivalency for every rating scale, and in fact could be represented across all ratings with LOFIVIB. V9 was a set of distinct pulses, with no dynamic ramps; it thus may have been well suited to translation to LOFIVIB.

Study 1 Summary – In general, these results indicate promise, but also need improvement and combination of proxy modalities. Unsurprisingly, participant ratings varied, reducing confidence and increasing the width of confidence intervals (indeed, this is partial motivation to access larger samples). Even so, both differences and equivalencies were found in every rating/proxy modality pairing. Most

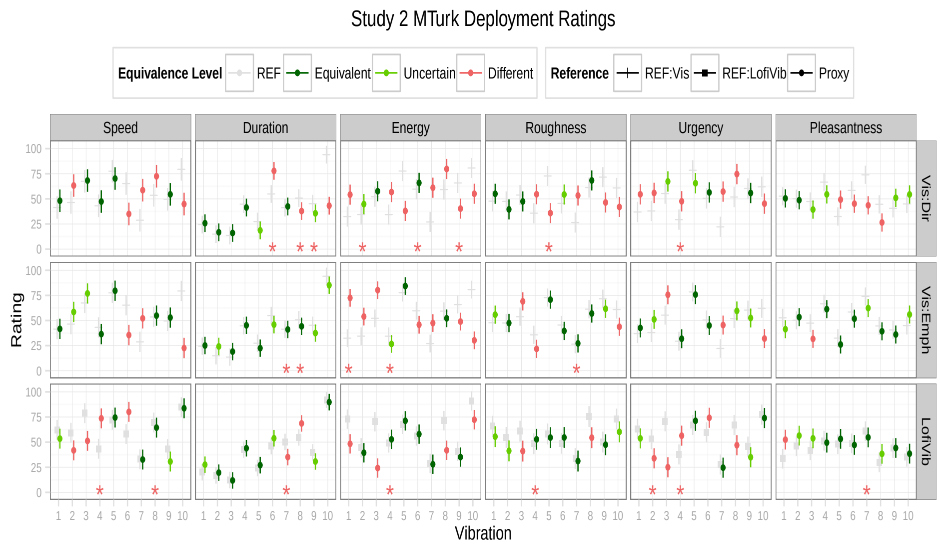


Figure 2.10: 95% Confidence Intervals and Equivalence Test Results for Study 2 - MTurk Deployment Validation. Equivalence is indicated with dark green, difference is indicated with red, and uncertainty with light green. Red star indicates statistically significant difference between remote and local proxy ratings.

vibrations were equivalent with at least one modality, suggesting that we might pick an appropriate proxy modality depending on the vibration; we discuss the idea of triangulation in more detail later. Duration and Pleasantness were fairly well represented, Urgency and Speed were captured best by LOFIVIB, and Roughness was mixed. Energy was particularly difficult to represent with these modalities. We also find that results varied depending on vibration, meaning that more analysis into what makes vibrations easier or more difficult to represent could be helpful.

Though we were able to represent several features using proxy modalities within a bounded error rate, this alone does not mean they are crowdsource-friendly. All results from Study 1 were gathered in-lab, a more controlled environment than over MTurk. We thus ran a second study to validate our proxy modality ratings when deployed remotely.

2.3.4 Study 2: Deployment Validation with MTurk (G2)

To determine whether rating of a proxy is similar when gathered locally or remotely, we deployed the same computer-run proxy modality surveys on MTurk.

We wanted to discover the challenges all through the pipeline for running a VT study on MTurk, including larger variations in phone actuators and experimental conditions (G4). We purposefully did not iterate on our proxy vibrations or survey, despite identifying many ways to improve them, to avoid creating a confound in comparing results of the two studies.

The visualization proxies were run as a single MTurk Human Intelligence Task (HIT), counterbalanced for order; the LOFIVIB survey was deployed as its own HIT. Each HIT was estimated at 30m, for which participants received $2.25 USD. In comparison, Study 1 participants were estimated to take 1 hour and received $10 CAD. We anticipated a discrepancy in average task time due to a lack of direct supervision for the MTurk participants, and expected this to lead to less accurate participant responses, prompting the lower payrate. On average, it took 7m for participants to complete the HIT while local study participants took 30m.

We initially accepted participants of any HIT approval rate to maximize recruitment in a short timeframe. Participants were post-screened to prevent participation in both studies. 49 participants were recruited. No post-screening was used for the visual sub-study. For the LOFIVIB proxy survey, we post-screened to verify device used [**?**]. We asked participants (a) confirm their study completion with an Android device via a survey question (b) detected actual device via FluidSurvey's OS-check feature, and (c) rejected inconsistent samples (eg. 9 used non-Android platforms for LOFIVIB). Of the included data, 20 participants participated each in the visual proxy condition (6F) and the LOFIVIB condition (9F).

