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# Haptic experience design: What hapticians do and where they need help

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ABSTRACT

From simple vibrations to roles in complex multisensory systems, haptic technology is often a critical, expected component of user experience – one face of the rapid progression towards blended physical-digital interfaces. Haptic experience design, which is woven together with other multisensory design efforts, interfaces is now becoming part of many designers' jobs. We can expect it to present unique challenges, and yet we know almost nothing of what it looks like "in the wild" due to the field's relative youth, its technical complexity, the multisensory interactions between haptics, sight, and sound, and the difficulty of accessing practitioners in professional and proprietary environments. In this paper, we analyze interviews with six professional haptic designers to document and articulate haptic experience design by observing designers' goals and processes and finding themes at three levels of scope: the multisensory nature of haptic experiences, a map of the collaborative ecosystem, and the cultural context of haptics. Our findings are augmented by feedback obtained in a recent design workshop at an international haptics conference. We find that haptic designers follow a familiar design process, but face specific challenges when working with haptics. We capture and summarize these challenges, make concrete recommendations to conquer them, and present a vision for the future of haptic experience design.



## 1. Introduction

Haptic feedback can provide value in several ways, such as accessibility (Bliss et al., 1970), unintrusive feedback (MacLean, 2009), and motor skill training (Milot et al., 2010). Recently, high-fidelity haptic technology has expanded the available range of user experience, improving support for emotional therapy (Sefidgar et al., 2015; Vaucelle et al., 2009), education (Sato et al., 2008; Minaker et al., 2016), and entertainment (Schneider et al., 2015a). Technological advances enable more compelling haptic sensations in consumer products by making it possible to render variable friction on direct-touch surfaces (Levesque et al., 2011; Winfield et al., 2007), and produce forces without needing to ground devices to a table or wall (Culbertson et al., 2016; Winfree et al., 2009). Even commodity vibrotactile displays are increasing in expressiveness, with high-quality actuation a priority in devices such as the Apple Watch (http://www.apple.com) and the Pebble watch (http://www.pebble.com), although often at the cost of painstaking and costly design effort. Touch is now increasingly studied within market research and business strategy planning because well-designed tactile aspects can improve the quality of product opinions and encourage consumer purchases (Jansson-Boyd, 2011), potentially enhancing the overall multisensory experience (Spence and Gallace, 2011). Part of the power of touch is the emotional, visceral (Norman, 2004) value with it has within a design, giving haptics a close relationship with user experience.

In this paper, we use the engineering and human-computer interaction (HCI) definition[5] of "haptic" to refer to one or more perceived sensations of touch; this includes tactile and proprioceptive feedback, active human touch, and passive experience of actuated technology.

### 1.1. Haptic Experience Design (HaXD)

We define HaXD as

*The design (planning, development, and evaluation) of user experiences deliberately connecting interactive technology to one or more perceived senses of touch, possibly as part of a* multisensory experience.

[5] In contrast, in psychology and neuroscience usage, "haptic" refers only to active touching.

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[2] Provided supervision, contributed to research design, writing and ideas.

[3] Collected interview data and field notes, led initial qualitative analysis, suggested initial ideas.

[4] Provided supervision, contributed to writing and initial ideas.

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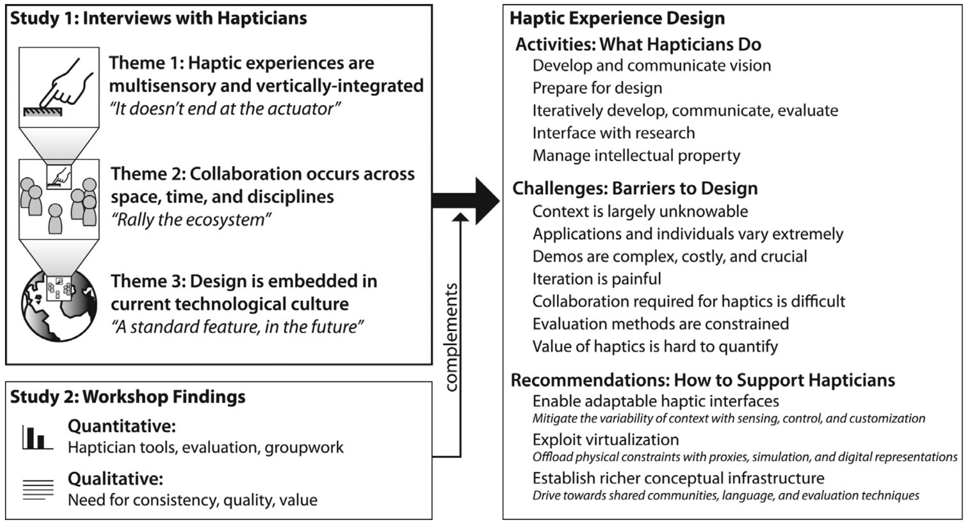



**Fig. 1.** Overview of our process and contributions. Two complementary studies inform a first characterization of haptic experience design (HaXD).

Our focus is on gaining a better understanding of the workflow and processes currently used by *hapticians*, including those related to integrating haptics into a multisensory experience. We define a haptician as *one who is skilled at making haptic sensations, technology, or experiences.* We use this term to capture the diversity of people who currently make haptics, and the diversity of their goals. Many people with a need to design haptics may not have formal design training, and may focus on subsets of the entire experience, e.g., technical demonstrations or creating stimuli for psychological tests.

We describe two studies examining how contemporary hapticians design haptic experiences for use in real-world products. We begin by identifying current obstacles to good HaXD and the target audience for our work, then we provide a roadmap to the rest of the paper. Fig. 1 provides a visual overview of our work.

### *1.2. Obstacles to design*

The academic literature suggests many challenges to design for haptic experience. Haptic content remains scarce and design knowledge is limited. Some issues are technological, such as highly variable hardware platforms and communications latency (Kaaresoja et al., 2014). Other issues are human-centered, arising from individual user characteristics in perception and preferences: low-level perceptual variation (Lofvenberg and Johansson, 1984), responses to programmed (Levesque et al., 2011) and natural (Hollins et al., 2000) textures, sensory declines due to aging (Stevens, 1992; Stevens and Choo, 1996), and varied interpretation and appreciation of haptic effects and sensations (Seifi and MacLean, 2013; Seifi et al., 2015) – often because of personal experience (Schneider and MacLean, 2014), or of the close relationship between touch and other senses.

