THESIS PROPOSAL:

Supporting Haptic Experience Design

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: r4

Contents

Chapter 1

Introduction

Haptic sensations enable engaging, personal, and low-attention experiences, but this is limited due to little support for *designing* a haptic sensation. Computer-controlled haptic experiences are a recent phenomenon; the focus on technology requirements and rapidly changing field has left little room for examining processes of design in a methodical way. In this dissertation, I propose to study the process of haptic experience design ("HaXD") to understand how to build interactive software to support haptic experience designers.

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 want to develop practical tools that support the HaXD process, building a body of knowledge of how to facillitate this difficult subfield of design. I approach this problem with two different strategies:

1. **Vibrotactile design 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, and working software tools that have been employed by designers. Chapter 3, Chapter 4, and Chapter 5 outline these.

2. **Synthesis into preliminary theory.** While the case studies provide an in-depth investigation into vibrotactile sensation design, results may not generalize to other devices. Furthermore, despite the recent growth of the field, haptic designers remain relatively rare and difficult to recruit. To generalize our findings to other situations and ground it with haptic experience designers, I plan to draw from other data sources: a workshop held at World Haptics 2015, already-collected interviews with haptic designers, and a number of side-projects. This synthesized contribution will help refine our findings, such as tasks, goals, barriers, strategies, and practices designers use and face when working with haptics.

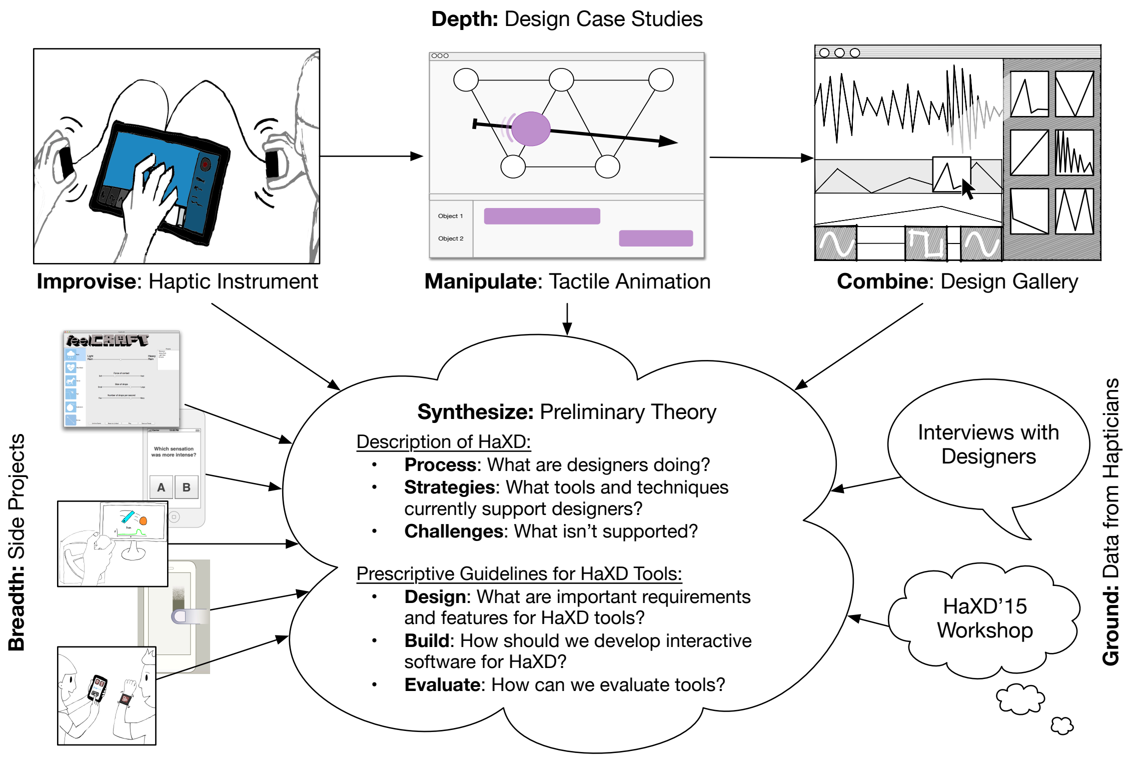
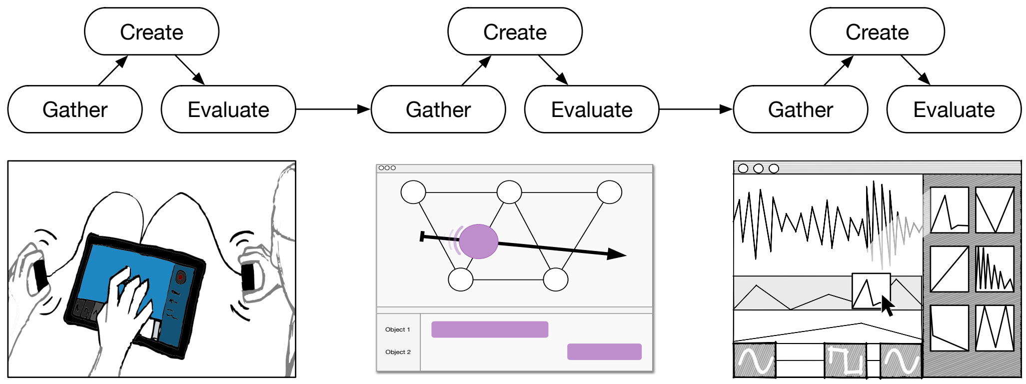


Figure 1.1: Methodology overview. Three case studies investigate VT tools in-depth; findings are synthesized with side projects and grounded data into a preliminary theory.

1.1 Vibrotactile Design 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. This study is codenamed "Project Macaron" and consists of two phases. Phase I, "algorithms and interaction techniques", builds a set of perceptually-verified ways to manipulate examples and incorporate them into designs. In Phase II, we use the results of Phase I to create a haptic design gallery interface, and study how and when users incorporate examples into their VT designs. In this way we hope to consolidate our findings from mHIVE and Mango, and capture our participants' design process more concretely through logging of user actions.

These studies are described in more detail in Chapter 3, Chapter 4, and Chapter 5. Each chapter is presented as an outline of what will appear in the final dissertation, summarizing methods and results for completed work and outlining planned work.

1.2 Synthesis of Contributions

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. 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?

This process is described in Chapter 6.

1.3 Summary of Progress

I am currently working on the *create* stage of the third case study; the first two have papers either published or in peer-review. Multiple side projects are underway, primarily carried out by undergraduate students I'm co-supervising. All side projects are expected to be substantially developed or completed by the end of summer 2015; the FeelCraft side project has already been published and presented. For more information on current progress, please see Chapter 7.

The proposal continues as follows. First, in Chapter 2, 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 case study in Chapter 3, Chapter 4, and Chapter 5. After, I describe the planned data synthesis in more detail in Chapter 6. Finally, I present milestones and a timeline for my PhD in Chapter 7.

Chapter 2

Background

In this chapter, I discuss haptic technology, haptic design tools, and non-haptic theory of design.

2.1 Haptic Technology

Haptic technology is typically separated into two classes based on the main sense modality: *tactile* sensations, perceived through the skin, and *proprioception*, or the sense of body location and force.

The most common consumer-facing tactile technology is vibrotactile (VT), where vibrations stimulate the skin. Eccentric mass motors (sometimes "rumble motors" or, when small, "pager motors") are found in many mobile devices and game controllers. However, these have only a single degree of freedom: the input voltage or current, which corresponds to the combined amplitude and frequency of the device. Eccentric mass motors are cheap, salient, widespread, but inexpressive.

More expressive are tactors, or voice coils, implemented in a variety of ways. Behaving similar to small speakers, tactors offer two degrees of freedom: frequency and amplitude, and are typically more responsive than rumble motors. One of the more common and expressive is the C2 tactor, intended to directly stimulate the skin through contact or a thin membrane; the tactile animation project (Chapter 4) uses an array of C2 tactors. Another common device, commonly used in research or prototyping, is the Haptuator [74]. Instead of directly stimulating the skin, this actuator typically shakes another device held by the user, such as a mobile device [75], pen [15], or other handle. Both the haptic instrument (Chapter 3) and Macaron editor (Chapter 5) use Haptuators.