For both studies, Study 1's data was used as a "gold standard" that served as a baseline comparison with the more reliable local participant ratings [**?**]. We compared the remote proxy results (from MTurk) to the REF results gathered in Study 1, using the same analysis methods.

2.3.5 Study 2 Results

Study 2 results appear in Figure 2.10, which compares remotely collected ratings with locally collected ratings for the respective reference (the same reference as for Figure 2.8). It can be read the same way, but adds information. Based an analysis of a different comparison, a red star indicates a statistically significant difference between remote proxy ratings and corresponding local *proxy* ratings. This analysis revealed that ratings for the same proxy gathered remotely and locally disagreed 21 times (stars) out of 180 rating/modality/vibration combination; i.e., relatively infrequently.

Overall, we found similar results and patterns in Study 2 as for Study 1. The two figures show similar up/down rating patterns; the occasional exceptions correspond to red-starred items. Specific results varied, possibly due to statistical noise and rating variance. We draw similar conclusions: that proxy modalities can still be viable when deployed on MTurk, but require further development to be reliable in some cases.

2.4 Discussion

Here we discuss high level implications from our findings and relate them to our study goals (G1-G4 in Introduction).

Proxy modalities are viable for crowdsourcing (G1,G2:feasibility) – Our studies showed that proxy modalities can represent affective qualities of vibrations within reasonably chosen error bounds, depending on the vibration. These results largely translate to deployment on MTurk. Together, these two steps indicate that proxy modalities are be a viable approach to crowdsourcing VT sensations, and can reach a usable state with a bounded design iteration (as outlined in the following sections). This evidence also suggests that we may be able to deploy directly to MTurk for future validation. Our two-step validation was important as a first look at whether ratings shift dramatically; and we saw no indications of bias or overall shift between locally running proxy modalities and remotely deploying them.

Triangulation (G3:promising directions/proxies) – Most vibrations received equivalent ratings for most scales in at least one proxy modality. Using proxy modalities in tandem might help improve response accuracy. For example, V6 could be rendered with LOFIVIB for a pleasantness rating, then as VIS_{EMPH} for Urgency. Alternatively, we might develop an improved proxy vibration by combining modalities - a visualization with an accompanying low-fidelity vibration.

Animate visualizations (G3:promising directions) – Speed and Urgency were not as effectively transmitted with our visualizations as with our vibration. Nor was Duration well portrayed with VIS_{DIR}, which had a shorter time axis than the exaggerated VIS_{EMPH}. It may be more difficult for visual representations to portray time effectively: perhaps it is hard for users to distinguish Speed/Urgency, or the time axis is not at an effective granularity. Animations (e.g., adding a moving line to help indicate speed and urgency), might help to decouple these features. As with triangulation, this might also be accomplished through multimodal proxies which augment a visualization with a time-varying sense using sounds or vibration. Note, however, that Duration was more accurately portrayed by VIS_{EMPH}, suggesting that direct representation of physical features *can* be translated.

Sound could represent Energy (G3:promising directions) – Our high-fidelity reference is a voice-coil actuator, also used in audio applications. Indeed, in initial pilots we played vibration sound files through speakers. Sound is the closest to vibration in the literature, and a vibration signal's sound output is correlated with the vibration energy and sensation.

However, in our pilots, sometimes the vibration sound did not match the sensation; was not audible (low frequency vibrations); or the C2 could only play part of the sound (i.e, the sound was louder than the sensation).

Thus, while the raw sound files are not directly translatable, a sound proxy definitely has potential. It could, for example, supplement where the VIS$_{\text{DIR}}$ waveform failed to perform well on any metric (aside from Duration) but a more expressive visual proxy (VIS$_{\text{EMPH}}$) performed better.

Device dependency and need for Energy model for Vibrations (G4:challenges) – Energy did not translate well. This could be a linguistic confusion, but also a failure to translate this feature. For the visualization proxies, it may be a matter of finding the right representation, which we continue to work on.

However, with LOFIVIB, this represents a more fundamental tradeoff due to characteristics of phone actuators, which have less control over energy output than we do with a dedicated and more powerful C2 tactor. The highest vibration energy available in phones is lower than for the C2; this additional power obviously extends expressive range. Furthermore, vibration energy and time are coupled in phone actuators: the less time the actuator is on, the lower the vibration energy. As a result, it is difficult to have a very short pulses with very high energy (V1,V3,V8). The C2's voice coil technology does not have this duty-cycle derived coupling. Finally, the granularity of the energy dimension is coarser for phone actuators. This results in a tradeoff for designing (for example) a ramp sensation: if you aim for accurate timing, the resulting vibration would have a lower energy (V10). If you match the energy, the vibration will be longer.