These research findings are reinforced by many interactions the authors have had with practitioners in industry. Prior to our studies, we suspected that there were many challenges related to haptics, but we found little direct evidence in the literature to back this up and guide our research. As we discovered, hapticians who are free to speak about their work are rare because of intellectual property concerns, which may partially account for the lack of prior work in this area within the literature. Thus motivated, we conducted two studies on the workflows used by hapticians when they were engaged in HaXD – an aspect of design that has been largely unexplored.

**In our studies, we take a first in-depth look at haptic designers' experiences in order to describe HaXD, identify its unique challenges, and connect it to other fields of design** . We focus specifically on HaXD instead of the more general notion of "haptic design," which can also refer to design practices related to haptics not directly involving user experience, e.g., mechanical design of a new actuator or software design of a new control method. Our definition of HaXD encompasses pseudo-haptics (Pusch and Lécuyer, 2011) and other multisensory illusions that compel a user to perceive a haptic sensation in the absence of direct tactile or proprioceptive tic stimulation, or modify their perception of one on the basis of conflicting input in another sense. These represent ways in which haptic design must involve other perceptual modalities, alongside direct motivations to create fully multisensory experiences. Much of what we discuss can also be gainfully applied to the design of tangible interfaces, even with their lack of actuation, although we leave them out of our scope to focus on actuated interfaces. Similarly, we believe many of our findings can inform general multisensory experience design, but limit our claims to HaXD.

### *1.3. Target audience*

We primarily target readers who are one step removed from HaXD, but who have other design, haptics, or business expertise relevant to haptics.

We expect that experienced *haptic experience* design experts will be unsurprised by the insights herein. Although not our primary audience, we hope that the articulated challenges and recommendations will nevertheless still be useful for their practice (particularly for those still early in their learning curve) because it consolidates and extends their *ad hoc* knowledge into a formal framework.

We expect that **non-haptic** *design* experts will find our discussion of the specific challenges to HaXD informative because it reveals processes of design that are invisible or are taken for granted in other fields. We also hope non-haptic designers might lend their expertise to accelerate the generation of tools and techniques for creatively working with these complex interactive systems.

We expect that *haptic* experts engaged in research or device design that is not directly user-facing will develop a further appreciation for how UX design is important for successful haptic technology, and will see ways in which their devices or research findings can be applied in practice. The recommendations we provide may also motivate several avenues of either basic or applied haptic research that these experts could pursue.

We expect that **industry practitioners** who are not experts in any of these fields will gain insight into how the business case for haptic technology might be more quickly built. This includes those already involved with haptics or similar technologies such as wearables, as well as those looking to become involved. We believe our findings may help cultivate connections between the diverse stakeholders involved with HaXD, and that the challenges (and thus the opportunities) that we identify will inspire people to work more with this emerging modality and that researchers and practitioners engaged in multisensory HCI will find parallels in their work.

### 1.4. Roadmap for the reader

In this paper, we describe two studies in which we sought to gain a solid understanding of HaXD as it is currently practiced "in the wild" by actual practitioners (hapticians) in their day-to-day work. After a review of the existing literature in **Section 2** , we report on the first study in Section 3: a grounded theory (Corbin and Strauss, 2008) analysis of intensive interviews with six professional haptic designers. We describe observations of haptic designers' process organized into three cross-cutting themes: the holistic, multisensory, and vertical-integrated nature of the experiences they design; the *collaborative ecosystem* in which haptic experience designers play multiple roles; and the influences of the *cultural contexts* in which haptic experiences are used and the value and risk this poses. In Section 4 we describe a second study conducted as part of a workshop at a major international haptics conference (World Haptics 2015). The second study complements the first by collecting quantitative and qualitative feedback from a broader sector of industry and academic designers regarding tool use, collaboration, evaluation methods, and challenges facing hapticians. In Section 5, we summarize and discuss our overall findings in three major areas:

1. A description of current HaXD practice showing how it has already emerged as a distinct field of design.
2. A list of challenges facing haptic experience designers, and some unique considerations HaXD requires compared to other more established fields of design.
3. Recommendations for accelerating the development of HaXD as a full-fledged field of design.

We conclude with a few remarks imagining what a mature discipline of HaXD might look like in the near future and its role within multisensory HCI.

## 2. Related work

In this section, we discuss key elements of contemporary thinking about user experience design (UX design or XD) and a specific approach known as "design thinking." We then briefly review haptic technology (hardware and software) and relevant aspects of human perception before providing a critical summary of previous efforts to understand and support HaXD.

### 2.1. Design thinking as a unifying framework

Design thinking is an empowering way to approach technology and user experiences. At the heart of this practice is the rapid generation, evaluation and iteration of multiple ideas at once (Buxton, 2007). We observed so much evidence that hapticians practice – or attempt to practice – design thinking, that we found it productive to frame our findings and consider the significant barriers they encounter within its established process. Therefore, to ground our later observations and discussion, in this section we review design activities with relevance for hapticians that have been described in the "design thinking" framework: problem preparation, sketching-like iteration, and collaboration. There are several general design activities that we observed in our participants that reflect design thinking, most notably problem preparation, sketching-like iteration, and collaboration.

*Problem Preparation:*cates of design thinking refer to an explicit problem preparation step preceding initial design (Schön, 1982; Warr and O'Neill, 2005; Shneiderman, 2000), which involves "getting a handle on the problem" and drawing inspiration from previous work. Designers find value in this stage because creative acts can be accurately seen as recombination of existing ideas, with a twist of novelty or spark of innovation by the individual creator (Warr and O'Neill, 2005). This stage draws from the designers' experience, including their understanding of the *domain* (symbolic language of the field) (Csikszentmihalyi, 1996), and their ability to *frame* a design problem to match it to their repertoire – their collected professional (and personal) experience (Schön, 1982). External examples are especially useful for inspiration and aiding initial design (Herring et al., 2009; Buxton, 2007); they can increase creativity, although early exposure to external examples brings a risk of conformity (Kulkarni et al., 2014).

Later in this paper, we describe the evidence we found that HaXD naturally includes a dedicated problem preparation step. For example, hapticians collect requirements from stakeholders and maintain collections of example haptic designs.

