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: r0.1

Preface

At **UBC!** (UBC!), a preface may be required. Be sure to check the **FoGS!** (FOGS!) guidelines as they may have specific content to be included.

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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

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.

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 **??** 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 design-

ers, 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.

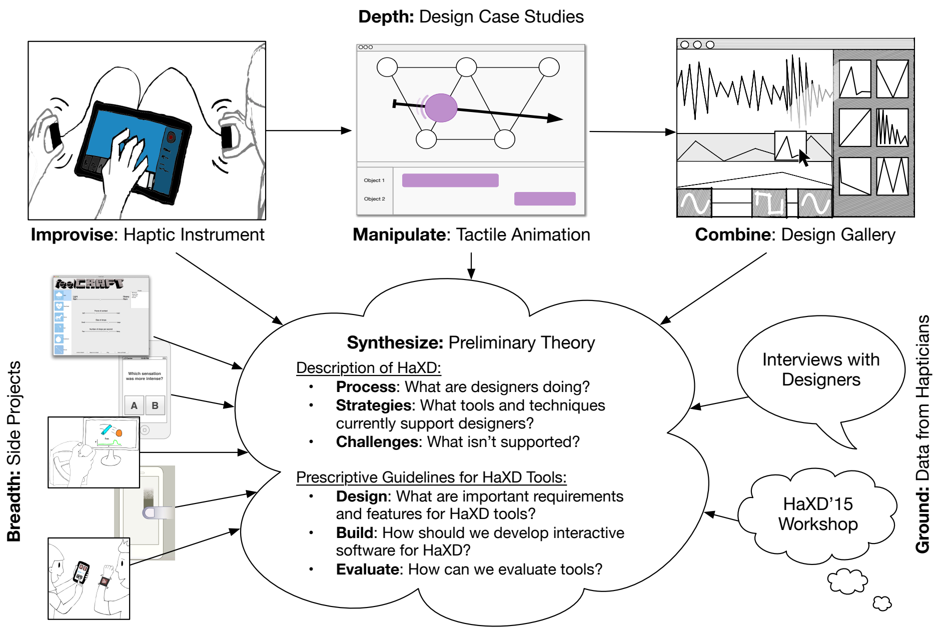
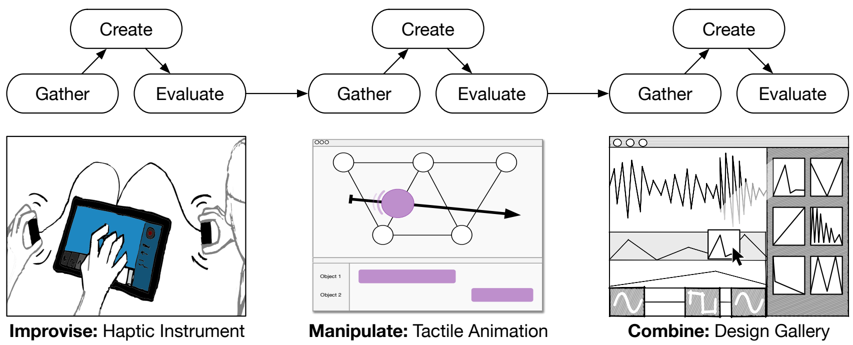


Figure 1.1: Methodology overview. Three case studies investigate VT tools in-depth; findings are synthesized with side projects and grounded data into a preliminary theory.

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 **??**. 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 8.

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 9.

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 **??**. After, I describe the planned data synthesis in more detail in Chapter 8. Finally, I present milestones and a timeline for my PhD in Chapter 9.

1.4 Contributions

In Chapter 3, 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 Chapter 5, 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.

In **??**, 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

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 (**??**) 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 **??**.

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 8).

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,

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

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.

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.

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

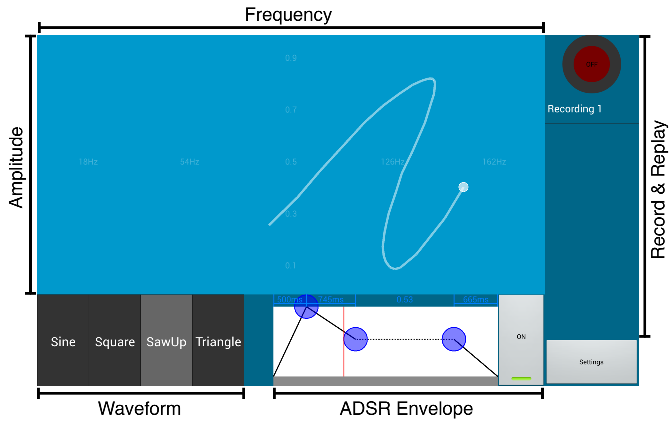


Figure 3.2: mHIVE interface. Primary interaction is through the amplitude-frequency view, where visual feedback is provided through a circle (current finger position) and a trail (interaction history).

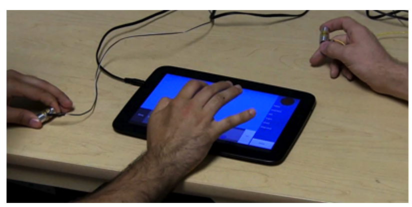


Figure 3.3: Study setup. Both the participant (left) and the interviewer (right) feel the same sensation as the participant controls mHIVE.

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 **??**, we attempt to mitigate the difficulty of describing haptics and draw upon examples by using a VT design gallery.