Proprioception, on the other hand, is synthesized from the muscle spindle and golgi-tendon organ (GTO), as well as tactile and visual cues [38]. Common devices include Geomagic Touch (previously the Sensable PHANTOM) and Falcon devices, offering three degrees-of-freedom: force in three directions and torque in three orientations. Simpler one degree-of-freedom devices are used in education, prototyping, and experimentation. Devices include the Twiddler (a haptic knob from UBC) and the HapKit (a low-cost paddle by the Stanford CHARM lab).

2.2 Haptic Design Tools

Currently, haptic designers have access to a limited number of hardware and software platforms, a set of philosophical design perspectives, and authoring tools.

2.2.1 Platforms

Many software libraries aim to support developers. The UPenn Texture Toolkit contains 100 texture models created from recorded data, rendered through VT actuators and impedance-type force feedback devices [15]. The HapticTouch Toolkit [40] and Feel Effect library [34] control sensations using semantic parameters, like "softness" or "heartbeat intensity" respectively. Vibrotactile libraries like Immersion's Haptic SDK (immersion.com) connect to mobile applications, augmenting Android's native vibration library. Force feedback devices have software platforms like CHAI3D (chai3d.org), H3D (h3dapi.org), and OpenHaptics (geomagic.com).

Hardware prototyping platforms like Arduino (arduino.cc) provide an open source microcontroller and development platform for physical prototyping. Phidgets (phidgets.com) facilitate rapid hardware prototyping with over 20 programming languages [24]. More recently, Wooden Haptics gives open-source access to fast laser cutting techniques for force feedback development [23], and faBrickation streamlines prototyping for 3D printing [53]. These platforms, especially Arduino, have made significant improvements to enable rapid iteration and hardware sketching. However, I believe we can do much better: these platforms require programming, hardware, and haptics expertise, and include inherent time costs like compilation, uploading, and debugging.

2.2.2 Design Perspectives

Some higher-level perspectives offer outcome targets or design attitudes to guide haptic practitioners. "DIY Haptics" categorize feedback styles and design principles [28, 45]. "Ambience" is proposed as one target for a haptic experience [46]. Haptic illusions can serve as concise ways to explore the sense of touch, explain concepts to novices and inspire interfaces [27]. "Simple Haptics", epitomized by *haptic sketching*, emphasizes rapid, hands-on exploration of a creative space [50, 51]. Haptic Cinematography [16] uses a film-making lens, discussing physical effects using cinematographic concepts. The notion of distributed cognition [31] has particular relevance for haptic design, suggesting that people situate their thinking both in their bodies and in the environment. Haptics courses are taught with a variety of foci including perception, control, and design, providing students with an initial repertoire of skills [37, 56].

Haptics has often made use of metaphors from other fields. Haptic icons [44], tactons [3], and haptic phonemes [21] are small, compositional, iconic representations of haptic ideas. Touch TV [49], tactile movies [39], haptic broadcasting [9], and Feel Effects [34] attempt to add haptics to existing media types, especially video.

Musical analogies have frequently been used to inspire haptic design tools, especially VT sensations. The Vibrotactile Score, a graphical editing tool representing vibration patterns as musical notes, is a major example [42, 43]. Other musical metaphors include the use of rhythm, often represented by musical notes and rests [5, 7, 10, 72]. Earcons and tactons are represented with musical notes [3, 4], complete with tactile analogues of crescendos and sforzandos [6]. The concept of a VT concert found relevant tactile analogues to musical pitch, rhythm, and timbre for artistic purposes [25]. Correspondingly, tactile dimensions have been also been used to describe musical ideas [18].

The language of tactile perception, especially affective (emotional) terms, is another way of framing haptic design. Many psychophysical studies have been conducted to determine the main tactile dimensions with both synthetic haptics and real-world materials [20, 55]. Language is a promising way of capturing user experience [54], and can reveal useful parameters, e.g., how pressure influences affect [76]. Tools for customization by end-users, rather than expert designers, are another way to understand perceptual dimensions [66, 67]. However, this work is far from complete; touch is difficult to describe, and some even question the existence of a tactile language [36].

2.2.3 Authoring Interfaces

As long as designers have considered haptic effects for entertainment media, they have needed compositional tools [25]. A great deal of previous work has focused on how to prototype or author haptic phenomena using non-programming methods.

Many user-friendly interfaces help designers create haptic sensations, especially with vibrotactile devices. The Hapticon editor [20], Haptic Icon Prototyper [70], and posVibEditor [61] use graphical mathematical representations to edit either waveforms or profiles of dynamic parameters (torque, frequency) over time. The Vibrotactile Score [43] was shown to be generally preferable to programming in C and XML, but required familiarity with musical notation [42]. The Demonstration-Based Editor [30] allows control of frequency and intensity by moving graphical objects on a touchscreen. Similar to the SPIN lab's Haptic Instrument (mHIVE, Chapter 3), this mobile tool was shown to be intuitive and easy to use for exploration or communication, but faltered when refining more elaborate sensations.

Commercially, Apple's end-user vibration editor has been present in iOS since 2011 (iOS 5) but only produces binary on/off timing information. Immersion provides two tools: TouchSense Engage is a software solution for developers, while Touch Effects Studio lets users enhance a video from a library of tactile icons supplied on a mobile platform. Vivitouch Studio allows for haptic prototyping of different effects alongside video (screen captures from video games) and audio, and supports features like A/B testing [71].

The control of multi-actuator outputs has been explored by TactiPEd [57], Cuartielles' proposed editor [14], and the tactile movie editor [39]; the latter combined spatial and temporal control using a tactile video metaphor for dense, regular arrays of tactile pixels ("taxels"), including a feature of sketching a path on video frames. However, these approaches embrace the separate control of different actuators, rather than a single perceived sensation produced by the multi-actuator device, which we address with tactile illusions in Chapter 4.

2.3 Non-Haptic Design Theory

In this section, we present related work on non-haptic design organized into three major elements: problem preparation, hands-on design, and collaboration.

2.3.1 Problem Preparation

Creative tasks, like design, are often defined as the recombination of existing ideas, with a twist of novelty or spark of innovation by the individual creator [73]. Also known as the "problem setting" [65], "analysis of problem" [73], or "collect" [69] step, problem preparation involves getting a handle on the problem, drawing inspiration from previous work. Schön demonstrated that designers initially frame their problems before developing a solution [65]. Schön also describes the designer's repertoire, their collected experience, which aids in design. External examples are especially useful for inspiration and aiding initial design [8, 29], which we explore in Chapter 5.

2.3.2 Hands-On Design

There has recently been a shift in how we interpret the act of thinking. No longer is thinking relegated to the head; cognition is now seen as being situated in the physical world [31]. The designer must iteratively generate a varied set of initial ideas (ideation) and then prune them (evaluation), repeating this step many times to settle on a single design [8]. Working with multiple ideas simultaneously is a boon to good design. Developing interfaces in parallel can facilitate generation and evaluation, delaying commitment to a single design [26, 58], while in groups, sharing multiple designs improves variety and quality of designs [17].

Sketching supports ideation, evaluation, and multiple ideas, allowing the designer to explicitly make moves in a game-like conversation with the problem [65]. It is so important that some researchers declare it to be the fundamental language of design, like mathematics is the language for scientific thinking [13]. The power of sketching, according to Cross, is contained in its ability to describe a partial model of a proposed design or problem. Detail can be subordinated, allowing a designer to zoom-in, solve a problem, and then abstract it away when returning to a high-level view. This has implications for software tools: designers must easily navigate the design space with undo, copy and paste, and a history of progress, creating tools with a "high ceiling" and "wide walls" [58].