*Sketching* is another generally critical design activity that supports ideation, iteration, and evaluation. More general than pen and paper, we refer here to techniques that suggest, explore, propose, and question (Buxton, 2007), including physical ideation (Moussette, 2010). Some researchers declare sketching to be the fundamental language of design thinking, analogous to mathematics being considered the language of scientific thinking (Cross, 2006). Sketching is rapid and exploits ambiguity, allowing partial views 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. It can also support multiple, parallel designs, delaying commitment to a single design (Hartmann et al., 2008; Resnick et al., 2008). The fluidity and *ad hoc* nature of sketching extends to software tools: designers must be able to rapidly undo, copy and paste, and see a history of progress (Resnick et al., 2008).

We later discuss previous techniques for haptic sketching to support HaXD (e.g., Moussette (2010)), and describe barriers to achieving fluidity that our hapticians reported encountering.

*Collaboration* can improve design. Involving more people increases the potential for generating more varied ideas (Warr and O'Neill, 2005), and is recognized as being important for creativity support tools (Resnick et al., 2008; Shneiderman, 2000). Although group dynamics can influence the design process negatively, proper group management often results in more creativity and better designs (Herring et al., 2009), and can even influence the work of crowds (Dow et al., 2012). Collaboration can be categorized by intent, such as informal conversations with colleagues or widespread dissemination (Shneiderman, 2000), or by physical and temporal context: collocated (collaborators in the same location) or distributed (in different locations), and synchronous (simultaneous) or asynchronous (at different times) (Ellis et al., 1991).

We find these categorizations useful in identifying where collaboration can break down for haptic design, especially remotely, asynchronously, and with limitations on informal or widespread sharing. In Section 3.2.3 we present the first data-informed description of collaboration in HaXD.

### 2.2. Haptic perception and technology

Here we provide a selective coverage of the literature on haptics to frame our results and discussion. We also suggest additional sources for more comprehensive coverage. Haptic technology is typically separated into two broad classes based on the complementary human sense modalities: *tactile* sensations, perceived through the skin, and *proprioception*, or the sense of body location and forces; the latter includes *kinaesthetic* senses of force and motion. On the human side these are further subdivided into different perceptual mechanisms, each targeted with different actuation techniques. We review the complexity of the different senses that make up touch, then describe common actuation technologies, focusing on those mentioned by participants in our study. Finally, we review major application areas that use haptics for both utility and emotional value.

Human haptic perception, following our definition in the Introduction, is synthesized from the tactile and proprioceptive senses, and is influenced by vision and hearing. Tactile sensations rely on multiple sensory organs in the skin, each of which detects different properties, e.g., Merkel disks detect pressure or fine details, Meissner corpuscles detect fast, light sensations (flutter), Ruffini endings detect stretch, and Pacinian corpuscles detect vibration (Choi and Kuchenbecker, 2013). Proprioception, the sense of force and position, is synthesized from multiple sensors as well: the muscle spindle (embedded in muscles), golgi-tendon organs (GTO, in tendons), and tactile and visual cues (Kandel et al., 2000). Humans use these senses together to learn about the world, e.g., stroking, bending, poking, and weighing objects in active exploration (Lederman and Klatzky, 1987). Haptic perception is also heavily influenced by other senses. In the classic size-weight illusion (Charpentier, 1891), when two weights have the same mass but different sizes, the smaller is perceived to be heavier, whether size is seen or felt (Hayward, 2016); similarly, sound can affect how a texture feels (Hayward, 2016). Interactive systems can exploit multisensory cross-modal perception to reinforce or improve haptic sensations. To be effective, these effects need to be temporally synchronized, sometimes as closely as 20–100 ms (Kaaresoja et al., 2014). For more information about haptic perception, we direct the reader to Lederman and Klatzky (2009); Kandel et al. (2000); Choi and Kuchenbecker (2013), and Gallace and Spence (2014).

Haptic technology to produce stimuli for humans to feel is at least as diverse as the human senses that feel it. Today, the most common approach is vibrotactile (VT) feedback, where vibrations stimulate Pacinian corpuscles in the skin, e.g., smartphone vibrations. VT actuators can take many forms. Eccentric mass motors ("rumble motors"), affordable but inexpressive, are commonplace in mobile devices and game controllers. More expressive mechanisms such as voice coils offer independent control of two degrees of freedom, frequency and amplitude. Piezo actuation is a very responsive technique that is typically more expensive than other vibrotactile technology. Linear resonant actuators (LRAs) shake a mass back and forth to vibrate a handset in an expressive way; a common research example is the Haptuator (Yao and Hayward, 2010). Currently, LRAs are increasingly deployed in mobile contexts (e.g., the Apple Watch Taptic engine). Our study participants also employ force-feedback, which engages proprioception. Common force-feedback devices include Geomagic Touch (previously the Sensable PHANTOM) and Falcon devices, offering three degrees-of-freedom: force in three directions. At other times, entire screens might push back on the user in a single degree-of-freedom. These are only the most common feedback methods discussed by our participants. Many other types of feedback can be used, e.g., temperature displays (Jones and Berris, 2002) or programmable friction display on touch screens (Levesque et al., 2011; Winfield et al., 2007).

### 2.3. Efforts to establish HaXD as a distinct field of design

Researchers have developed several approaches to support HaXD. Some have directly applied design metaphors from other fields to haptics. Others have built collections of haptic sensations and toolkits that facilitate programming. These approaches have developed focused understandings of particular aspects of HaXD, but they do not adequately describe the process as it is actually practiced.

There are many examples of designers drawing from other fields to frame the practice of haptic design. Haptic Cinematography (Danieau et al., 2014) uses a film-making metaphor, discussing physical effects using cinematographic concepts and establishing principles for editing based on cinematic editing (Guillotel et al., 2016). Similarly, Tactile Movies (Kim et al., 2009) and Tactile Animation (Schneider et al., 2015b) draw from other audio-visual experiences, and Cutaneous Grooves (Gunther et al., 2002) draws from music to explore "haptic concerts" and composition as metaphors. Academic courses on haptics can train people to work with haptic perception, control, and design (Okamura et al., 2012; Jones, 2014). These and other ways of framing HaXD have been incorporated into rapid prototyping techniques that allow for faster, easier iteration of haptic designs. Simple Haptics, epitomized by *haptic sketching*, emphasizes rapid, hands-on exploration of a creative space (Moussette, 2010; Moussette and Banks, 2011). Hardware platforms such as Arduino (arduino.cc) and Phidgets (phidgets.com) (Greenberg and Fitchett, 2001), as well as the recent trend of DIY haptic devices (Orta Martinez et al., 2016; Gallacher, 2016; Forsslund et al., 2015; Bucci et al., 2017), encourage hackers and makers to include haptics in their designs. A recent series of workshops has also encouraged people to work with haptics tools, such as the TECHTILE toolkit (Minamizawa et al., 2012; Nakatani et al., 2016) and Stereohaptics (Israr et al., 2016).