Knowing these tradeoffs, designers and researchers can adjust their designs to obtain more accurate results on their intended metric. Perhaps multiple LOFIVIB translations can be developed which maintain different qualities (one optimized on timing and rhythm, the other on energy). In both these cases, accurate models for rendering these features will be essential.

VT affective ratings are generally noisy (G4:challenges) – Taken as a group, participants were not highly consistent among one another when rating these affective studies, whether local or remote. This is in line with previous work [75], and highlights a need to further develop rating scales for affective touch. Larger sample sizes, perhaps gathered through crowdsourcing, may help reduce or characterize this error. Alternatively, it gives support to the need to develop mechanisms for individual customization. If there are "types" of users who do share preferences and interpretations, crowdsourcing can help with this as well.

Response & data quality for MTurk* LOFIVIB *vibrations (G4:challenges) – When deploying vibrations over MTurk, 8/29 participants (approximately 31%) completed the survey using non-Android based OSes (Mac OS X, Windows 7,8.1, NT) despite these requirements being listed in the HIT and the survey. One participant reported not being able to feel the vibrations despite using an Android phone. This suggests that enforcing a remote survey to be taken on the phone is challenging, and that additional screens are needed to identify participants not on a particular platform. Future work might investigate additional diagnostic tools to ensure that vibrations are being generated, through programmatic screening of platforms, well-worded questions and instructions, and (possibly) ways of detecting vibrations actually being played, perhaps through the microphone or accelerometer).

Automatic translation (G4:challenges) – Our proxy vibrations were developed by hand, to focus on the feasibility of crowdsourcing. However, this additional effort poses a barrier for designers that might negate the benefits of using a platform of MTurk. As this approach becomes better defined, we anticipate automatic translation heuristics for proxy vibrations using validated algorithms. Although these might be challenging to develop for emotional features, physical properties like amplitude, frequency, or measures of energy and roughness would be a suitable first step. Indeed, crowdsourcing itself could be used to create these algorithms, as several candidates could be developed, their proxy vibrations deployed on MTurk, and the most promising algorithms later validated in lab.

2.4.1 Limitations

A potential confound was introduced by VIS_{EMPH} having a longer time axis than VIS_{DIR}: some of VIS_{EMPH}'s improvements could be due to seeing temporal features in higher resolution. This is exacerbated by V10 being notably longer than the next longest vibration, V8 (13.5s vs. 4.4s), further reducing temporal resolution vibrations other than V10.

We presented ratings to participants by-vibration rather than by-rating. Because participants generated all ratings for a single vibration at the same time, it is possible there are correlations between the different metrics. We chose this arrangement because piloting suggested it was less cognitively demanding than presenting metrics separately for each vibration. Future work can help decide whether correlations exist between metrics, and whether these are an artifact of stimulus presentation or an underlying aspect of the touch aesthetic.

Despite MTurk's ability to recruit more participants, we used the same sample size of 40 across both studies. While our proxies seemed viable for remote deployment, there were many unknown factors in MTurk user behaviour at the time of deployment. We could not justify more effort without experiencing these factors firsthand. Thus, we decided to use a minimal sample size for the MTurk study that was statistically comparable to the local studies. In order to justify a larger remote sample size in the future, we believe it is best to iterate the rating scales and to test different sets of candidate modalities.

As discussed, we investigated two proxy modalities in this first examination but look forward to examining others (sound, text, or video) alone or in combination. ⌈**OS** *TODO: Connect more with other chapter discussions and intros.*⌋

Bibliography

[1] D. Alles. Information Transmission by Phantom Sensations. *IEEE Transactions on Man Machine Systems*, 11(1):85–91, Mar. 1970. ISSN 0536-1540. doi:10.1109/TMMS.1970.299967. URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4081935. → pages

[2] Android Open Source Project. Android Developers, 2012. URL http://developer.android.com/index.html. → pages

[3] R. A. Bolt. Put-that-there: Voice and Gesture at the Graphics Interface. *ACM SIGGRAPH Computer Graphics*, 14(3):262–270, July 1980. ISSN 00978930. doi:10.1145/965105.807503. URL http://dl.acm.org/citation.cfm?id=965105.807503. → pages

[4] S. Brewster and L. M. Brown. Tactons: structured tactile messages for non-visual information display. In *AUIC '04*, pages 15–23, Jan. 2004. URL http://dl.acm.org/citation.cfm?id=976310.976313. → pages

[5] S. A. Brewster, P. C. Wright, and A. D. N. Edwards. An evaluation of earcons for use in auditory human-computer interfaces. In *CHI '93)*, pages 222–227, New York, USA, May 1993. ACM Press. ISBN 0897915755. doi:10.1145/169059.169179. URL http://dl.acm.org/citation.cfm?id=169059.169179. → pages

[6] L. Brown, S. Brewster, and H. Purchase. A First Investigation into the Effectiveness of Tactons. In *World Haptics '05*, pages 167–176. IEEE, 2005. ISBN 0-7695-2310-2. doi:10.1109/WHC.2005.6. URL http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=1406930. → pages