2.3.3 Collaboration

Design is a collaborative process with the potential for generating more varied ideas [73], and is important for creativity support tools [58, 69]. Although sometimes group dynamics influence the design process negatively, proper group management and sharing of multiple ideas results in more creativity and better designs [29]. Shneiderman in particular has championed collaboration in design [69], and suggests two different types of collaboration to be supported by creativity tools: *relating*, informal discussions with colleagues, and *donating*, disseminating information to the public/annals of time. Orthogonal to these intended purposes (relating and donating) is the collaboration context. Computer-supported collaborative work often separates interactions into four contexts ordered into two dimensions: collocated (same location) or distributed (different locations), and synchronous (simultaneous) or asynchronous (at different times) [19]. Collaboration is notable because it is inherently challenging to haptic design: two people can look at the same image or hear the same sound from across a room, but touch is a local sense, far easier in a collocated, synchronous setting. We explore collaboration with the Haptic Instrument (Chapter 3) and the FeelCraft and HapTurk side-projects (described in Chapter 6).

Chapter 3

Improvise: The Haptic Instrument

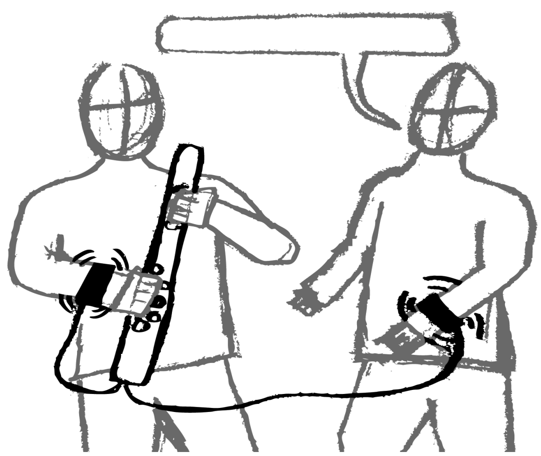


Figure 3.1: Concept sketch of a haptic instrument. Both users are experiencing the same sensation, controlled in real-time.

The Haptic Instrument case study[1] investigates the role of real-time feedback and synchronous collaboration on haptic experience design, using participants with some haptics experience, serving as proxies for haptic experience designers. Conventional haptic design tools contain a slow iteration, requiring programming or rendering before playback. Using a music composition metaphor (as in [43]), we are writing music without ever playing a note: composing a work in its entirety, then listening to the result before making changes. In contrast, musicians often use their instruments as a tool for serendipitous exploration when designing music. Furthermore, music is collaborative, with communication facilitated by a reference point of a sound.

[1]Published in Haptics Symposium 2014 [63] and at a CHI 2014 workshop [64].

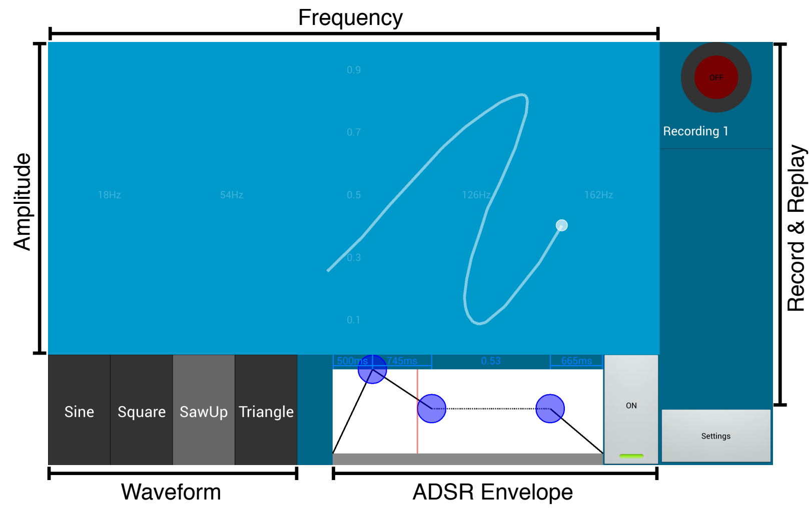


Figure 3.2: mHIVE interface. Primary interaction is through the amplitude-frequency view, where visual feedback is provided through a circle (current finger position) and a trail (interaction history).

Our approach is to directly use a *haptic instrument*, inspired by musical instruments but producing (for example) vibrotactile (VT) sensations rather than sound (Figure 3.1). Haptic instruments are intended to have two main uses: they provide real-time feedback to the user to facilitate improvisation and exploration, and produce haptic output to multiple users as a *what-you-feel-is-what-I-feel* (WYFIWIF) interface. This allows for a dialogue that includes a haptic modality: haptic instruments create a shared experience of touch, allowing for a common reference point.

3.1 mHIVE, a mobile Haptic Instrument for Vibrotactile Exploration

We developed mHIVE to begin to explore how a haptic instrument should work and what it should do (Figure 3.2). mHIVE is a collocated, synchronous haptic instrument for a single user. It accommodates shared display via dual Haptuators [74] and is operated with a single-touch tablet-based interface for direct manual control (Figure 3.3). mHIVE is designed for for VT sensations, which are common, do not require interactive programming, are controlled through waveforms (analogous to music), and their low-level control parameters are well understood.

mHIVE offers real-time control of frequency, amplitude, waveform, envelope, duration, and rhythm, identified as the most important parameters for VT sensations [3, 6, 7, 25, 60]. mHIVE is implemented in Java using the Android SDK [2], and the FMOD sound synthesis library [22] to produce sounds, sent to two or more Haptuators through an audio jack. We deployed mHIVE on an Android Nexus 10 tablet running Android 4.2.1.

Figure 3.3: Study setup. Both the participant (left) and the interviewer (right) feel the same sensation as the participant controls mHIVE.

3.2 Study

We conducted a preliminary qualitative study to investigate two questions. First, is mHIVE an effective tool for the expression, exploration, and communication of affective phenomena? Second, what language, mental models, and metaphors do people use to describe VT sensations, and how do they relate to mHIVE's low-level control parameters?

We collected and analyzed our data using the methodology of phenomenology, an established variant of qualitative inquiry used in psychology to investigate topics ranging from visual illusions to tactile experience [12, 54, 59], but always as a means to explore subjective experience.

Four participants were recruited through email lists and word-of-mouth (P1-4, three male, ages 26-35 with self-reported occupations including graduate students or post-docs in information visualization, HCI, and human-robot interaction). All had experience working with haptic technology. The small sample size, typical for phenomenological studies [12], was appropriate for the rich data we wanted. Data collection ended when we achieved saturation of new results, and had a clear direction for future iterations.

3.3 Results

In this section, we outline the three major themes that emerged during analysis: mHIVE's success as a haptic instrument, mHIVE's limitations that reveal more detail about the haptic design process, and the use of language in the study.

Our results suggest that mHIVE was well received and **succeeded as a haptic instrument**. Participants reported that mHIVE was best served to explore the design space, generate a number of ideas, and *"accidentally stumble upon something"* (P2) as they explored the device. mHIVE also established an additional modality for dialogue. The dual outputs created a shared context, demonstrated by deictic phrases: the additional context of the VT sensation was required to make sense of the statements like "that" and "there".

The second theme, **tweaking through visualization and modification**, established key directions for future design. Though mHIVE supported exploration and collaboration, we found it was inadequate as a standalone design tool. Few created sensations were considered to be final, partly due to cognitive limitations for both memory and attention. Participants found it difficult to remember what they had tried before, and to pay attention to the output while simultaneously controlling it. Participants suggested additional visualization and recording features, such as repetition or looping, both to aid memory and allow for focus on the sensation independent of device control. Allowing persistent, modifiable sensations could also help participants overcome these limitations.

The final theme was that VT sensations have **a difficult language**. Our study was too small to analyze language patterns in detail, but exposes emerging trends. Participants often started with a statement of like or dislike rather than a description, with pleasant sensations often including ramp-in and ramp-out ("echo" or "ringing") of the ADSR envelope or lower-frequency sensations. Changes of waveform were noticeable but difficult to describe. Participants also frequently used concrete examples and direct analogies to describe sensations, often drawn from their previous experiences. One stand-out strategy employed by all participants was onomatopoeias (e.g., *"beeooo"* (P1&4)). Other common metaphors were sound-based (e.g., *"bell"* (P1&2)) or haptic (e.g., *"cat pawing"* (P3)).