The language associated with tactile perception (terms related to haptic sensation and how they are used), especially affective (emotional) terms, is another way of framing haptic design. Many psychophysical studies have been conducted to determine primary perceived tactile dimensions for both synthetic haptics and real-world materials (Enriquez and MacLean, 2003; Okamoto et al., 2013; Hollins et al., 1993). Language is a promising way of capturing user experience (Hwang et al., 2011; Obrist et al., 2013), and can reveal useful parameters, e.g., how pressure influences affect (Zheng and Morrell, 2012). Tools for customization by end-users, rather than by expert designers, are another place that efforts have been made to understand perceptual dimensions using a language-based approach (Seifi et al., 2014, 2015). However, this work is far from complete; touch is difficult to describe, and some researchers even question the existence of a tactile language (Jansson-Boyd, 2011).

Meanwhile, software developers who want to incorporate haptics into their systems are supported by large collections of haptic sensations and programming toolkits. Sensation collections most commonly support VT stimuli. The UPenn Texture Toolkit contains 100 texture models created from recorded data, rendered through VT actuators and impedance-type force feedback devices (Culbertson et al., 2014). The Feel Effect library (Israr et al., 2014), implemented in FeelCraft (Schneider et al., 2015a), lets programmers control sensations using semantic parameters, e.g., "heartbeat intensity." Immersion's TouchSense SDK (immersion.com) connects to mobile applications, augmenting Android's native vibration library with both a library of presets and, on some mobile devices, low-level drivers for effects like fade-ins. VibViz (Seifi et al., 2015) is a free online tool with 120 vibrations organized around five different perceptual facets. Force-feedback environments tend to be supported through programming toolkits. CHAI3D (chai3d.org), H3D (h3dapi.org), and OpenHaptics (geomagic.com) are major efforts to simplify force rendering. Table-top haptic pucks can use the HapticTouch Toolkit (Ledo et al., 2012), which includes parametric adjustment (e.g., "softness") and programming support.

Finally, several software-based editing tools support haptic design for different devices. These tend to focus on VT stimuli or simple one-degree-of-freedom force feedback. Many haptics editors (Enriquez and MacLean, 2003; Swindells et al., 2006, 2014; Ryu and Choi, 2008; Meyer et al., 2016; Schneider and MacLean, 2016) use graphical mathematical representations to edit either waveforms or profiles of dynamic parameters (torque, frequency, friction) over time. Of these, Vivitouch Studio (Swindells et al., 2014) offers the most integration with other modalities in game environments. The web-based Macaron system (Schneider and MacLean, 2016) is an opportunity to observe the effect of high availability. The Vibrotactile Score (Lee et al., 2009) uses a musical metaphor, shown to be preferable to a programming metaphor as long as the designer has musical experience (Lee and Choi, 2012). Mobile "sketching" tools like the Demonstration-Based Editor (Hong et al., 2013) and mHIVE, a Haptic Instrument (Schneider and MacLean, 2014) are useful for exploration, but not refinement. Since iOS 5 (2011), Apple has let end-users create on/off vibrations as custom vibration ringtones but provides no control over amplitude. Immersion's Haptic Studio lets users design tactile effects from primitives and effect libraries for rendering on a wide variety of devices, including mobile devices. Actuator sequencing (Panëels et al., 2013), movie editing (Kim et al., 2009), and animation (Schneider et al., 2015b) metaphors enable multi-actuator, spatiotemporal VT editing.

Some of these tools are founded in an understanding of haptic designers' needs (Schneider et al., 2015b; Swindells et al., 2014), e.g., displaying multisensory feedback; they begin to capture a slice of the HaXD process (Schneider and MacLean, 2016), but none fully captures the context and activities of contemporary haptic design.

## 3. Study 1: interviews with hapticians about HaXD in the Wild

In this section, we present findings from our first study, a qualitative analysis of interviews with six professional hapticians.

### 3.1. Method

We recruited hapticians in industry through our professional networks, by asking them to discuss aspects of their experience that their institutions' confidentiality practices did not preclude. The third coauthor, trained in interviewing techniques, interviewed the participants in April-May 2012 using structured qualitative inquiry techniques over a video conference link. Each interview lasted 30–60 min and consisted of initial ice-breaker and general open-ended questions. To both cover our initial research questions and allow for emergent findings, interviews were semi-structured: a single set of prepared questions was asked, from most general to most specific, but the interviewer flexibly and opportunistically followed up on interesting points as they arose. Details about the interview protocol are included in the supplementary materials.

#### 3.1.1. Participants

Six participants were recruited, 5 male and 1 female. We sought a diverse, representative set of participants, but found it extremely difficult to find professional hapticians who were available to speak about their work. Our participants were those we could reach through our professional networks, word of mouth, and online profiles. From an initial set of 11 potential contacts, we found three of our participants; we were eventually referred on to the other three.

We describe each participant in terms of experience and training, area of focus within HaXD, types of projects, and constraints or other factors that might situate or provide insight into the interview. Experience and position are reported as of the interview year (2012). **P1** (M, over 15 years of human factors experience, PhD) held a design and human factors position at a major healthcare company. He worked with auditory alarms, signals, and emotional experience. Despite a focus on audio, he frequently related his work to haptics and described the haptic and audio processes as being the same. P1 used a number of psychology and human factors techniques, such as semantic differential scales, factor analysis, and capturing the meaning that users find in haptic sensations.

**P2** (M, 5–6 years in haptics, PhD) described two projects: his experience adding mechanical feedback to touch screens at a major automotive company, and his PhD work on remote tactile feedback, where feedback was displayed on one hand while the other interacted with a touch screen. P2's main concern is "rich feedback", to communicate information such as affordances to the user. P2 focused on button presses on a touchscreen, rather than exploring "roughness" of a touchscreen or other surface.

**P3** (M, 10 years leadership experience with actuation, sensing, and multimedia, MEng) worked at a company that sells actuators used to add haptics to technology (like a tablet computer, game controller, or mobile phone). P3 had 20–30 projects going on at any time, each with their own size, goals, constraints, and contexts.

**P4** (M, 11 years of design, development, and analysis/simulation experience, PhD) also puts actuators into new form factors (e.g., touch screens in cars).