[7] L. M. Brown, S. A. Brewster, and H. C. Purchase. Tactile crescendos and sforzandos. In *CHI Extened Abstracts '06*, pages 610–615, New York, USA,

Apr. 2006. ACM Press. ISBN 1595932984. doi:10.1145/1125451.1125578. URL http://dl.acm.org/citation.cfm?id=1125451.1125578. → pages

[8] L. M. Brown, S. A. Brewster, and H. C. Purchase. Multidimensional tactons for non-visual information presentation in mobile devices. In *MobileHCI '06*, pages 231–238, New York, USA, Sept. 2006. ACM Press. ISBN 1595933905. doi:10.1145/1152215.1152265. URL http://dl.acm.org/citation.cfm?id=1152215.1152265. → pages

[9] B. Buxton. *Sketching User Experiences: Getting the Design Right and the Right Design*. Morgan Kaufmann Publishers Inc., 2007. → pages

[10] J. Cha, Y.-S. Ho, Y. Kim, J. Ryu, and I. Oakley. A Framework for Haptic Broadcasting. *IEEE Multimedia*, 16(3):16–27, July 2009. ISSN 1070-986X. doi:10.1109/MMUL.2009.42. URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5228689. → pages

[11] A. Chan, K. MacLean, and J. McGrenere. Designing haptic icons to support collaborative turn-taking. *International Journal of Human-Computer Studies*, 66(6):333–355, 2008. URL http://www.sciencedirect.com/science/article/pii/S1071581907001565. → pages 12, 13

[12] J. Corbin and A. Strauss. *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory*. Sage Publications, Inc., 3 edition, 2008. → pages

[13] J. W. Creswell. *Qualitative inquiry and research design: choosing among five approaches*. Sage Publications Inc, 3rd edition, 2013. → pages

[14] N. Cross. *Designerly Ways of Knowing*. Springer-Verlag London Limited, 2006. → pages

[15] N. Cross. *Design Thinking: Understanding How Designers Think and Work*. Berg Publishers, Oxford, UK, 2011. → pages

[16] D. Cuartielles, A. Goransson, T. Olsson, and S. Stenslie. Developing Visual Editors for High-Resolution Haptic Patterns. In *HAID'12 Posters and Demos*, pages 42–44, 2012. URL http://www.english.certec.lth.se/haptics/HAID12/-proceedings.pdf. → pages

[17] H. Culbertson, J. Unwin, and K. J. Kuchenbecker. Modeling and rendering realistic textures from unconstrained tool-surface interactions. *IEEE Transactions on Haptics*, 7(3):381–93, Jan. 2014. ISSN 2329-4051. doi:10.1109/TOH.2014.2316797. URL http://www.ncbi.nlm.nih.gov/pubmed/25248220. → pages

[18] F. Danieau, J. Fleureau, P. Guillotel, N. Mollet, A. Lécuyer, and M. Christie. HapSeat: producing motion sensation with multiple force-feedback devices embedded in a seat. In *VRST '12*, pages 69–76, New York, New York, USA, Dec. 2012. ACM Press. ISBN 9781450314695. doi:10.1145/2407336.2407350. URL http://dl.acm.org/citation.cfm?id=2407336.2407350. → pages

[19] F. Danieau, J. Fleureau, P. Guillotel, N. Mollet, M. Christie, and A. Lecuyer. Toward Haptic Cinematography: Enhancing Movie Experiences with Camera-Based Haptic Effects. *IEEE MultiMedia*, 21(2):11–21, 2014. ISSN 1070-986X. doi:10.1109/MMUL.2013.64. URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6695749. → pages

[20] S. Dow, J. Fortuna, D. Schwartz, B. Altringer, D. Schwartz, and S. Klemmer. Prototyping dynamics: sharing multiple designs improves exploration, group rapport, and results. In *CHI '11*, pages 2807–2816. ACM Press, May 2011. ISBN 9781450302289. doi:10.1145/1978942.1979359. URL http://dl.acm.org/citation.cfm?id=1978942.1979359. → pages

[21] Z. Eitan and I. Rothschild. How music touches: Musical parameters and listeners' audio-tactile metaphorical mappings. *Psychology of Music*, 39(4): 449–467, Nov. 2010. ISSN 0305-7356. doi:10.1177/0305735610377592. URL http://pom.sagepub.com/content/39/4/449.short. → pages

[22] P. Ekman, I. R. Davidson, P. Ellsworth, and W. V. Friesen. Are There Basic Emotions? *Psychological Review*, 99(3):550–553, 1992. → pages