3.4 Discussion

Ultimately, mHIVE was able to achieve the two main goals of a haptic instrument, facilitating both exploration and collaboration, which showed value in real-time exploration and a shared output context. mHIVE also had limitations - participants could not edit sensations and found it difficult to keep track of multiple sensations. This is understandable given the broader context of the musical instrument analogy we used for inspiration. Musical instruments are not used to write songs on their own, but combined with notation or recording media. There may be no silver bullet with haptic design tools, with haptic instruments solving a particular set of processes (quick, easy ideation and communication for experts) but not others (final touches, distribution). Ultimately, haptic instruments may be most useful as one element in a suite, or component of a more general tool.

We follow-up on these leads in our subsequent design studies. In Chapter 4, we use a persistent model of a VT sensation for an editor, and confirm the value of real-time feedback while expanding the design palette to include spatial haptics. In Chapter 5, we attempt to mitigate the difficulty of describing haptics and draw upon examples by using a VT design gallery.

Chapter 4

Manipulate: Tactile Animation

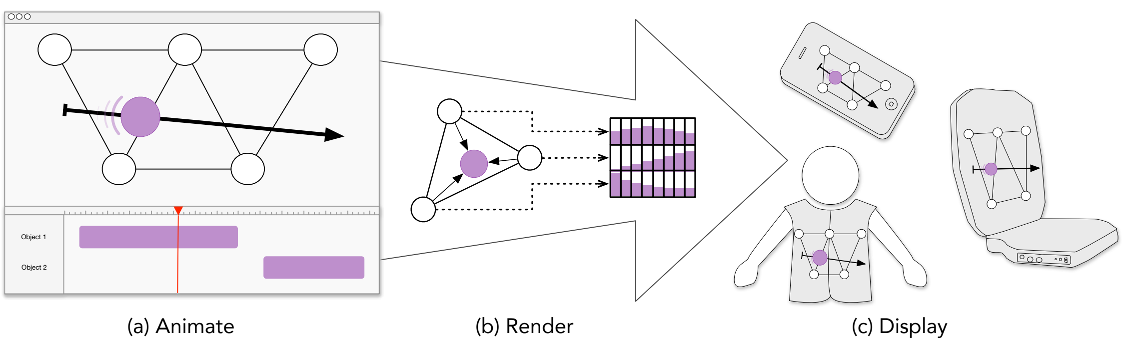


Figure 4.1: Concept sketch for tactile animation. An artist draws an animated sequence in the user interface and the user experiences phantom 2D sensations in-between discrete actuator grids.

In this second case study, we iterate on some of our findings from the haptic instrument to design a full authoring tool, using real-time feedback but supporting refinement with time-based editing. This work[1] targeted professional media designers (especially animators) creating spatial vibrotactile sensations. To afford real-time manipulation, we developed the *tactile animation object*, a persistent, manipulable primitive rendered through phantom vibrotactile sensations, and implement Mango, an editing tool built for animators. In our evaluation, professional animators found it easy to create a variety of vibrotactile patterns, with both experts and novices preferring the tactile animation object over controlling actuators individually. Furthermore, the tactile animation metaphor is a generalizable concept that can extend to several devices.

[1]In peer review at the time of this writing.

4.1 Mango, a Tactile Animation Authoring Tool

To create a familiar and efficient framework for dynamic haptic content, we gathered two sets of requirements: Literature ("LRs"), from prior research on haptic authoring tools, and Industry ("IRs") from interviews with five industry experts in haptic media creation and animation. Our prototype, Mango, was built in Python 2.7 and Tkinter (Figure 4.2), communicating with a devices via USB.

Designers create tactile animations on Mango as they would in a graphical animation tool. The animation object is placed in space, and the designer adjusts its size on the visual outline of the VT array. The designer then adds movements and special effects to the object using Mango's toolset, and play it to observe timing.

Mango's rendering engine translates visual animations to tactile animations on the VT array using three **datatype models**: *Tactile animation objects*, high-level hardware-independent data types for tactile animation; *vector formats*, high-level hardware-specific control common in previous work; and *raster formats*, low-level hardware-specific formats for rendering and playback. Data types are stored as JavaScript Object Notation (JSON) files.

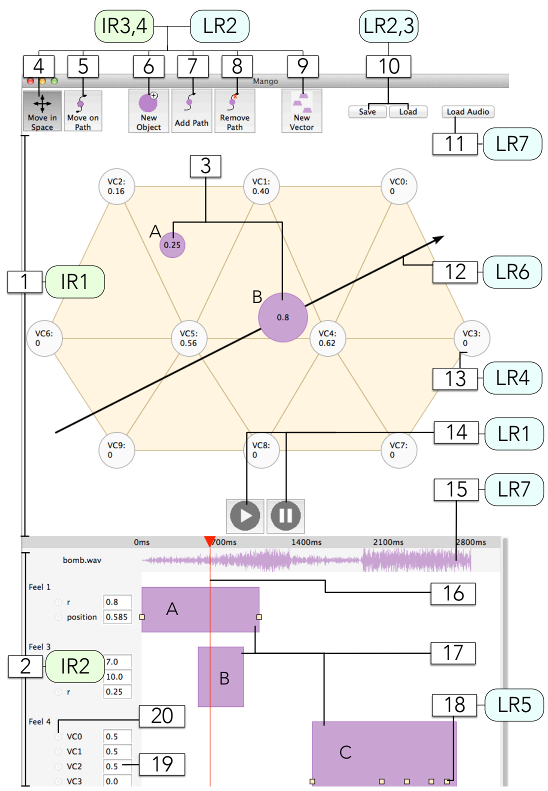
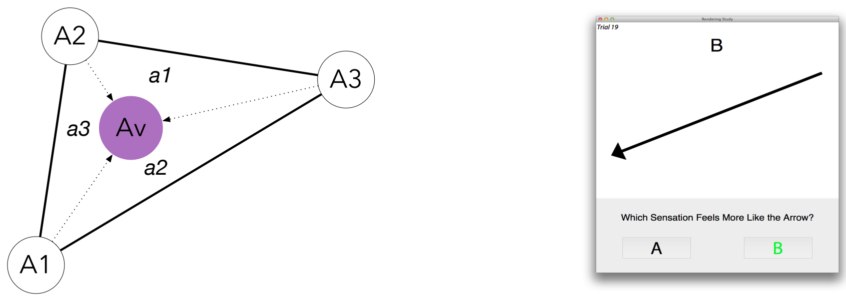


Figure 4.2: Mango graphical user interface. Key components are labeled and linked to corresponding design requirements (LRs and IRs, not described in this proposal).



(a) Barycentric coordinates. **(b)** Rendering study interface

Figure 4.3: We ran a study to determine the preferred interpolation function to map barycentric coordinates (a1-3) to physical actuator output (A1-3) given a virtual intensity (Av).

4.2 Rendering Algorithm

Mango's rendering algorithm translates animations in the animation window to animated VT patterns on the hardware. The rendering algorithm generalizes from 1D phantom sensations (between two VT actuators along a line [1, 33, 68]) to 2D (between 3 or more actuators, Figure 4.3a).

We had to choose between three interpolation models from prior psychophysical understanding of phantom tactile sensations [1] and propose them as candidates for the Mango tool: (i) *linear*, (ii) *logarithmic ("log")*, and (iii) *Pacinian power ("power")* interpolation.

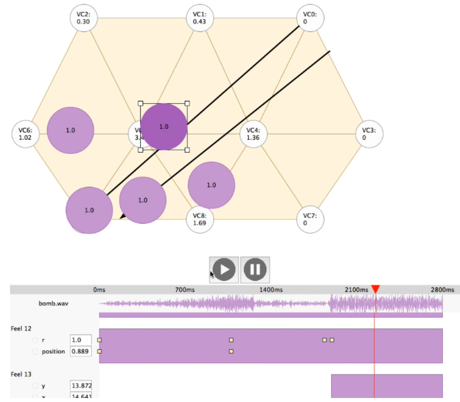
We performed a pairwise comparison of our three candidate interpolation models. Eighteen volunteers took part (6 female, between age 20-35). Analysis with stepwise regression revealed that logarithmic interpolation outperformed linear and was equivalent to Pacinian power model. We proceeded with the logarithmic model for Mango's implementation, as the power model did not outperform either of the others. Figure 4.3b shows the experiment interface, in which an arrow represents the sensation direction.