**P5** (M, 12 years of haptics UX experience, MSc) held a user experience leadership position at a major haptics company that sells haptic control technology and content; he described mostly software solutions. His company worked with different domains, but most examples are from mobile phones (handhelds), with a brief mention of automotive haptic feedback.

**P6** (F, 5–6 years in haptics, PhD) worked at a major car manufacturer. She primarily designed "feel" properties such as friction, inertia, and detents of physical controls inside automobiles. P6 also works on active haptic controls.

#### 3.1.2. Analysis

One researcher (the first author, trained in qualitative methods), analyzed the transcripts of the interviews through grounded theory (Corbin and Strauss, 2008), influenced by phenomenology (Moustakas, 1994) and thematic analysis (Ryan and Bernard, 2003). The researcher first transcribed interviews and then examined every participant statement, tagging each with relevant and recurring concepts and keeping written notes for reflection and constant comparison. Emergent sub-themes (sub-categories) (Ryan and Bernard, 2003) were discovered using qualitative techniques of memoing, iterative coding (Corbin and Strauss, 2008), and clustering and affinity diagrams (Moustakas, 1994). Statements were later grouped according to tags, organized using affinity diagrams and clustering, and iteratively developed with further writing and reflection. The 15 sub-themes clustered into three themes (categories) (Corbin and Strauss, 2008; Ryan and Bernard, 2003). We describe the themes in Section 3.2 after an introduction to the designers themselves and the procedure that was followed for the interviews. We delay a detailed discussion of the results until Section 5 so we can include the findings of the second study, presented in Section 4.

Interviews with P2-P5 were fully recorded and transcribed. Interviews with P1 and P6 were collected only as interviewer notes. In the presentation of our findings, double quotation marks ("…") denote direct transcription quotes for P2-P5 while single quotation marks ('…') denote interviewer notes for P1 and P6. We use qualitative reporting techniques such as rich or "thick" descriptions (Geertz, 1973), in-vivo codes where participants' actual words are used to describe concepts (Corbin and Strauss, 2008), and quotations to provide the reader with a sense of verisimilitude and to give our participants a more direct voice. For example, we retain P3's colloquial term "guts" to refer to the tightly-coupled internal components of a system (Section 3.2.2/Ex1).

### 3.2. Results

Most of the emergent themes that we identified persist throughout the design process (Fig. 2). We found participants generally followed a process typical of experience design (UX) (Buxton, 2007) in which they initially tried to gain an understanding of the design problem, then iteratively developed ideas and evaluated them. We first outline these confirmatory observations about process, then report on the themes, which comprise our main findings. Throughout, we cross-reference themes by section number and theme label (e.g., 3.2.2/Ex1).

#### 3.2.1. Observations on design process

Participants described the initial stages of a project as a time to establish and understand requirements, gather initial design concepts, and define or negotiate project parameters. Designers often collected examples of haptics, such as mechanical buttons and knobs, for inspiration (Section 3.2.3/Co5), and they gathered requirements – both direct requirements for haptic designs (Section 3.2.4/Em1), and project parameters around the value, cost, and risk of haptic technology (Section 3.2.4/Em4,Em5).

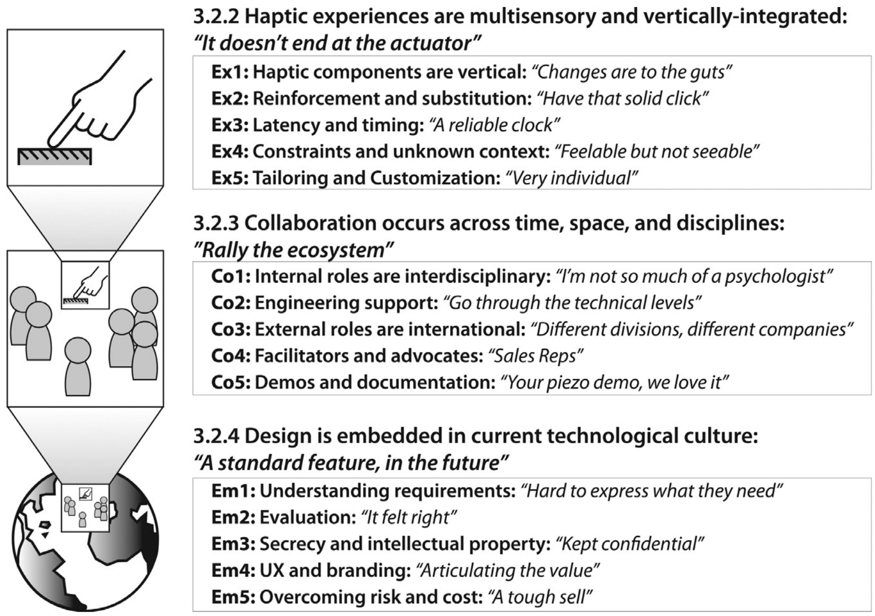



**Fig. 2.** Our three themes, each exploring different levels of scope through 5 emergent sub-themes.

P2-P6 explicitly referred to an iterative process. They all found different ways to fit it into their collaborative ecosystem and constraints. As we elaborate below, prototyping and assessment in the physical medium of haptics has many challenges that set it apart from graphical or auditory domains even as designers navigate very common-place objectives. For example, initial requirements were often not actually what clients wanted, so our designers would have to iterate (Section 3.2.4/Em1). P5's teams explicitly follow a conventional user-centered design process, iterating simultaneously on prototypes and their understanding of customer needs. P3 sometimes has to ship mockups and devices back and forth with their customers (Section 3.2.3/Co5). Each design problem faced by our participants had to be treated as a unique problem, with designers fine-tuning their design to fit the problem (3.2.2/Ex5). Our designers used a variety of evaluation techniques to choose their final designs (3.2.4/Em2).

We now proceed with our cross-cutting themes, organized by scope (Fig. 2): the haptic experience and its implementation (Section 3.2.2), the designers' collaborative ecosystem (Section 3.2.3), and implications from the wider cultural context of haptic technology and business requirements (Section 3.2.4).

### 3.2.2. [Theme Ex] Haptic experiences are multisensory and vertically-integrated: "It doesn't end at the actuator"

Context affects user experience at multiple levels, but this is difficult for a designer to foresee or control. Aspects of context range from the immediate, very local electromechanical environment (material properties, casing resonance, computational latencies), through the user's manner of touching the haptic element (grip, forces, longevity of contact), to the user's momentary environment, attention, and goals.