[23] C. A. Ellis, S. J. Gibbs, and G. Rein. Groupware: some issues and experiences. *Communications of the ACM*, 34(1):39–58, Jan. 1991. ISSN 00010782. doi:10.1145/99977.99987. URL http://dl.acm.org/citation.cfm?id=99977.99987. → pages

[24] M. Enriquez and K. MacLean. The hapticon editor: a tool in support of haptic communication research. In *HAPTICS '03*, pages 356–362. IEEE Comput. Soc, 2003. ISBN 0-7695-1890-7.

doi:10.1109/HAPTIC.2003.1191310. URL
http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=1191310. → pages

[25] M. Enriquez, K. MacLean, and C. Chita. Haptic phonemes: basic building blocks of haptic communication. In *ICMI '06*, page 302, New York, USA, Nov. 2006. ACM Press. ISBN 159593541X. doi:10.1145/1180995.1181053. URL http://dl.acm.org/citation.cfm?id=1180995.1181053. → pages

[26] FMOD. FMOD Ex API, 2013. URL http://www.fmod.org. → pages

[27] J. Forsslund, M. Yip, and E.-L. Sallnäs. WoodenHaptics. In *TEI '14*, pages 133–140. ACM Press, Jan. 2015. ISBN 9781450333054. doi:10.1145/2677199.2680595. URL http://dl.acm.org/citation.cfm?id=2677199.2680595. → pages

[28] S. Greenberg and C. Fitchett. Phidgets: Easy development of physical interfaces through physical widgets. In *UIST '01*, page 209, New York, New York, USA, Nov. 2001. ACM Press. ISBN 158113438X. doi:10.1145/502348.502388. URL http://dl.acm.org/citation.cfm?id=502348.502388. → pages

[29] S. Guest, J. M. Dessirier, A. Mehrabyan, F. McGlone, G. Essick, G. Gescheider, A. Fontana, R. Xiong, R. Ackerley, and K. Blot. The development and validation of sensory and emotional scales of touch perception. *Attention, perception & psychophysics*, 73(2):531–50, Feb. 2011. ISSN 1943-393X. doi:10.3758/s13414-010-0037-y. URL http://www.ncbi.nlm.nih.gov/pubmed/21264727. → pages

[30] E. Gunther, G. Davenport, and S. O'Modhrain. Cutaneous grooves: composing for the sense of touch. In *NIME '02*, pages 1–6, New York, NY, USA, May 2002. ISBN 1-87465365-8. URL http://dl.acm.org/citation.cfm?id=1085171.1085181. → pages

[31] B. Hartmann, L. Yu, A. Allison, Y. Yang, and S. R. Klemmer. Design as Exploration : Creating Interface Alternatives through Parallel Authoring and Runtime Tuning. In *UIST*, pages 91–100, 2008. ISBN 9781595939753. → pages

[32] V. Hayward. A brief taxonomy of tactile illusions and demonstrations that can be done in a hardware store. *Brain research bulletin*, 75(6):742–52, Apr. 2008. ISSN 0361-9230. doi:10.1016/j.brainresbull.2008.01.008. URL

http://www.sciencedirect.com/science/article/pii/S0361923008000178. → pages

[33] V. Hayward and K. Maclean. Do it yourself haptics: part I. *IEEE Robotics & Automation Magazine*, 14(4):88–104, Dec. 2007. ISSN 1070-9932. doi:10.1109/M-RA.2007.907921. URL http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=4437756. → pages

[34] S. R. Herring, C.-C. Chang, J. Krantzler, and B. P. Bailey. Getting inspired! Understanding How and Why Examples are Used in Creative Design Practice. In *CHI '09*, pages 87–96, New York, New York, USA, Apr. 2009. ACM Press. ISBN 9781605582467. doi:10.1145/1518701.1518717. URL http://dl.acm.org/citation.cfm?id=1518701.1518717. → pages

[35] K. Hong, J. Lee, and S. Choi. Demonstration-based vibrotactile pattern authoring. In *TEI '13*, page 219, New York, New York, USA, Feb. 2013. ACM Press. ISBN 9781450318983. doi:10.1145/2460625.2460660. URL http://dl.acm.org/citation.cfm?id=2460625.2460660. → pages

[36] E. Hutchins. *Cognition in the Wild*, volume 19. MIT Press, 1995. ISBN 0262082314. doi:10.1098/rsbl.2011.0352. URL http://www.ida.liu.se/~nilda/CST-papers/Hutchins.pdf. → pages

[37] I. Hwang, J. Seo, M. Kim, and S. Choi. Vibrotactile Perceived Intensity for Mobile Devices as a Function of Direction, Amplitude, and Frequency. *IEEE Transactions on Haptics*, 6(3):352–362, July 2013. ISSN 1939-1412. doi:10.1109/TOH.2013.2. URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6420831. → pages