4.3 Design Evaluation

To evaluate Mango's animation metaphor and expressive space with critical functional features implemented, we asked media professionals to create a variety of designs. Six participants (P1-6, 3 females) were introduced to Mango driving the VT hardware described for the pairwise comparisons. Each entire session took 40 to 60 minutes and consistened of a training task then three design tasks: design a heartbeat sensation, a "turn left" sensation, and a sensation that matched a sound. A semi-structured interview followed the design tasks informed by phenomenological protocols [52]. Results were analyzed according to grounded theory methods [11], creating four themes.

Theme 1 - Animation Metaphor Participants found the tool easy to use. All six participants were able to accomplish all five tasks (object alert, vector alert, heartbeat, turn left, sound) within their session. Negative feedback focused on polish and feature completeness.

(a) Output device with highlighted actuators



(b) Example of P2's animation for matching a sound.

Figure 4.4: Evaluation study setup and example design.

Theme 2 - Tactile Animation Object vs Vector Sensations Participants relied more on animation objects than vector sensations. Animation objects were described as easier to use and more intuitive, especially to represent location or for non-animators. Vectors were preferred for more fine-tuned control when motion didn't matter as much, often using many keyframes.

Theme 3 - Designing-in-action with direct manipulation Participants used direct manipulation to feel their designs in real time, dragging animation objects and scrubbing through the timeline. More generally, participants used feedback from their experience or external examples. P1 stopped to think about her heartbeat, P2 used a YouTube video of a heartbeat as a reference, and P3 based her alert on her phone. Similarly, participants were excited when prompted by an audio sensation.

Theme 4 - Replication through Copy and Paste Replication in both space and time was common while using Mango. Many designs had symmetrical paths to reinforce sensations (Figure 4.4b). All but P4 requested copy / paste as a feature.

4.4 Discussion

The Tactile Animation project expanded our understanding from the Haptic Instrument study in Chapter 3. Specifically, it reaffirmed the value of real-time feedback and the need for examples, and showed that a persistent object model reduces cognitive load. It also suggests again that examples and user experiences are extremely valuable to the design process, providing motivation for example-based haptic design discussed next in Chapter 5.

Chapter 5

Combine: Design Galleries

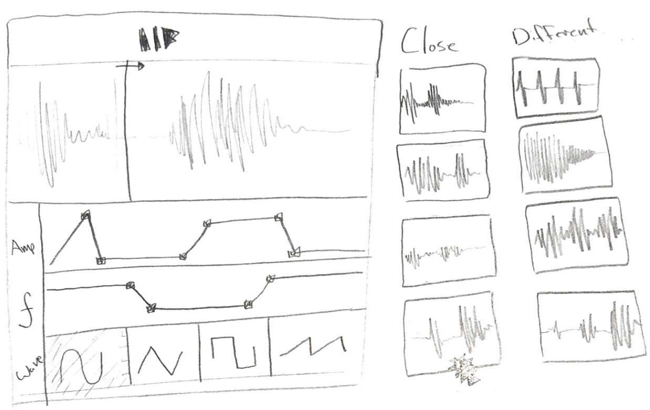


Figure 5.1: Concept sketch for a vibrotactile design gallery.

In both the Haptic Instrument and Tactile Animation case studies, participants drew from their experience or external examples and requested features for repetition. This is unsurprising; creative tasks, like design, are often defined as the recombination of existing ideas, with a twist of novelty or spark of innovation by the individual creator [73]. Examples are critical to provide inspiration, guidance, and inform design [8, 29]; for example, industrial designers collect various knobs and materials, and web designers bookmark sites [29]. Managing these examples effectively is already a significant task even in these more visual fields, but there is no explicit support for vibrotactile (VT) design. I will investigate interaction techniques to directly use examples in haptic design through a design gallery tool for VT icons (Figure 5.1).

Design galleries are used in graphics and web design to facilitate the use of examples [41, 48]. While there are several challenges involved with examples in design, including capture, search, management, use, and sharing, I limit this project's scope to the *combining* existing examples to create new VT icons. This project takes place in two phases: Phase I, where we develop a set of tools to manipulate VT icons through interpolation and combination, and Phase II, creating a design gallery and investigating how users work with it (or would like to, if they are unable to do so). For this study, we use a single Haptuator bound to a mobile device to simulate mobile VT icons (Figure 5.2).

Figure 5.2: Apparatus. A Haptuator is mounted onto a Galaxy Nexus smartphone to simulate mobile VT icon development, similar to [32].

5.1 Phase I – Algorithms and Interaction Techniques

In Phase I, I will develop and evaluate algorithms for manipulating examples by adjusting low-level parameters (frequency, amplitude, duration, and waveform), interpolating between examples, and combining aspects of different examples (for example, combining the frequency profile of one example with the amplitude profile of another). These algorithms will be evaluated using a perceptual study to examine two criteria: a smooth, linear interpolation method between VT icons, and to produce a varied corpus of VT icons.

5.1.1 VT Icon Editing

The design parameters of VT icons are already well understood to be frequency, amplitude, waveform, rhythm, and location. In this study, we focus on a single actuator display. Direct editing is supported with a track-based editor, similar to previous work [70], using keyframes like those in the tactile animation prototype, Mango, with one track each for frequency, amplitude, and waveform. These tracks constitute envelopes of each parameter over the duration of the VT icon. Rhythm emerges as the amplitude envelope. In order to use waveform as a time-varying parameter, we cross-fade between phase-synchronized waveforms, as used with haptic knobs in [47]. As this would be the first instance of continuous, time-varying waveform as a VT design parameter, we validate using piloting. A more thorough study would be valuable to the VT literature, but is secondary to our research questions about the design process.

5.1.2 VT Icon Replacement

In addition to directly editing parameters, we want to enable using examples directly in the design process. By using a track-based approach to VT icons, we get another interaction technique: full or partial replacement. In a design gallery, users can select an icon as a starting point, which we call *full replacement*. However, tracks can also be replaced, as long as some normalization technique is applied to accommodate different durations. This *partial replacement* is a weak form of example-based design, where users can combine examples in a limited way to create a new VT icon. A richer tool would be to more fluidly morph between icons.

5.1.3 Morphing

I propose to develop a *morphing* algorithm for VT icons, based on dynamic time warping (DTW) of keyframes in each of the parameter tracks. The goal is to have a linear, perceptually-smooth transition between VT icons that lets users mix examples, much like a painter might mix colours from a palette. Similar to VT icon replacement, morphing could be between entire VT Icons (*full morphing*), or between tracks (*partial morphing*).

5.1.4 Multidimensional Scaling Study

To evaluate the morphing algorithm, and to develop a suitable set of VT icons for Phase II, I plan to conduct a multidimensional scaling (MDS) study. MDS is a psychophysical technique that uses similarity scores between stimuli to build a visualization along underlying perceptual dimensions. We can use this study to find two results:

1. From an initial set of 20-30 VT icons, we can identify clusters of similar icons, and select a diverse set of examples for Phase II.

2. By including a VT icons produced by the morphing algorithm, we can see whether they lie on a smooth perceptual path between their parent icons. If so, the morphing algorithm does indeed provide a perceptually smooth transition between parents.

The possible outcomes for Phase I are visualized in Figure 5.3.