At the local end, the complexity of the haptic sense itself is a major factor in expanding the haptic experience design space substantially beyond what are usually its initial requirements – for example, for the changing feel of a modal physical control in an automobile cockpit. As we have discussed, the haptic sense is really a collection of subsenses (Kandel et al., 2000; Choi and Kuchenbecker, 2013), working together to construct an overall percept, e.g., material properties deduced from stroking, tapping, or flexing a surface or object (Lederman and Klatzky, 1987). Grip, materials, dynamics as well as visual and audio aspects all play a part in the result.

> "*The problem is it doesn't end at the actuator, there's a lot to do with the case of the device, the mass of the device, the mechanical coupling between the device and the hand…this all comes into play because it's a tangible experience, and so if there's [sic] mechanical resonances that get stimulated by the actuator that make it sound noisy, then it becomes a cheap experience, even if it has a piezo actuator*" (P5).

Thus, designers both face multifaceted constraints and have opportunities to circumvent those constraints. We begin by discussing implications for implementation, wherein haptic components are directly related to the internal mechanics – the "guts" – of the system (Sub-theme Ex1). Then, we move on to opportunities for improving design: strategies like reinforcement and substitution are powerful tools for haptic designers (Ex2). Timing is critical, enabling the abovementioned opportunities while imposing constraints: designers must introduce no new delays and carefully synchronize feedback (Ex3). However, the full extent of a sensory context is sometimes uncontrollable or unknown, and at such times prevent designers from using their tricks (Ex4). We finish this section by discussing how haptic experiences are often bespoke, tailored to constraints of known contexts, or customizable to unknown contexts (Ex5).

**Ex1**: **Haptic components are vertical:**"*Changes are to the guts*". Haptic experiences are created when the actuating component physically interacts with other system components. Changing a haptic component can thus affect the entire system's design, unlike many other upgrades, such as improving memory in a mobile phone: *"you get the impression every other month they have a new phone…but the guts of it do not change much"* (P3). New phones often just have a faster CPU or more memory swapped into an essentially unchanged system; but when adding or modifying haptic components, designers must consider the entire system including the physical casing, and possibly modify it as well:

> "*First we had to get the outer dimensions [of the prototype's case] roughly about right, to get the visual impression close to what it resembles later in the application*" (P4).

This effect is bidirectional. Changing the size or material of the casing can have a profound effect on the sensation; correspondingly, any changes to the haptics will have an effect on the entire structure of the device. Changes to software are also cross-cutting: *"we're digging into the source code of Android…we need to make sure that we have the right hooks in the right locations…that's a software architecture issue, right?"* (P5).

**Ex2**: **Tricks to create great feels**: "*Have that solid click*". Haptic designers have an array of techniques to create great experiences, working around constraints and uncertainty. The first step is to have a fast, responsive actuator when possible. Previously, creating good actuators was a goal for our participants: *"[what we] strived in the past significantly to do was to push the market towards high mechanical bandwidth actuators, so actuators that can respond in 15 ms or less"* (P5). Now, high-quality actuators are a main competitive advantage:

> "*High-definition feels [which are rendered] over a very broad frequency range, with enough strength and small enough, and especially very fast response time, that's our business*" (P3).

As discussed in Ex1, the actuator does not determine the experience alone, but interacts with physical materials and non-haptic senses. When a haptic device's ultimate situation is known at design time – such as a car dashboard – designers can modify properties of the larger physical system to improve the overall haptic experience: '*metal makes unwanted sound, so change it with a plastic*' (P6). The designer can also make a sensation more convincing with multisensory reinforcement, e.g., adding visual or audio feedback:

> "*Need to have that solid [haptic] click at 150 [Hz] plus some audio at 300 or 400 Hz, which is going to give you that sense of quality, and consistency, across the whole dashboard*" (P5).

When a known physical context has constraints, designers can use substitution to enable or improve the haptic interaction. P2 describes two such occasions, one for sensing input and one for displaying output. Because P2 could not sense input pressure, he instead used how long the user was pressing the screen ("dwell time"): *"we were substituting the forces that are needed on the actual buttons with dynamic dwell times"* (P2). This was only possible because P2 had knowledge of *how* the user would be touching the control, and thus could deduce that dwell time was a reasonable proxy for pressure. In another case, P2 could not actuate a touch screen, so he used tactile feedback on the other hand – again, requiring knowledge of and considerable design access to the device's and user's larger situation, in this case the steering wheel of an automobile.

**Ex3: Latency and Timing**: "*A reliable clock*". One underlying requirement for great haptic experiences is responsive timing. Feedback must be fast; modalities must be synchronized. Effective reinforcement requires simultaneity and hence tight (millisecond) control over timing. This is well established in the literature (Levitin et al., 2000; Kaaresoja et al., 2014) and known to our designers: *"I think audio feedback and tactile feedback and visual feedback has to happen at a certain time to have a real effect"* (P2).

Latency accumulates throughout the computational pipeline, with actuator responsiveness the very last stage and rarely the most impactful. Designers must minimize computational delays wherever possible. P2 describes unintentionally adding latency to one project: *"we had this Python program and Arduino and all this communication going on"* and how he *"threw out some of the serial communication which [had] made the whole thing a little slow"*, and thus, the *"latency again felt right"*. Timing problems between components can happen at any time: *"we've gotten in situations before where we've been very near to completion in design projects, and for whatever reason we can't get a reliable clock, from the CPU, then the whole thing falls apart"* (P5).

When simultaneity constraints are met, the user perceptually *fuses* these non-collated events (activating a graphical element on a screen, and feeling a tick on the steering wheel) into a single percept: *"somehow you connect these two things, the action with the dominant hand and the reaction that is happening somewhere else"* (P2). Haptic designers thus need access to the computational pipeline to circumvent physical constraints with multisensory tricks.

**Ex4**: **Unknown user constraints and context**: "*Feelable but not seeable*". Haptic designers sometimes contend with unavoidable constraints emerging from physical context or the application space. Some constraints not only limit multisensory synergies, but go on to actively limit haptic display. For example, eyes-free interaction in cars means that visual reinforcement is unavailable; indeed, visual movement may have to be avoided altogether for safety reasons. P4 is tasked with creating a *"feelable but not seeable"* sensation to *"avoid having to use visual feedback"*, because *"driver distraction is always a big topic"* (P4). This means P4 has limited control over his designed haptic sensation, as it cannot visibly move, but P4 can use audio reinforcement or substitution to handle constraints.