Chapter 4

Manipulate: Tactile Animation

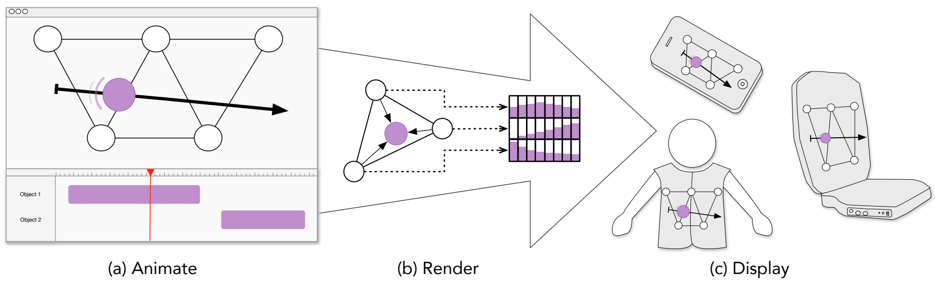


Figure 4.1: Concept sketch for tactile animation. An artist draws an animated sequence in the user interface and the user experiences phantom 2D sensations in-between discrete actuator grids.

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.

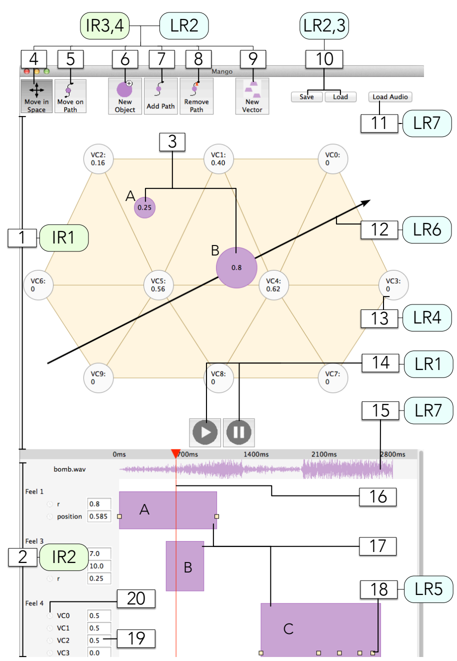
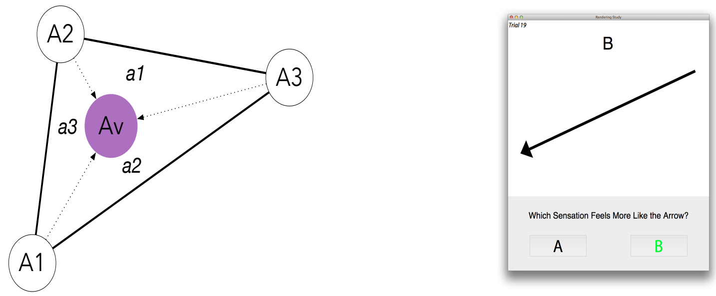


Figure 4.2: Mango graphical user interface. Key components are labeled and linked to corresponding design requirements (LRs and IRs, not described in this proposal).



(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).

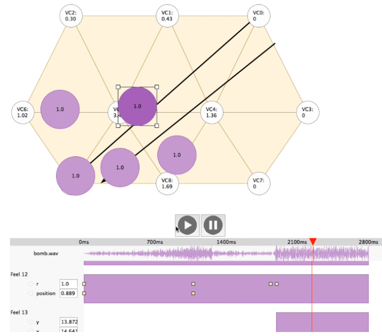
We had to choose between three interpolation models from prior psychophysical understanding of phantom tactile sensations [1] and propose them as candidates for the Mango tool: (i) *linear*, (ii) *logarithmic ("log")*, and (iii) *Pacinian power ("power")* interpolation.

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) Output device with highlighted actuators



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

Figure 4.4: Evaluation study setup and example design.

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.

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

Combine: Macaron

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 (**??**).

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 (**??**). Creativity often sparks when an inventor, examining existing ideas, sees a way to combine them with a novel twist [73]. An environment rich with *examples* is fuel for this fire. In industrial and graphic design [8, 29] their use improves process and final results [17, 41].

Several effect libraries are available to designers of vibrotactile (VT) sensations, e.g., for accessible wayfinding [**?**] or media experiences [15, 34, 62**?**]. But despite the need for effect customizability [66], VT library elements are generally

Figure 5.1: Macaron interface, "`hi`" version featuring both composability (copy and paste), and visibility of underlying parameters. The user edits her sensation on the left, while examples are selected and shown on the right. One editor has focus at a time, shown by the red playhead. Examples are non-modifiable (keyframes cannot be inserted or moved). Macaron is publicly available at `hapticdesign.github.io/macaron`.

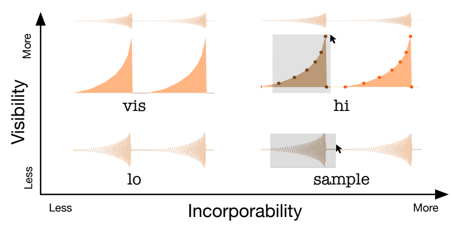


Figure 5.2: Design space for Macaron versions. `hi` and `sample` both allow for selection and copying of example keyframes. `vis` and `hi` both show the underlying profiles. `lo` represents the current status quo; only a waveform is shown.

opaque in construction and immutable. Recent advances include limited parameter adjustability [34, 62] and faceted library search and browsing [67]. Despite this, designers still must either choose a pre-existing sensation or build from scratch: *elements cannot be sampled, recombined, built upon or adapted*. In contrast, web designers can access a page's source; graphic and sound designers can sample and incorporate colours and sounds from other media.

Here, we *examine the potential role of examples* in VT design, to establish how to best support their use. We designed a web-based editor and interactive *design gallery* [41, 48] (Figure 5.1) for VT sensations, then asked users to compare versions (Figure 5.2) that vary in example accessibility via *visibility* and *incorpora-*

bility, as they create VT effects for animations (Figure 5.3).