[38] A. Israr and I. Poupyrev. Tactile brush: drawing on skin with a tactile grid display. In *CHI '11*, pages 2019–2028, Vancouver, BC, May 2011. ACM Press. ISBN 9781450302289. doi:10.1145/1978942.1979235. URL http://dl.acm.org/citation.cfm?id=1978942.1979235. → pages

[39] A. Israr, S. Zhao, K. Schwalje, R. Klatzky, and J. Lehman. Feel Effects: Enriching Storytelling with Haptic Feedback. *Transactions on Applied Perception (TAP)*, 11(3), 2014. → pages

[40] A. Israr, S. Zhao, and O. Schneider. Exploring Embedded Haptics for Social Networking and Interactions. In *CHI Extended Abstracts '15*, pages 1899–1904, New York, New York, USA, Apr. 2015. ACM Press. ISBN

9781450331463. doi:10.1145/2702613.2732814. URL http://dl.acm.org/citation.cfm?id=2702613.2732814. → pages 13, 14

[41] C. V. Jansson-Boyd. Touch matters: exploring the relationship between consumption and tactile interaction. *Social Semiotics*, 21(4):531–546, Sept. 2011. ISSN 1035-0330. doi:10.1080/10350330.2011.591996. URL http://dx.doi.org/10.1080/10350330.2011.591996. → pages

[42] J. Johnson and A. Henderson. Conceptual models: begin by designing what to design. *Interactions*, 9(1):25–32, Jan. 2002. ISSN 10725520. doi:10.1145/503355.503366. URL http://dl.acm.org/ft_gateway.cfm?id=503366&type=html. → pages

[43] L. Jones. News from the Field: Courses in Haptics. *Transactions on Haptics*, 7(4):413–414, 2014. → pages

[44] E. R. Kandel, J. H. Schwartz, and T. M. Jessell. *Principles of Neural Science*. McGraw-Hill, 4th edition, 2000. → pages

[45] Y. Kim, J. Cha, I. Oakley, and J. Ryu. Exploring Tactile Movies: An Initial Tactile Glove Design and Concept Evaluation. *IEEE Multimedia*, PP(99):1, 2009. ISSN 1070-986X. doi:10.1109/MMUL.2009.63. URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5255212. → pages

[46] D. Ledo, M. A. Nacenta, N. Marquardt, S. Boring, and S. Greenberg. The HapticTouch toolkit. In *TEI '12*, pages 115–122, New York, USA, Feb. 2012. ACM Press. ISBN 9781450311748. doi:10.1145/2148131.2148157. URL http://dl.acm.org/citation.cfm?id=2148131.2148157. → pages

[47] B. Lee, S. Srivastava, R. Kumar, R. Brafman, and S. R. Klemmer. Designing with interactive example galleries. In *CHI '10*, pages 2257–2266, New York, New York, USA, Apr. 2010. ACM Press. ISBN 9781605589299. doi:10.1145/1753326.1753667. URL http://dl.acm.org/citation.cfm?id=1753326.1753667. → pages

[48] J. Lee and S. Choi. Evaluation of vibrotactile pattern design using vibrotactile score. In *HAPTICS '12*, pages 231–238. IEEE, Mar. 2012. ISBN 978-1-4673-0809-0. doi:10.1109/HAPTIC.2012.6183796. URL http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6183796. → pages

[49] J. Lee and S. Choi. Real-time perception-level translation from audio signals to vibrotactile effects. In *CHI '13*, pages 2567–2576, Paris, France, Apr.

2013. ISBN 9781450318990. doi:10.1145/2470654.2481354. URL http://dl.acm.org/citation.cfm?id=2470654.2481354. → pages

[50] J. Lee, J. Ryu, and S. Choi. Vibrotactile score: A score metaphor for designing vibrotactile patterns. In *World Haptics '09*, pages 302–307. IEEE, Mar. 2009. ISBN 978-1-4244-3858-7. doi:10.1109/WHC.2009.4810816. URL http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4810816. → pages

[51] J. Lee, Y. Kim, and G. Kim. Funneling and saltation effects for tactile interaction with virtual objects. In *CHI '12*, page 3141, New York, New York, USA, May 2012. ACM Press. ISBN 9781450310154. doi:10.1145/2207676.2208729. URL http://dl.acm.org/citation.cfm?id=2207676.2208729. → pages

[52] K. Maclean and M. Enriquez. Perceptual design of haptic icons. In *Eurohaptics*, pages 351–363, 2003. URL http://citeseer.ist.psu.edu/viewdoc/summary?doi=10.1.1.138.6172. → pages

[53] K. MacLean and V. Hayward. Do It Yourself Haptics: Part II [Tutorial]. *IEEE Robotics & Automation Magazine*, 15(1):104–119, Mar. 2008. ISSN 1070-9932. doi:10.1109/M-RA.2007.914919. URL http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4476335. → pages