Perhaps even more difficult is when the experience's context is unknown. This can derive from at least two sources: protection of intellectual property (IP) through secrecy, and unconstrained end-user situations. Stakeholders often keep key contextual information such as the visual interface secret from third party designers (e.g., OEMs [original equipment manufacturers] or consult ants): *"we can suggest components, and suggest characteristics of the HMI [human-machine interface] system, but the exact visual design of the HMI system is the OEM's knowledge"* (P4). P3 has an *evaluation kit* to send to potential customers when customers' IP is a concern:

> "*[An evaluation kit is] basically a little box that consists of our actuator and some electronics, and that box is connected and driven through the USB port of a computer, and you can then mechanically integrate the box in your own way, so we don't need to know what their design looks like*" (P3).

We discuss IP and secrecy more in Section 3.2.4/Em3. Meanwhile, the lesson here is that designers must deal with sometimes unknowable end-user context, especially with mobile scenarios. A high quality LRA-type actuator on a metal table can sound cheap, while an affordable eccentric mass actuator can sound like purring if it's on rubber, and *"there's not much you can do from a haptic perspective, other than allow the user to turn it up or down"* (P5).

**Ex5**: **Tailoring and customization:** "*Very individual*". Because the context of haptic technology can vary so much, haptic designs need to be tailored for each client's problem and are often made customizable for end-users. For the former, several participants' business models are directly based on tailoring. P4's group makes a small set of actuators, adapting them to each specific request. This is exacerbated because it is *"hard for [customers] to really express what they need"* (P4) (discussed more in Section 3.2.4/Em1) so designers must rapidly and collaboratively fine-tune their solutions (Table 1).

Even if customer goals are clear, tailoring is necessary because of other requirements (e.g., branding or *"trademark"* (P2), 3.2.4/Em4) and hardware setup: *"it's important to tune the experience depending on whatever kind of motor they decide to put in"* (P5).

> "*Depending on the outer design, what's given to us by the customer, we have to choose the direction of movement. For some applications, for some ideas, it's possible to move the surface directly perpendicular, away from the user, and other applications, you have to move the surface perpendicular towards the user, so the same actuation module could feel completely different*"(P4).

Meanwhile, individual differences of end-users further complicate matters: *"feeling right is…something that is very individual"* (P2). As P5 mentioned, volume controls can help end-users and adapt to unknowable context.

### 3.2.3. [Theme Co] Collaboration occurs across space, time, and disciplines: "Rally the ecosystem"

In this section, we describe the collaborative ecosystem for HaXD. First, we provide an overview of group structure and interdisciplinary roles found in our participants' groups (Sub-theme Co1), including a focus on the role of engineering (Co2). We then discuss the dispersion of stakeholders internationally and in different organizations (Co3), including a focus on the connecting role of sales representatives, and the use of demos and documentation (Co5). We distinguish the

**Table 1**
Sub-theme summaries for Haptic Experiences (Ex1) theme.

| Code | Sub-theme descriptor | Explanation |
|---|---|---|
| **Ex1** | Haptic components are vertical | Changing a haptic component may influence the larger hardware/software system, and vice-versa. |
| **Ex2** | Tricks to create great feels | Haptic designers can improve designs and work around constraints through multisensory tricks. |
| **Ex3** | Latency and Timing | Without fast feedback and synchronized timing, haptic experiences fall apart. |
| **Ex4** | Constraints and unknown context | Other modalities may impose constraints; constraints may not always be knowable. |
| **Ex5** | Tailoring and customization | Designers tailor their solutions to each application; end-users benefit from customization. |

**Table 2**
Sub-theme summaries for the Collaboration (Co) theme.

| Code | Sub-theme descriptor | Explanation |
|---|---|---|
| **Co1** | Internal roles are interdisciplinary | It takes a multidisciplinary team to create a haptic design. |
| **Co2** | Engineering support | Prototyping is necessary and often delegated to engineers. |
| **Co3** | External roles are international | Haptic design teams work with other stakeholders around the world. |
| **Co4** | Facillitators and advocates | Sales reps handle demos and fight for a deal. |
| **Co5** | Demos and documentation | Designers often show instead of telling. |

Collaboration theme (Section 3.2.3) from the Cultural Context theme (Section 3.2.4) by focusing on specific communication methods and roles rather than underlying values and widespread public consciousness (Table 2).

All six participants indicated collaboration was an important part of their work and design process. Haptic designers are part of interdisciplinary, international teams, and do not make haptic experiences alone:

> "*We basically have to rally the ecosystem…we have to go and find, y'know, somebody to supply the amplifier part, somebody to make the motor, somebody who knows enough about the Android kernel…we have to be, kind of, Renaissance men if you like*"(P5).

**Co1: Internal roles are interdisciplinary:** "*I'm not so much of a psychologist*" Haptic design is interdisciplinary; hardware, software, psychology, and business all play a role. P5 describes his company's job as *"rallying the ecosystem"*, finding diverse expertise and establishing a production chain. P6 describes different roles in her team, who work more closely together at different stages: '*user [research], design, ergonomics, haptics, electronics, all come together*' (P6). This is reflected by the diverse internal roles (Table 3), but also in the diverse work in single projects by individuals:

> "*We do some mechanical integration work, we help [our international customers] with designing the electronics, we have reference designs there, we have a couple of reference effects, and then we ship the part back and they go on with further doing the software integration and designing the haptic effects*" (P3).

Our participants worked in groups of various sizes. P2 worked with a student in a team of 2, while P5 describes several teams: design, UX, engineering, each with different responsibilities. This collaboration can be collocated or remote: P6 describes the different divisions in her company as being physically close together, while P3 has sales representatives (*"reps"*) overseas to help with external collaboration.

Especially in smaller groups, team members fill multiple roles. Sometimes this falls naturally into their background: *"I guess [phone vibrations are] similar to mechanical control design, except that it's all virtual"* (P5). Otherwise, this lack of expertise reduces confidence: *"I don't know, I'm not so much of a psychologist to really, to dare to say I can evaluate subjective responses to tactile feedback"* (P2).

**Co2: Engineering support:** "*Go through the technical levels*" Larger groups are able to have more specialized individuals. Especially common was a dedicated engineering or technical support team, tasked with implementing prototypes for design and user research teams.

> "*In our design research team we don't do any internal prototyping, we rely on engineering resources to do all our prototyping*" (P5).