Analysis of user action logs provide an objective picture of the VT design process. To validate the deployment of this methodology at scale, we also interpret and validate logs with direct observation and interviews. Specifically, we:

- introduce *Macaron*, a web-based VT effect editor through which examples can be used directly in designs,
- find that *visible, incorporable examples make design easier* by providing a starting point for design and scaffolding to learn how to work with VT parameters,
- identify *implications for future tools and libraries*, and
- discuss the *opportunities afforded by a web-based editor* as a practical tool and platform for studying other aspects of VT design at scale.

5.1 Related Work

5.1.1 Salient factors in VT effect perception and control

Vibrotactile effects (e.g. haptic icons [44]) are typically manipulated with low-level engineering of signal parameters, beginning with amplitude, frequency and waveform [3, 25, 44**?**]. Rhythm can support large, learnable icon sets [72**?**]; combining waveforms enhances roughness [**?**]. Time-varying amplitude adds musical expressivity, from tactile crescendos [6] to envelopes [63]. Multi-dimensional scaling can be used to identify and elaborate these parameters [21, 44**? ?**].

Affect and metaphor are another way to structure and manipulate sensations at a level more cognitively relevant than engineering parameters. Perceived valence (pleasantness) and arousal can be influenced by frequency/amplitude combination [**? ?**]. Metaphors [54, 67**?**] and use cases [67**?**] offer structure, memorability and design language. Spatial displays require additional controls for location and direction, whether body-scale [25, 33], mobile [**?**], or mid-air [**?**]. While many parameters are available for VT design, we chose the most established (time-varying frequency and amplitude) for Macaron's initial implementation.

5.1.2 Past approaches to VT design

Past editors – e.g., the Hapticon Editor [20], Haptic Icon Prototyper [70], posVibEditor [61], Vivitouch Studio [71], and Haptic Studio (www.immersion.com) – are track-based, with graphical representations to edit either waveforms or profiles of dynamic parameters. Additional features (e.g., spatial control or mobile interfaces) are surveyed in [**?**].

A library of effects is critical for haptic design tools [**?**]. Most existing tools support feature saving/loading, and some have an internal component library [20, 70, 71]. However, previous implementations were primarily *compositional*, employing building blocks [21] rather than complete artifacts. Example use was not studied.

Large VT libraries contain complete artifacts, but impose a serious constraint on their use. In the Immersion Touch Effects Studio library, underlying structure and design parameters are hidden and cannot be incorporated into new designs. VibViz [67] features 120 VT examples with visualizations searchable by several taxonomies, but the selection model is all-or-nothing. FeelCraft [62] proposes a community-driven library of feel effects [34] for simple parametric customization and re-use. While end user customization-by-selection is important [66], experts need a more open, editable model, just as web designers rely on full access to source code with recent tools allowing search and easy incorporation [41].

5.1.3 Examples in non-haptic design

Problem preparation – also known as the “problem setting” [65] or “analysis of problem” [73] step of design – involves immersion in the challenge and drawing inspiration from previous work. Both may come from the designer’s experience, *repertoire* [65] or exposure to a symbolic domain, e.g., mathematical theorems and notation [**?**].

To this end, external examples are critical in inspiring, guiding and informing design [8, 29]. Industrial designers collect objects and materials; web designers bookmark sites [29]. In graphics and web design, *design galleries* organize examples to be immediately at hand [41, 48]. Example-based tools often use sophisticated techniques to mix and match styles and content [**?**]: this requires immediate access to the examples’ underlying structure.

5.2 Apparatus Design

To investigate VT design in the context of examples, we required a platform that would expose users’ natural procedural tendencies. Our Macaron design gallery is simple, flexible, and extensible. In this work, we add multiple types of example access to polished implementations of familiar concepts: *tracks*, *envelopes*, and *keyframes* (Figures 5.1,5.2).

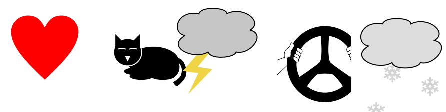
Tracks are the accepted language of temporal media editors (video, audio, and past haptic efforts [20, 61, 70]). We provide tracks for perceptually important

`hi`	Full access to gallery examples, with keyframes visible and selectable for copy and paste. Simulates source visibility, *e.g.*, viewing the source of a web page or having access to a `.psd` PhotoShop document.
`sample`	Hides underlying parameters of frequency and amplitude, whereas waveform regions (underlying keyframes) may be copied and pasted into a design, simulating example mixing in absence of visibility into underlying construction. While possible to see underlying representation by copying the entire example, the steps are indirect and inconvenient.
`vis`	Reveals underlying parameters, but hides keyframes, parameter scales, selection and copy/paste features. The inverse of `sample`, it exposes example structure, but does not support incorporating example elements into a design.
`lo`	Supplies a "black box" outer representation. Playback and visualization of the complete vibration reflect the status quo of non-visible, non-mixable example libraries.
`none`	No examples present.

Table 5.1: Macaron tool alternatives, varied on dimensions of internal visibility and element incorporability.

"textural" parameters (amplitude and frequency); the user accesses periodic and time-variant aspects by manipulating their *envelopes* using *keyframes*, with linear interpolation in-between. Users double-click to create a new keyframe, click or drag a box to select, and change or delete a selection by dragging or with the keyboard. A waveform visualization reflects changes.

Macaron's example access features are inspired by more recent graphics and web design galleries [41, 48**?**], which show examples side-by-side with the editor. Other implemented features, critical for polished creative control [**?**], include real-time playback, time control (scrubbing) copy-and-paste, undo and redo, and



(a) Heartbeat. **(b)** Cat. **(c)** Lightning. **(d)** Car. **(e)** Snow.