[54] K. E. MacLean. Putting Haptics into the Ambience. *IEEE Transactions on Haptics*, 2(3):123–135, July 2009. ISSN 1939-1412. doi:10.1109/TOH.2009.33. URL http://www.computer.org/portal/web/csdl/doi?doc=doi/10.1109/TOH.2009.33http://portal.acm.org/citation.cfm?id=1608573.1608735. → pages

[55] J. Marks, W. Ruml, K. Ryall, J. Seims, S. Shieber, B. Andalman, P. A. Beardsley, W. Freeman, S. Gibson, J. Hodgins, T. Kang, B. Mirtich, and H. Pfister. Design galleries. In *SIGGRAPH '97*, pages 389–400, New York, New York, USA, Aug. 1997. ACM Press. ISBN 0897918967. doi:10.1145/258734.258887. URL http://dl.acm.org/citation.cfm?id=258734.258887. → pages

[56] S. O. Modhrain and I. Oakley. Touch TV : Adding Feeling to Broadcast Media. 2001. → pages

[57] C. Moussette. Sketching in Hardware and Building Interaction Design: tools, toolkits and an attitude for Interaction Designers. In *Proc. of Design Research Society*, 2010. URL https://public.me.com/intuitive. → pages

[58] C. Moussette and R. Banks. Designing through making. In *TEI '11*, pages 279–282, New York, USA, Jan. 2011. ACM Press. ISBN 9781450304788. doi:10.1145/1935701.1935763. URL http://dl.acm.org/citation.cfm?id=1935701.1935763. → pages

[59] C. Moustakas. *Phenomenological Research Methods*. SAGE Publications, Inc., 1994. ISBN 978-0-8039-5798-5. → pages

[60] S. Mueller, T. Mohr, K. Guenther, J. Frohnhofen, and P. Baudisch. faBrickation - Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks. In *CHI '14*, pages 3827–3834. ACM Press, Apr. 2014. ISBN 9781450324731. doi:10.1145/2556288.2557005. URL http://dl.acm.org/citation.cfm?id=2611222.2557005. → pages

[61] M. Obrist, S. A. Seah, and S. Subramanian. Talking about tactile experiences. In *CHI '13*, pages 1659–1668. ACM Press, 2013. ISBN 9781450318990. doi:10.1145/2470654.2466220. URL http://dl.acm.org/citation.cfm?doid=2470654.2466220. → pages

[62] S. Okamoto, H. Nagano, and Y. Yamada. Psychophysical Dimensions of Tactile Perception of Textures. *IEEE Transactions on Haptics*, 6(1):81–93, Jan. 2013. ISSN 1939-1412. doi:10.1109/TOH.2012.32. URL http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6216375. → pages

[63] A. M. Okamura, S. Chan, B. Hannaford, K. MacLean, and W. Provancher. Best Practices for Teaching Haptics, 2012. → pages

[64] S. A. Paneels, M. Anastassova, and L. Brunet. TactiPEd: Easy Prototyping of Tactile Patterns. *INTERACT '13*, 8118:228–245, 2013. doi:10.1007/978-3-642-40480-1. URL http://link.springer.com/10.1007/978-3-642-40480-1. → pages

[65] S. Papert. *Mindstorms: Children, Computers, and Powerful Ideas*. Basic Books, 2nd edition, 1980. ISBN 0465046274. URL http://books.google.com/books?id=HhIEAgUfGHwC&pgis=1. → pages

[66] M. Resnick, B. Myers, K. Nakakoji, B. Shneiderman, R. Pausch, T. Selker, and M. Eisenberg. Design principles for tools to support creative thinking. In *NSF Workshop Report on Creativity Support Tools.*, Washington, DC, 2008.

URL http://medcontent.metapress.com/index/A65RM03P4874243N.pdf. → pages

[67] P. Richer. A phenomenological analysis of the perception of geometric illusions. *Journal of Phenomenological Psychology*, 8(2):123–135, 1978. → pages

[68] J. Rovan and R. Hayward. Typology of Tactile Sounds and their Synthesis in Gesture-Driven Computer Music Performance. *Trends in Gestural Control of Music*, pages 297–320, 2000. → pages

[69] J. Ryu and S. Choi. posVibEditor: Graphical authoring tool of vibrotactile patterns. In *HAVE '08*, pages 120–125. IEEE, Oct. 2008. ISBN 978-1-4244-2668-3. doi:10.1109/HAVE.2008.4685310. URL http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4685310. → pages

[70] O. Schneider, S. Zhao, and A. Israr. FeelCraft: User-Crafted Tactile Content. In *Proceedings of AsiaHaptics 2014*, 2014. → pages

[71] O. S. Schneider and K. E. MacLean. Improvising Design with a Haptic Instrument. In *HAPTICS '14*, Houston, USA, 2014. → pages 9