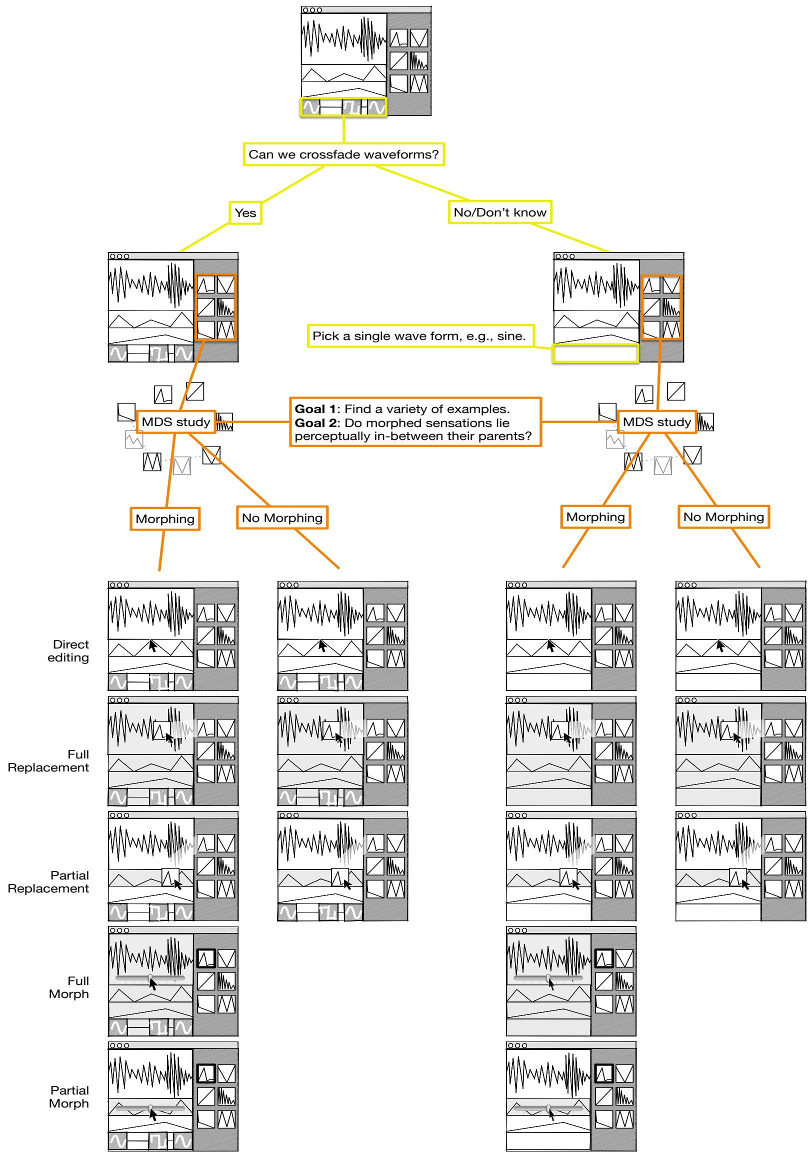
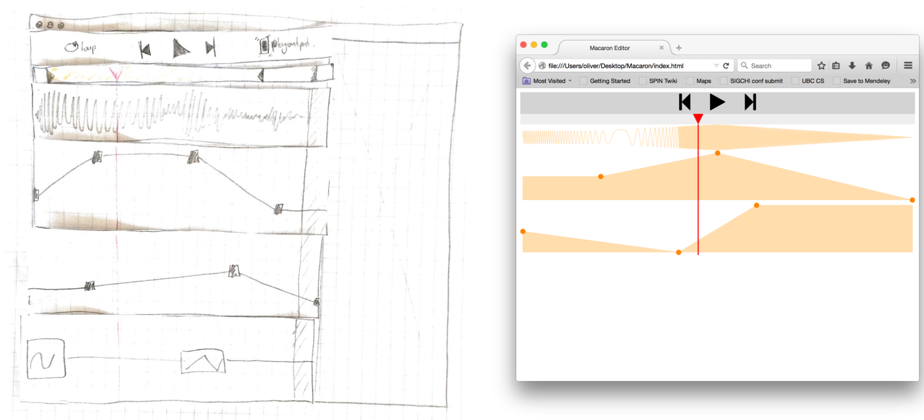


Figure 5.3: Phase I overview, with possible outcomes. We 1) pilot crossfading between waveforms, and 2) conduct an MDS study to find perceptually varied icons and evaluate morphing. The end result is a set of interaction techniques suitable for Phase II.

5.2 Phase II – Design Gallery Development and Evaluation

In Phase II, I will develop a design tool that implements these algorithms, and use it to study how users involve examples in their designs. An HTML/JavaScript prototype is under development (Figure 5.4), which generates sound that is streamed to the Haptuator through the audio jack. Our questions and planned studies are visualized in Figure 5.5.



(a) Paper prototype. **(b)** HTML/JavaScript prototype.

Figure 5.4: Initial prototypes for Macaron Editor.

5.3 Deliverables and Risk

This project is intended to be completed in fall 2015, with a planned paper submission to CHI'16 or HAPTICS'16 (deadline in September), DIS'16 (deadline expected in December), or a similar venue. I mitigate risk in following ways. Phase I studies are designed to result in actionable results with or without waveform crossfading and morphing (Figure 5.3). If vibrotactile icons are not found to be diverse, I can select icons via piloting or from the HapTurk side project, which currently has a diverse set of icons selected. Phase II studies are also designed to robustly provide results; we are primarily describing what users are doing. If our system encounters technical problems, we can adjust the scope to mitigate risk, focusing more or less on Phase I or Phase II. For example, if Phase II runs into unforeseen problems, we can submit a focused piece on Phase I (algorithms and interaction techniques) with more thorough investigation of morphing or waveform crossfading. Alternatively, if Phase I encounters much difficulty, we can extend Phase II and look more at user interactions and less at algorithms. Finally, if both Phases are compromised due to implementation problems, we can study these research questions by extending a previous tool: mHIVE, Mango, FeelCraft, and Feel Messenger could all be extended to investigate similar research questions.

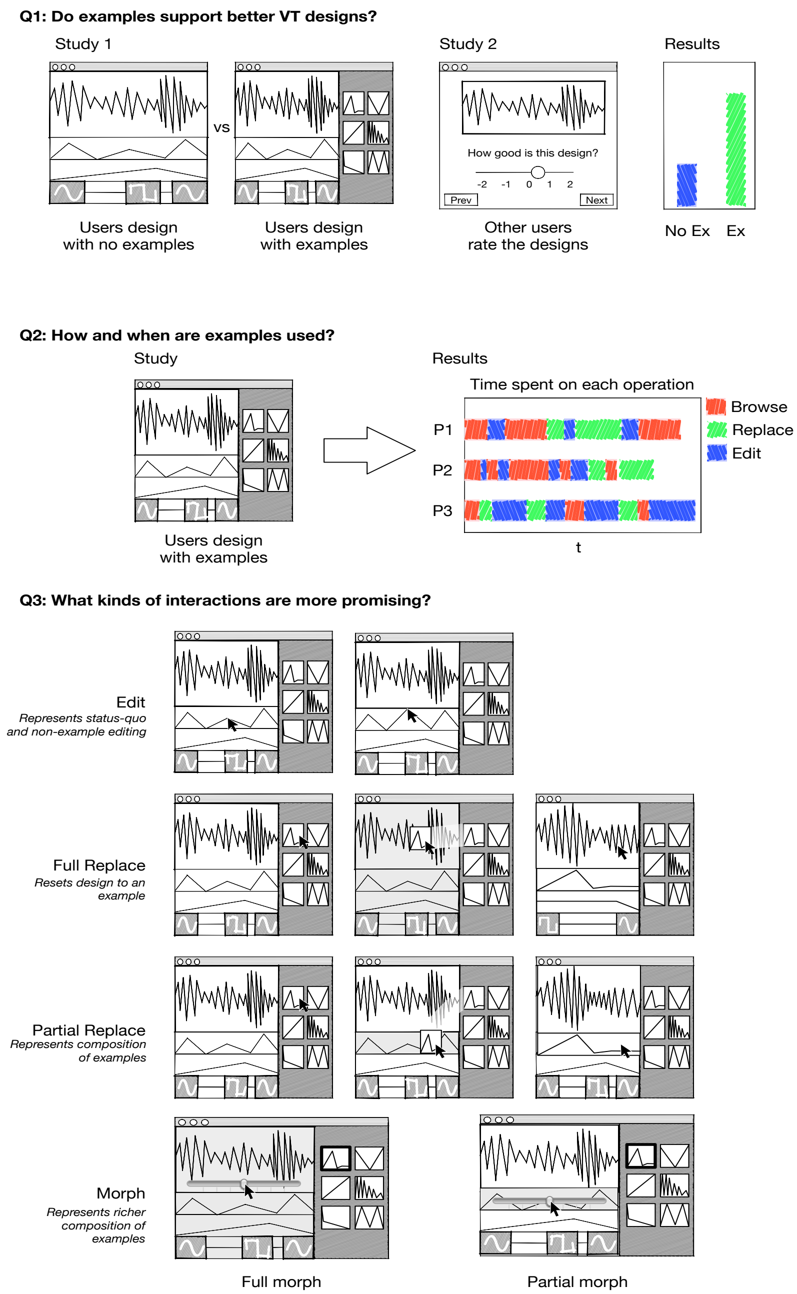


Figure 5.5: Phase II overview, split into research questions.