Figure 5.3: Animations used as design tasks, in presentation order. Heartbeat expands in two beats; the cat's back expands as breathing and purring; lightning has two arhythmic bolts; the car oscillates up and down, and makes two turns: left then right; snow has three snowflakes float down.

muting (disables realtime VT output). To support its use as an experimental tool, user interactions are logged; start / stop buttons allow the user to indicate when they began and completed their design process.

Macaron was built with HTML5 and JavaScript, using React, Reflux, D3, and Audiolet[1]. Real-time sound synthesis drove a C2 actuator. To leave hands free for keyboard and mouse, the C2 is attached to a wristband; we simulate the design process for a wrist-worn wearable (as in [67]).

Evaluation Versions: To study how examples impact design, we made four gallery versions by sampling two theoretical dimensions of example access: element *incorporability* and internal parameter *visibility* (Figure 5.2, Table 5.1). We hypothesized these would affect users' design processes, e.g., incorporable examples would encourage "mixing and matching" of examples, visibility might provide insight.

We compared these versions with each other and with a non-example version: `none`. In all versions with examples, the user can play or scrub the example, feeling it and seeing the waveform visualization. We did not allow users to modify the examples, to avoid study workflow confounds. To populate the gallery, we chose or adapted seven examples from [67], piloted them to confirm example variety, then regenerated keyframed versions with Macaron.

5.3 Study Methods

Participants were tasked with creating a sensation to accompany five animations (Figure 5.3) – SVGs (scalable vector graphics) which can be played or scrubbed by the same means as navigating Macaron's time control. We chose animation variety (concrete to abstract) and complexity to inspire non-obvious solutions without

[1]facebook.github.io/react, github.com/reflux, d3js.org, github.com/oampo/Audiolet

overwhelming.

Participants were first trained on `none` with no animation, then presented with five animation/version combinations. As the least crucial source of variance, animations were presented in Figure 5.3's constant order, while interface versions were counterbalanced in two 5x5 Latin square designs. Thus, each participant encountered each animation and each interface version once; over all participants, each animation/version combination appeared twice, with Latin squares balancing 1st-order carry-over effects. This design confounds learning with animation task. We believe this is an acceptable tradeoff at this stage, allowing us balance interface order with a single participant session of reasonable length (1-1.5h).

5.4 Results

We targeted a study size of 10 complete participants for a balanced Latin square design, and a manageable sample size for rich, exploratory, qualitative analysis. 13 untrained participants were recruited: P1-10 (7 female, ages 22-35) completed all five tasks, while I1-3 (2 female, ages 29-45) only completed the first three due to time restrictions. Because I1-3 (and P9) all had the same interface order (`lo`, `none`, `vis`, `hi`, `sample`), we suspect that beginning with 'sparse' versions gave insufficient insight into how to design quickly enough to finish the study. I1-3 showed no distinct patterns beyond this; we leave their data for future analysis.

Analysis and Data: A team member trained in qualitative methods analyzed screen recordings, interviews, and logs with grounded theory methods (memoing, open & closed coding [11]) and thematic analysis and clustering [52]. We visualized logs using D3 (Figure 5.4). We chose a qualitative analysis because our goal was to capture the design process, not compare Macaron with previous tools. Our analysis exposed three major qualitative findings, discussed below.

Tool Usability: Overall, the tool was well received, described as *"easy to use"* (P1), *"well made"* (P5), *"pretty neat"* (P9), *"the templates help a lot"* (P3).

Completion time: Overall mean task completion time for P1-10 was 5m48s (median 4m48s, sd 3m52s, min 40s, max 18m23s). We conducted two one-way ANOVAs on completion time; neither interface ($p = 0.87$) nor task ($p = 0.64$) had a significant effect.

5.4.1 Archetypal Design Process

Log visualizations (Figure 5.4) show that users could and did employ Macaron for all key design stages: preparation, initial design, iteration, and refinement. All participants followed this sequence. Some omitted one or more steps depending on personal style and strategies for using examples (below). We list observations

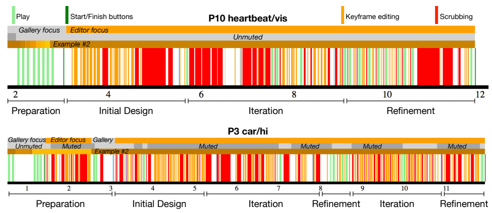


Figure 5.4: Log visualizations showing archetypal design process. Top: P10's heartbeat/`vis` condition (an"ideal" version). Bottom: P3's car/`hi` condition (variations: a return to example browsing after editing, repeated refinement, muted editing).

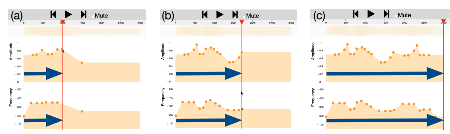


Figure 5.5: P9's cat/`none` design progressed sequentially in time. Note the red playhead helping alignment in (b).

of the basic process in Table 5.2, to document behaviour and frame discussion.

5.4.2 Micro Interaction Patterns Enabled by Tool

Several small-scale patterns further characterize behaviour within the archetypal process.

Different paths through the interface

We saw three design-path strategies.

– *Time* (Figure 5.5; P1,2,3,4,7,9): proceed through the timeline, creating amplitude and frequency at the same time.

– *Component* (Figure 5.6, P1,4,6,8,10): iterate on a design element, then repeat or copy/paste it later in time.

– *Track* (Figure 5.7, P2,3,6,7,8-10): proceed through one entire *track* (typically amplitude), then the other one.

Strategies were often combined hierarchically. P6 developed a car/`lo` component by track (amplitude, then frequency). Wanting additional flexibility, P1,3,7 requested copy/paste *between* tracks: *"The one thing I found missing was copy and pasting between amplitude and frequency"* (P7).