[72] O. S. Schneider and K. E. MacLean. Reflections on a WYFIWIF Design Tool. In *Workshop on Tactile User Experience Evaluation Methods at CHI 2014*, 2014. → pages

[73] D. A. Schön. *The Reflective Practitioner*. 1982. → pages

[74] H. Seifi, C. Anthonypillai, and K. E. MacLean. End-user customization of affective tactile messages: A qualitative examination of tool parameters. In *HAPTICS '14*, pages 251–256. IEEE, Feb. 2014. ISBN 978-1-4799-3131-6. doi:10.1109/HAPTICS.2014.6775463. URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6775463. → pages

[75] H. Seifi, K. Zhang, and K. MacLean. VibViz: Organizing, visualizing and navigating vibration libraries. In *World Haptics '15*, 2015. → pages 10, 11, 12, 23

[76] B. Shneiderman. Creating creativity: user interfaces for supporting innovation. *ACM Transactions on Computer-Human Interaction*, 7(1): 114–138, Mar. 2000. ISSN 10730516. doi:10.1145/344949.345077. URL http://dl.acm.org/citation.cfm?id=344949.345077. → pages

[77] C. Swindells, E. Maksakov, K. MacLean, and V. Chung. The Role of Prototyping Tools for Haptic Behavior Design. In *HAPTICS '06*, pages 161–168. IEEE, 2006. ISBN 1-4244-0226-3. doi:10.1109/HAPTIC.2006.1627084. URL http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1627084. → pages

[78] C. Swindells, S. Pietarinen, and A. Viitanen. Medium fidelity rapid prototyping of vibrotactile haptic, audio and video effects. In *HAPTICS '14*, pages 515–521. IEEE, Feb. 2014. ISBN 978-1-4799-3131-6. doi:10.1109/HAPTICS.2014.6775509. URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6775509http://ieeexplore.ieee.org/articleDetails.jsp?arnumber=6775509. → pages

[79] D. Ternes and K. E. MacLean. Designing Large Sets of Haptic Icons with Rhythm. *Haptics: Perception, Devices and Scenarios*, 5024:199–208, 2008. URL http://www.springerlink.com/index/atl5686222k242m4.pdf. → pages 14

[80] R. T. Verrillo and G. A. Gescheider. Perception via the sense of touch. *Tactile aids for the hearing impaired*, pages 1–36, 1992. → pages

[81] A. Warr and E. O'Neill. Understanding design as a social creative process. In *Creativity & cognition - C&C '05*, pages 118–127. ACM Press, Apr. 2005. ISBN 1595930256. doi:10.1145/1056224.1056242. URL http://dl.acm.org/citation.cfm?id=1056224.1056242. → pages

[82] J. Watanabe, T. Hayakawa, S. Matsui, A. Kano, Y. Shimizu, and M. Sakamoto. Visualization of Tactile Material Relationships Using Sound Symbolic Words. In P. Isokoski and J. Springare, editors, *Haptics: Perception, Devices, Mobility, and Communication*, volume 7283 of *Lecture Notes in Computer Science*, pages 175–180. Springer, Berlin, Heidelberg, 2012. ISBN 978-3-642-31403-2. doi:10.1007/978-3-642-31404-9. URL http://www.springerlink.com/index/10.1007/978-3-642-31404-9. → pages

[83] G. Wilson, T. Carter, S. Subramanian, and S. A. Brewster. Perception of ultrasonic haptic feedback on the hand. In *CHI '14*, pages 1133–1142, New York, New York, USA, Apr. 2014. ACM Press. ISBN 9781450324731. doi:10.1145/2556288.2557033. URL http://dl.acm.org/citation.cfm?id=2611105.2557033. → pages

[84] H.-Y. Yao and V. Hayward. Design and analysis of a recoil-type vibrotactile transducer. *The Journal of the Acoustical Society of America*, 128(2):

619–627, Aug. 2010. ISSN 1520-8524. doi:10.1121/1.3458852. URL http://link.aip.org/link/?JASMAN/128/619/1. → pages

[85] T. Yoo, Y. Yoo, and S. Choi. An Explorative Study on Crossmodal Congruence Between Visual and Tactile Icons Based on Emotional Responses. In *ICMI '14*, pages 96–103. ACM Press, Nov. 2014. ISBN 9781450328852. doi:10.1145/2663204.2663231. URL http://dl.acm.org/citation.cfm?id=2663204.2663231. → pages

[86] Y. Zheng and J. B. Morrell. Haptic actuator design parameters that influence affect and attention. In *2012 IEEE Haptics Symposium (HAPTICS)*, pages 463–470. IEEE, Mar. 2012. ISBN 978-1-4673-0809-0. doi:10.1109/HAPTIC.2012.6183832. URL http://ieeexplore.ieee.org/articleDetails.jsp?arnumber=6183832. → pages