Chapter 6

Synthesize: Generalization and Grounding

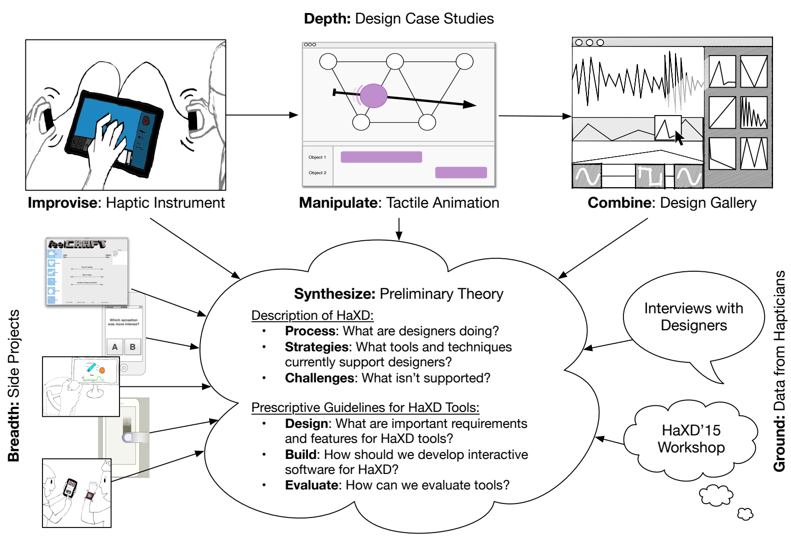


Figure 6.1: Planned synthesis of data for a preliminary theory of haptic experience design.

The three case studies provide rich but focused data on how to create vibrotactile (VT) experience design tools. To complement these studies, I propose to gather information more broadly to generalize the haptic design process to other use cases and ground in haptician experience (Figure 6.1). In this way, my final contributions will draw from several sources: 1) the three in-depth design studies, 2) insight gathered from several side projects, and 3) two sets of grounded data: interviews with professional designers, and a workshop at World Haptics '15.

Here, I describe the data collection process, then illustrate possible applications and forms for these contributions. However, any resulting theory will be emergent from the data, and can take many forms. To accomplish this in a principled way, I plan to use *memoing* and *constant comparison* [11], looking for common threads between data and double-checking conclusions as new theoretical developments appear. This theory will also draw from a literature review of design theory, summarized in this document's related work section.

6.1 Data Collection

In this section, I list the different sources I intend to use to collect data for theory design.

6.1.1 Vibrotactile design case studies

Each of the design case studies previously described investigates a specific user group working on a specific VT device with a specific software tool. Through my experience of gathering requirements, creating tools (through design and development), and evaluating them, I will have first-hand knowledge of supporting aspects of VT sensation design. Each also produces a small vignette of haptic design in action, giving us glimpses of the design process.

6.1.2 Side projects

In addition to the three design case studies that form this proposal, several side-projects are planned or underway as collaborative efforts. In these side-projects, I take an organizational or supervisory role, often as summer projects conducted by undergraduates.

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.

6.1.3 Grounded Data

A corpus of interviews with professional haptic designers has already been collected by UBC alumni Colin Swindells during his PhD, but has never been published. I will analyze these interviews to further ground our findings with real-world haptic designers.

To complement this we turn to the research community who do design as part of their work. The planned Workshop on Haptic Experience Design (http://oliverschneider.ca/HaXD) at World Haptics 2015 will also provide a data source. At this workshop, 4 experts of haptic experience design will speak, participants will reveal their own design challenges in a brainstorming activity, and the ensuing panel discussion should help illuminate practices and paths for future work.

6.2 Possible Format

While the theory can take many forms, I hope to characterize haptic experience design and contrast it with other design fields, especially graphic and audio design. I hope to find both descriptive and prescriptive results, including current practices, an identification of challenges uniquely facing haptic designers, and guidelines for designers and developers of haptic design support tools.

6.2.1 Descriptive Contributions: HaXD Process as Requirements

My first goal is to describe the **processes** employed by haptic designers. This could manifest, for example, as a catalogue of existing haptic design tools, appropriated tools (e.g., using a sound editor to create VT icons), techniques (e.g., design philosophies like Haptic Sketching), resources (e.g., libraries and APIs), platforms (what devices designers are using), practices in haptics education (undergraduate or graduate level courses), and tasks undertaken by haptic designers.

For example, to share of haptic experiences, haptic designers create demos to spread awareness of haptic research and gain feedback from peers. This is so ingrained into the culture of haptic research that recently a demo-only conference was launched: Asia Haptics.

Once collecting a description of current practices, I expect we might be able to identify **challenges** and **strategies** to addressing those strategies, including the ecosystem of available tools: what is working well, and what is broken. Using our example of collaboration and demos, we might see that in-person demos are effective, but remote collaboration or asynchronous sharing is challenging. Available tools include videos and visualizations of demos to explain concepts in lieu of the demo itself.

6.2.2 Prescriptive Contributions: Guidelines for HaXD Software Tools

After describing HaXD as a set of requirements, I will then develop guidelines for how to built supportive interactive software tools. Right now, I plan to organize this into three aspects: how to **design** tools, including important features relevant to different stages of HaXD; how to **build** tools, including relevant software architectures and ways to address technical challenges; and how to **evaluate** tools, methods to capture designer experience and inform future design.

Hypothetical use cases might best explain this contribution. One examples is using these guidelines for knowledge transfer to industry. I could use these guidelines to advise or create design software for companies developing haptic hardware platforms (such as the TPad team and UltraHaptics) or software platforms (such as Immersion and Phidgets), bridging the gap from research to industry application. Another example could be dissemination through haptics education. Developing a module for a haptic design course, such as CPSC 543, is an accessible way to encapsulate and test these ideas. This could also manifest in a multi-day workshop, similar to Camille Moussette's Haptic Sketching workshops, to validate ideas at different institutions.

6.3 Deliverables and Risk

There are two expected deliverables from this theory development. First, the HaXD'15 workshop on Haptic Experience design is planned, piloted, and scheduled for World Haptics in June, 2015. To get the most out of this workshop, photographs and notes will be recorded. Afterwards, a very small digest piece debriefing the workshop is planned in winter 2016; this may be submitted on its own as an short paper if an appropriate venue is available (e.g., a special journal issue similar to [37]), or subsumed into the second deliverable.

The second deliverable is a retrospective piece on our findings from all the data sources found here, but with a focus on data from haptic designer interviews. This interview data has already been collected by UBC alumnus Colin Swindells. I plan to digest and analyze those interviews in winter 2016 to generate requirements grounded in designer experience. This will likely be combined with synthesized findings from the three design studies and several side projects. To mitigate risk, we can combine interview findings to a greater or lesser extent with other data sources. If the interviews have a great deal of information, they could be a valuable contribution on their own. If not, I expect them to supplement our other data sources. This document will likely be submitted as a full paper to a peer-reviewed conference or journal.

Within each project, we mitigate risk through strategic planning and study design; many of these projects do not have to be successful to provide input. For example, HapTurk may never actually be deployed, but could still articulate the challenge of a large-scale, remote haptic user study. In addition, risk is partially managed through sheer attrition: one or two side projects or data sources could provide limited feedback and we would still have a diverse set of information. However, I will note that initial investigation has already been useful.

Chapter 7

Milestones and Timeline

In this chapter, I describe my progress-to-date, provide a full list of milestones, and present two corresponding timelines for my PhD program. Table 7.1 shows all dissertation milestones and their current status. Figure 7.1 presents a complete, but brief, overview of the entire PhD. Figure 7.2 presents a focused timeline of the remaining plans.