Prepare	All participants began with a problem preparation step [73]. They played the animation to understa problem, then typically looked at several (sometimes all) examples. Only P2, P8, and P9 had a task they did not begin with an example. Otherwise, participants browsed examples, chose a best ma the animation (*"I was trying to find the best match with the visual"* (P7, heartbeat/`hi`)), then tran into initial design. Participants rarely returned to examples for more exploration; only P3 (car/`hi`) (car/`lo`) switched to a different example after beginning their initial design. Preparation is characteri a large number of plays and example switches: on average, 47.45% of all session plays were before t edit (sd 30.15%), and participants switched examples an average of 6.75 times (sd 5.17).
Initial Design	Participants either used their example choice to help create their initial design, or ignored it because it close enough to what they wanted to do. Participants typically recreated the example in their ed copy/paste of the entire design (P1,2,4-8,10) or sometimes a component (P3,10) in incorporable con (`hi` and `sample`), or by manually recreating the design (P5,6) or a component (7,10) with `vis`. In condition, we only observed P5 somewhat recreating an example. Occasionally, participants would c new design loosely based on the example rather than recreating it (P3,4,6-8), when using the *Inspire* ex use strategy (described later).
Iterate	Participants refined designs with longer periods of editing typically book-ended by playing the entire (discussed as "real-time feedback" micro interaction pattern). In some cases, especially when the ex was "close enough", participants skipped iteration (*Adjust* or *Select* example use strategies, described
Refine	Smaller changes forecast design conclusion, e.g., incremental global changes: constant fre (P1,2,5,6,10), alignment (P1,3,6), or pulse height adjustment (P1,3,8,10). This step is sometimes vis activity logs, as most participants (P1,3-10) exhibited more frequent plays of the entire design, and periods of editing/scrubbing. Occasionally, participants repeated larger iterations and refinement (P3 c Figure 5.4).

Table 5.2: Steps in observed archetypal design process.

Further showing diverse workflows, participants requested more powerful controls to work with keyframes as a group, such as widen (P5), reverse (P7), shift everything (P9), move up/down and smooth (P4). Other requested features include looping (P1), hovering over a point to see the value (P1), more detail through a zoomable interface (P4).

Alignment and Copy/Paste are Precise, Convenient

Precision was valued; alignment and copy/paste were used to achieve it. Alignment was sought both in time and to keyframe values. A common technique (Figure 5.5b) was to use the red playhead like a plumb-line to align keyframes with animation features (P1-5,7,9,10) and between the two tracks (amplitude and fre-

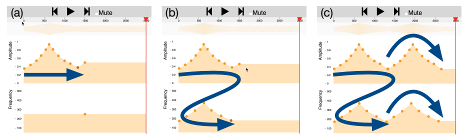


Figure 5.6: P6's car/`lo` design progressed by component, developing the component then repeating it.

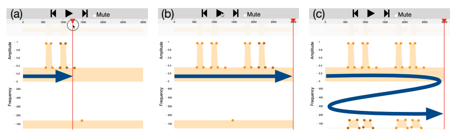


Figure 5.7: P10's heartbeat/`vis` design progressed by track. Amplitude was developed first, then frequency.

quency) (P3-5,7,9,10): *"Using that red arrow thing and placing the dots when it makes the heartbeat"* (P2). Some participants, including those who used the plumb-line, requested more refined alignment features: *"I couldn't keep it straight"* (P1).

Copy/paste was used for improved work efficiency (especially helpful during initial layout or when creating long or repeating designs) and precision: *"Copy and paste...was also the most precise, because if you feel like it's a perfect fit, you can use it exactly"* (P6). Correspondingly, conditions without copy/paste (*i.e.*, `lo` and `vis`) took additional effort: *"It's harder...because there's no copy and paste"* (P5). Precision also depended on context: *"For monitoring someone's health, you would have to be very accurate"* (P9)

Editing and playback

During iteration, participants edited in bursts of primarily scrubbing activity, bookended by full playthroughs. They took time to realize each new version of the design before observing an overview. When editing, participants scrubbed back-and-forth, varying speed (P1-4,7,9,10), and dragging keyframes to try ideas out (P1,3,4,7,9,10) Figure 5.8. This feature was valued by those who used it: *"The real-time part is pretty important"* (P1); some rarely played, showing more frequent or longer periods of scrubbing instead (P2,9,10). Others rarely scrubbed (P5, P8), possibly to have an overall sense of the design: *"Trying to get a general sense of how it might feel"* (P8). P3, P4, and P7 all exhibited focused editing with mute enabled, unmuting for the bookended play sections; others did not use muting.

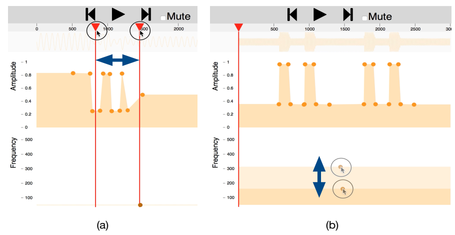


Figure 5.8: Participants used real-time feedback to explore, both (a) in time by scrubbing back and forth (P3 lightning/`lo`), and (b) by moving keyframes (P10 heartbeat/`vis`).

Encoding and Framing

Some participants encoded parameters using consistent rules, often aligned to events like heartbeats or lightning bolts. Others sought to create moods or metaphors for sensation.

Encoding was most visible in the lightning task, where participants represented lightning bolts in regular ways: *"if there was a lightning bolt on the left, I put amplitude and frequency a little longer than a lightning bolt on the right"* (P9). When the animation had two simultaneous bolts, several (P2-4,7,9) encoded it by superimposing two bolt representations on top of one another. Participants were forced to reframe their encoding strategy: *"...two [lightning bolts]...I divided it into two equal partitions, .6 and 1"* (P7).

Encoding failed when participants did not find a direct mapping: *"When the three [snow flakes] come together I think my strategy broke down"* (P7). Metaphors helped in these cases. Car took extra imagination, either for the experience of driving (P6, P8, and P9 didn't drive), or because it's hard to *"know what it would feel like on the wrist"* (P1). P6 describes her process for both lightning and snow as using mood: *"...what I think the mood is...like snow fall, it's kinda like, very gentle and calm"* (P6).

5.4.3 Example Use

As seen, examples played a major role in users' design processes. Analysis revealed the effect of examples to be more nuanced than a one-to-one mapping of the theoretical dimensions of incorporability and visibility. Emergent themes were instead organized on the *role* of examples: as a *direct starting point* for each design; and to *indirectly scaffold learning* throughout a session. The latter was related to additional themes: task difficulty and individual differences.

Ignore	Deliberately do not choose an example, through either lack of match: *"I didn't [find] the examples that I wanted"* (P1); a desire to challenge themselves or be creative: *"I wanted to do my own thing!"* (P9); or difficulty in using the examples.
Inspire	Choose an example, but do not explicitly copy/paste or replicate it in the editor; instead, design based loosely on example parts, sometimes as an adaptation from memory: *"I just tried to remember what the keyframes were like before, and then I modified it"* (P6 car/`lo`).
Template	Choose an initial example, but alter it considerably. In this case, participants use the example to expedite the process.
Adjust	Find an initial example, skipped major iteration and went directly to the refine stage, sometimes because the example was a close match. To enable this, some participants wanted a more powerful manipulation methods, like inverting (P7).
Select	Copy/paste an example (or manually recreate it), then do not modify; sometimes because the example seemed to match: *"...copy and paste, then confirmed it was the same."* (P5)

Table 5.3: Strategies used by participants to directly use examples as a starting point. Ignore and Inspire did not start with copy/paste; Template, Adjust, and Select did, with varying amounts of editing afterwards. When copy/paste was not available, manual re-creation was used as a stand-in.

Direct example use – task starting point

When participants *prepared* for each task by browsing to find a best-match example, then using it as a starting point, they did this with a spectrum of strategies. These strategies, elaborated in Table 5.3, range from Ignore (examples not used) to Select (an example was the final design).

Indirect example use – observe how to design

Over the course of the session, participants used underlying structures of examples to understand how to design VT icons. This was most evident in the `none` or `lo` condition after participants were first exposed to examples: *"I sort of remembered"* (P4 car/`none`). Some explicitly described learning: *"It gave me a general idea of thinking in big shapes rather than little dots"* (P9 lightning/`vis`).

Most participants commented on the difficulty or ease of their task (P1-5, 7-9). Task difficulty was connected learning (*"It's easy...maybe it's more experience"* (P4 snow/`lo`)) and individual differences. Some people were motivated to learn, and challenge themselves; others were not.

Connections between these factors are complex and difficult to unravel with this data. We speculate on the utility of flow theory [**?**] as a useful lens to connect these issues, as it considers creativity, education, and the relationship between perceived challenge and perceived ability. We plan to use it to frame future exploration.

5.5 Discussion

We discuss implications for design, then limitations we hope to progress on with future work.

5.5.1 Implications for Design

Expose example structures for learning

When exposed to examples' underlying structure, participants are able to build their repertoire and learn VT design conventions like *"big shapes"* (P9). Such scaffolding is particularly crucial in an environment where experienced VT designers and training possibilities are rare. Whether through exploratory tool use or structured with online training programs, examples can expand the VT design practices available to novice designers.

Examples as templates

Participants typically copied an example first before iterating and customizing, suggesting a template model of modifiable source documents as a way to expose structure and reduce effort for designers.

Example Recommender

The time participants spent searching for the suitable examples suggests a recommender system could be very valuable. AI techniques might recommend examples similar (or dissimilar) to a source stimuli, as with previous tools in other sensory modalities [41] and VT visualization tools like VibViz [67].

Clarify example context

Participants often repeated gallery searches for each new animation; they needed to compare examples alongside the target graphic. In addition, though our examples were designed independently of our animation tasks, some participants showed confusion about whether they were supposed to match. Clarifying the context for each example, by presenting it either in connection to its original design goal or as a candidate for the participant's current goal, will help participants choose an example.

Hideable examples

Some participants wanted to be individualistic with their designs and actively disliked the most powerful `hi` condition, saying that the `none` condition was cleaner, or that while examples were helpful to learn, they felt "more creative" with fewer examples present. A hideable gallery, which can be opened when needed but kept hidden otherwise, could accommodate user preference. An intelligent gallery could even time example appearances or suggestions to occur at helpful design stages, e.g., by recognizing by activity patterns [17, 73].

Realtime "prefeel" then render

Macaron's real-time feedback supported exploration, with full play-throughs providing an overview or evaluation in-between editing sessions. In addition, P4, who was familiar with haptics, felt that the scrubbing synthesis was "muddy" relative to waveforms pre-rendered with audio tools – a common challenge, noted also by the researchers but deemed suitable for this study. While we hope this technology deficit inspires improved realtime rendering algorithms, it also suggests an explicit workflow compromise. Many video editing and compositing tools show a low-resolution previsualization in design mode; a clip is then fully rendered for playback. For tactile design, coarse, "prefeel" sensations would be synthesized for immediate feedback during a rough design stage, and a high-fidelity rendering generated for less frequent play-throughs. This could help computationally demanding, perceptually-based models or multi-actuator setups (e.g., tactile animation [**?**

] as a prefeel for tactile brush [33]).