I

Progress on in-depth case-studies: I have currently finished and presented the work described in Case Study 1 (The Haptic Instrument, Chapter 3) at Haptics Symposium 2014 [63] and a CHI 2014 workshop [64]. I have also finished and written up the work described in Case Study 2 (Tactile Animation, Chapter 4); a paper has been submitted to UIST 2015. I have already reviewed the literature, prototyped algorithms, and started building my study platform for Case Study 3 (Design Gallery, Chapter 5), with plans to finish the study platform (Phase I) and begin the design study (Phase II) in summer 2015, and submit a paper to a top-tier conference in fall 2015.

Progress on side-projects: I have also began all side projects. The FeelCraft project, on software architecture for adding customized vibrotactile (VT) effects to video games, has already been written and presented at Asia Haptics 2014 [62] and as a UIST 2014 demo. The Feel Messenger project, on sending customized VT sensations via commercial smartphones, has had a work-in-progress published at CHI 2015 [35] and a demo accepted to World Haptics 2015. Other side projects are currently underway as projects led by summer students in 2015. Paper submissions are planned in fall 2015, on which I will participate as an author in a supervisory role; the RoughSketch project will result in a demo at World Haptics 2015, presented by summer students.

Progress on theory development: The HaXD'15 workshop on Haptic Experience design is planned, accepted, and scheduled for World Haptics in June 2015; afterwards, a small retrospective piece is planned in winter 2016 (either on its own or as part of a larger submission). The data from haptic designers has already been collected by UBC Alumnus Colin Swindells; I plan to digest and analyze those interviews in winter 2016, and submit findings for my preliminary theory to a conference or journal in 2016 (depending on my dissertation submission timeline).

Date		Component	Milestone	Status
2013	Sept	Haptic Instrument	Tool	Complete
			Paper & Demo	Published: HAPTICS'14
2014	June	*Side Project:* FeelCraft	Paper	Published: AsiaHaptics'14
	Sept	Tactile Animation	Tool	Complete
			Paper	In Review
	Oct	*Side Project:* FeelCraft	Demo	Published: UIST'14
	Dec	PhD Requirements	Course Requirement	Complete
2015	Jan	*Side Project:* Feel Messenger	Short Paper	Published: CHI'15
	June	**PhD Requirements**	**Proposal Defence**	Scheduled
		HaXD Workshop	Workshop	Accepted
		Side Project: Feel Messenger	Demo	Accepted
		Side Project: RoughSketch	Demo	Accepted
	Sept	Design Gallery	Tool	In Progress
		Side Project: CuddleBit	Paper	In Progress
		Side Project: HapTurk	Paper	In Progress
		Side Project: CyberHap	Paper	In Progress
	Nov	Design Gallery	Paper	Planned
2016	Jan	HaXD Workshop	Short Paper	Planned
	March	PhD Requirements	Dissertation Draft	Planned
	May	HaXD Theory	Paper	Planned
	July	PhD Requirements	Final Defence	Planned

Table 7.1: PhD milestones and current status.

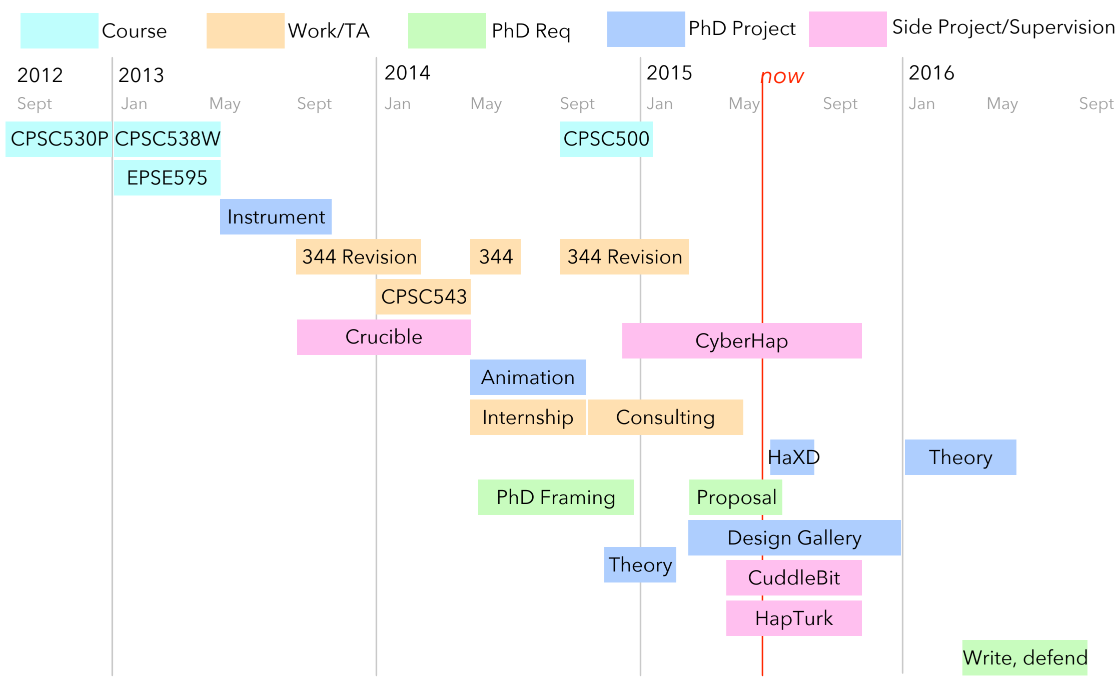


Figure 7.1: Overview of PhD from start (September 2012) to intended finish (August 2016).

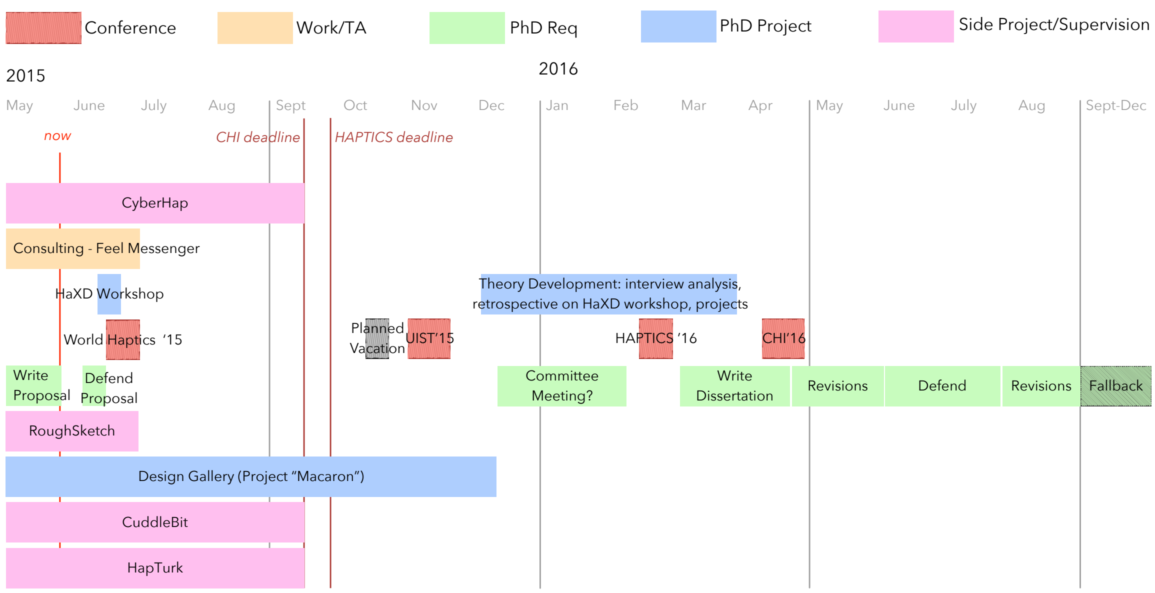


Figure 7.2: Detailed timeline of remaining plans, from May 2015 to intended finish (August 2016). Note that several projects are targetting the CHI'16 deadline, but could also be submitted to the coinciding HAPTICS deadline based on fit.

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