Tool flexibility

Macaron was used in very different ways depending on the participant. Some progressed by time, by track, by component, or a combination thereof. Some mirrored frequency and amplitude, using them together, while others used them to express different ideas. This suggests that tools should be flexible and accommodate different strategies; perhaps offering a choice to group by parameters (e.g., [**?**]) or work along parameter tracks (e.g., [70, 71]).

Alignment tools

Participants frequently used the playhead for alignment, finding locations in the video or aligning points between amplitude and frequency. Participants requested using modifier keys to align points (as in other editing tools), or a visualization of events in video. This suggests several features, providing ability to:

– Align comparison sensations from each modality - visual or audio sensation alongside VT.

– Place anchors for attaching a VT sensation (or keyframe within it) to a point in a target visual or audio sensation. This might be automatically assisted, e.g, with video analysis techniques to find scene changes.

– Automatically align keyframes to nearby keyframes, or use a modifier key to constrain or nudge keyframe movement.

Reuse

Copy/paste, especially from a template, speeded design and facilitated otherwise tedious approaches. Several participants made use of element repetition, which had to be re-done upon design re-framing. While copy/paste was helpful, more powerful repetition tools (e.g. looping, and "master templates", as in PowerPoint) would likely find use by many designers.

Automated Encoding

Some participants applied consistent rules in translating an animation to a tactile rendering – e.g., representing left/right lightning bolts differently in the lightning animation, or directly matching amplitude to up-down motion in the car animation. Some of these practices might be automated into generative rules. For example, video analysis could detect up/down motion for a visual object, and translate that automatically to a level for amplitude, similar to how motion trackers can track a moving object and link that to position of an animation; or, a designer might want to specify the mapping. More complex parameterizations could provide a useful tool for expert users, much like how `fmod` allows for parametrized audio in game design.

5.5.2 Limitations & Future work

Limitations in our study suggest future lines of inquiry: following up on additions study factor by deploying online.

Study factors

Our Latin square design allowed qualitative comparison of several gallery variants, but did not have the power for comparative statistical tests between the alternatives. Meanwhile, five design tasks presented in a uniform order did not permit systematic insights into other factors: learning, or task features such as abstractness and complexity. Flow was identified after-the-fact as an important framework for future analysis, but only after our study was designed and data was collected.

Our proposed example-usage dimensions of visibility and incorporability were a useful starting point, but did not line up well with the task processes that people actually used with Macaron. We did see behaviors that aligned well with *learning* and *design-starting* from examples, as well as hints of a more rich and nuanced view of what makes examples useful and in what way.

First, the examples-as-starting-point strategies actually used (Table 5.3) suggest that visibility and incorporability at minimum are not quite right and probably insufficient in dimensionality – there is a concept of edibility regardless of starting point; whereas incorporability could entail editing, but certainly requires an example as a start.

Additionally, observations (including details not reported due to space limits) suggest other factors that influence example use, e.g., *difficulty*, from task, interface and personal confidence and experience; and *task*, from task complexity and abstraction, user strategy, e.g. encoding and metaphor, and user confidence and experience. These hints are far from orthogonal, and will require further research, with focus turned to elements like task abstraction and user background, to disentangle and prioritize.

Online deployment

Triangulation will be helpful in studying factors like difficulty, task abstraction, and user background. In this study, Macaron was deployed and studied locally. We were able to validate the editor's design support and utility of its logging methods, and expose many interesting insights into natural end-user design practices.

Our next plan to answer these questions is to deploy Macaron at a larger scale: online, as a free-to-use design tool for the haptics community, with an initial study in haptics courses. This will allow research *in-situ* with larger, more quantitative, remote-based methods for data collection, triangulated with the less scalable qualitative methods used in-lab. Interaction logs, use statistics, and A/B tests will help us further develop Macaron as a tool for VT design and more generally as a lens for the haptic design process.

5.6 Conclusion

In this paper, we present initial findings from a vibrotactile (VT) design gallery, Macaron. This tool revealed insights both into how examples are used in VT design and implications for other VT design tools. Macaron was implemented using web tools, offering a unique opportunity to follow-up on the design process we observed here, helping designers to create engaging experiences while understanding their craft.

Chapter 6

Synthesize: Generalization and Grounding

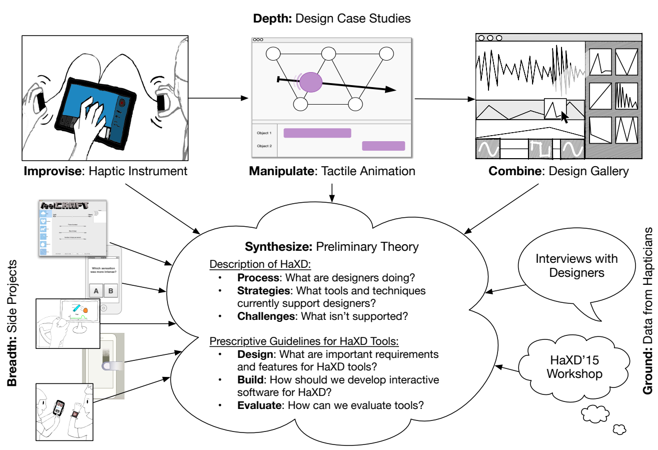


Figure 6.1: Planned synthesis of data for a preliminary theory of haptic experience design.

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 8.1). 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.

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

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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.

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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.

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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, appro-

priated 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.

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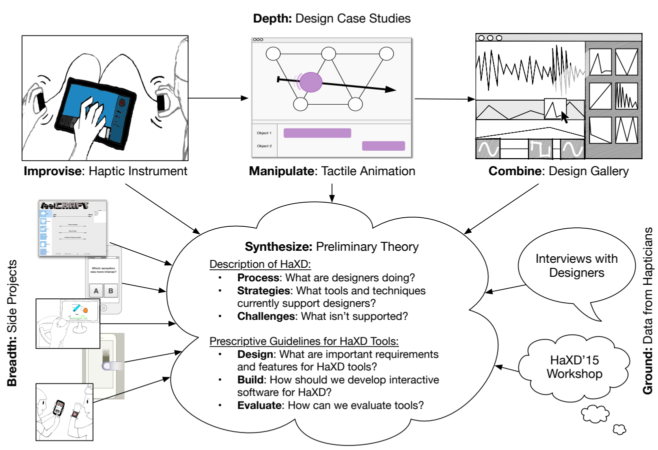
Chapter 7

Synthesize: Generalization and Grounding



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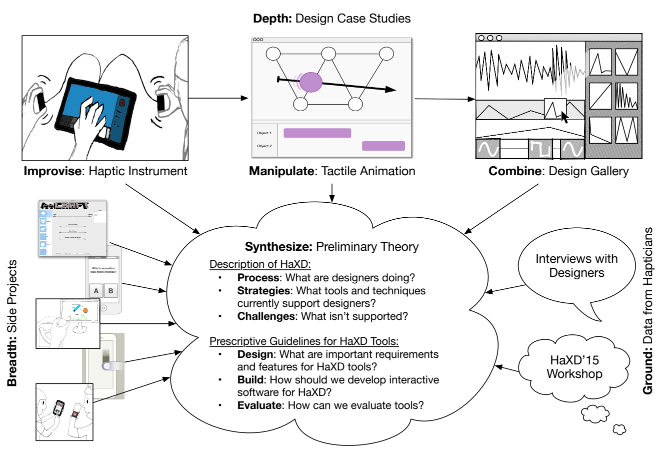

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Chapter 9

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 9.1 shows all dissertation milestones and their current status. Figure 9.1 presents a complete, but brief, overview of the entire PhD. Figure 9.2 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, **??**), 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 Expe-

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 9.1: PhD milestones and current status.

rience 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).

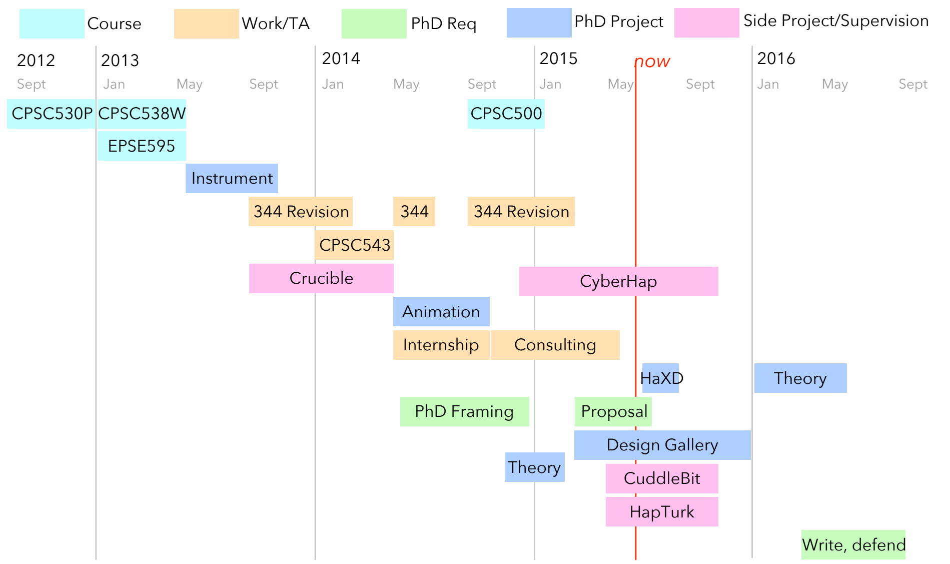

Figure 9.1: Overview of PhD from start (September 2012) to intended finish (August 2016).

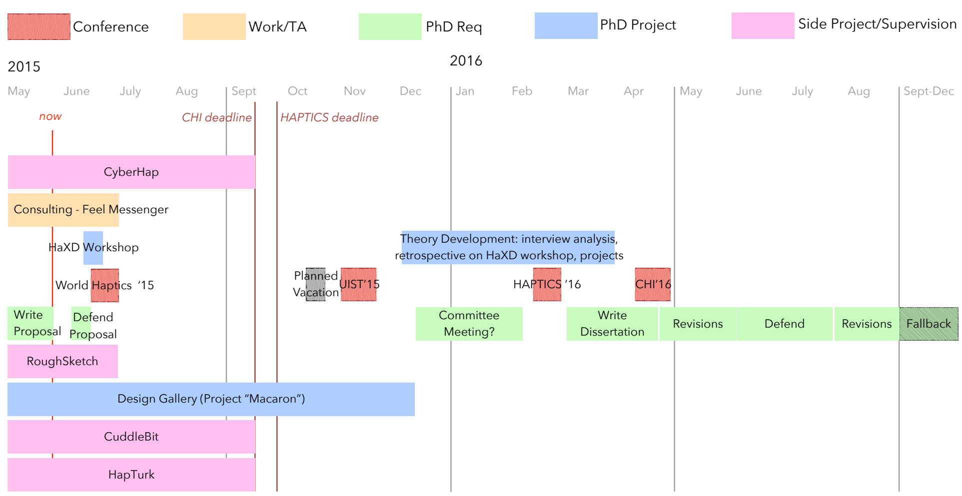

Figure 9.2: Detailed timeline of remaining plans, from May 2015 to intended finish (August 2016). Note that several projects are targetting the CHI'16 deadline, but could also be submitted to the coinciding HAPTICS deadline based on fit.

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