P5's group says that neither the design team nor the UX team build prototypes, though the UX team facillitates and evaluates them. P1's team is similar: '*give qualitative feedback and ranges to the technicians*' (P1). Engineering departments are sometimes '*physically very close to other departments*' (P6), presumably to interact with different divisions and groups. However, separating expertise can cause gulfs of collaboration, e.g., when P3 tries to propose a deal:

> "*If you try to go through the technical levels from a technology scout to a technical manager and then maybe to a senior manager, you usually get blocked with something, because nobody wants to take the risk or the blame*" (P3).

Those in engineering roles are risk-adverse: *"[it's] risky to suggest changes to their component"* (P3). P3 says that to pitch to other companies, you need to reach *"C-level people"* like the CEO, or other business or manager types: *"engineers look at it from a perspective well I'm going to take a risk if I change something in my design, and if it doesn't work everybody's going to blame me"* (P3), '*technicians won't give pushback if there is a problem*' (P1).

**Co3: External roles are international:** "*Different divisions, different companies*" Haptic designers also worked closely with external stakeholders like potential customers and manufacturers. Our designers have diverse suppliers, especially hardware suppliers, and often sell to manufacturers who then sell their own product to the end-user. Table 4 provides details on these external-facing roles.

> "*Automotive is very much a tiered and compartmentalized manufacturing business, and so the person who makes the control surface is different than the person who makes the mounting for it…and those people often never talk to each other, and so for us it's even worse than different divisions in a company, it's different companies*" (P5).

Often these groups are distributed internationally. P5's group, based in North America, received international demographics to research: *"here's phone X from OEM Y and it's targeted at Asian ladies from 15 to 30 years old"* (P5). P3, who has a headquarters in the North America and clients in Asia, describes *sales reps* as critical team members who can bridge language and cultural barriers (Table 5).

**Co4: Facilitators and advocates:** "*Sales reps*". P3 describes sales reps in-depth as key team members. Sales reps are trained locally at headquarters in North America, then are sent to the customers' area, often in countries like Korea, Japan, China, and Taiwan which have large consumer electronics and gaming markets. It is important that they speak the local language and understand the local culture; they also facilitate demos and persuade customers to pursue business with the designer's team. If a demo is sent to a company without a sales rep, customers may respond by shipping the device back and requesting assistance, but often they don't respond at all:

> *"If we try to just ship them a part…in the best case they come back and say well it doesn't work as we thought, can you help us?…in the worst case they don't even contact us back and we never learn why they didn't pursue an idea or an opportunity. It's still a complicated setup to make haptics work, there's lots of aspects that you have to take into*

**Table 3**
Internal roles, the various descriptors used to label them, and descriptions. Roles were grouped and named by the authors based on participant-provided descriptors.

| Role | Descriptors | Description |
|---|---|---|
| UX | User division (P6), User research (P5), Ergonomics (P6), Human factors (P1), Psychologist (P2,6) | The UX team does research: '*facilitate prototypes, validate, communicate those results*' (P5). Here we include psychologists and human factors roles because they conduct user research such as evaluation: '*psychologists there who do usability tests*' (P6), '*study how effectively how users interact w/ goals*' (P1). |
| Design | Design team (P5) | Related to UX but a separate and in some ways higher-level role. The design group ideates and communicates vision, developing a value proposition. Designers usually have a similar background to the UX group (P5). |
| Engineering | Tech manager (P3), Engineering (P3,5) Electronics, mechanics, tech team (P6) | Often a separate division, handling prototyping and implementation (P5). They might test components, do physical construction, take requirements from design, ergonomics, electronics, mechanics, etc. and generate required (haptic) feedback (P6). This can involve both hardware and software. |

**Table 4**
External roles, the various descriptors used to label them, and descriptions.

| Role | Descriptors | Description |
|---|---|---|
| Connections | Sales rep, technology scout (P3) | Sales reps from haptic companies handle local expertise (language and culture), haptics expertise (they run demos), and can be advocates for products. Technology scouts from large companies talk to haptics companies to learn their technology. |
| Business | Business dev people, C-level people (P3) | Internal business development people are *"here [in HQ]"* (P3), while external business people make decisions; they're who you need to persuade, rather than technology-focused roles. |
| Supply chain | Vendor, developer, manufacturer, OEM (P5), supplier (P4,6), content provider (P3) | Haptic designers are heavily embedded in a supply chain involving hardware and software manufacturers. Some manufacturers provide hardware (e.g, actuators) and software (e.g., Android API) to the haptician, others are the intended customer (phone or car manufacturers, software developers). It is unclear who creates haptic content in this ecosystem. |

**Table 5**
Sub-theme summaries for the Embedded Context (Em) theme.

| Code | Sub-theme descriptor | Explanation |
|---|---|---|
| **Em1** | Understanding requirements | Customers and designers have trouble articulating and understanding goals. |
| **Em2** | Evaluation | Getting experiences to feel right, usually with acceptance testing and deployment. |
| **Em3** | Secrecy and intellectual property | Haptic technology and sourced components are often cutting edge and secret. |
| **Em4** | UX and branding | Tactile experiences provide intangible benefits. |
| **Em5** | Overcoming risk and cost | Haptics are risky and expensive to include in a product. |

> *account, and if you don't do it properly, you're going to be most likely very disappointed about what the outcome is"* (P3).

Big tech companies sometimes invert this from a push model (where the haptics company uses a sales rep) to a pull model with tech scouts (who reach out to haptics companies). Sometimes, companies fill this role without dedicated sales reps: P4 goes to customers regularly in confidential meetings, receiving specifications and working collocated with the customer to get their product to feel *"just right"*:

> "*There is always [the] option, as we did with one of our customers, that we simply went into the lab for a day or two, and just worked on simulated button feel, together with the customer, to get the feel just right*" (P4)

In all cases, content can fall through the cracks. P3's company provides technology, but *"the issue that we are having with uh, the content providers that need to get interested and believe in it…creating the haptic effects is something that we haven't been involved in a lot of detail in the past"* (P3). P5's company does have a set of 150 effects, from which they select themes. The other participants all mention technology they develop, with content directly related to their hardware solution.

**Co5:** "*Your piezo demo, we love it*" Demos are essential to showing both the value of a haptic experience and enabling two-way communication with the customer. They can clarify requirements and grab attention from clients: *"we'll often get the OEMs who will say, well you showed us your piezo demo, and we love it, it feels great"* (P5). Demos can be conducted in-person (synchronously) at events like tech-days or one-on-one meetings: *"the customer either comes directly to us, we go towards our customers regularly, have our tech days, similar to automotive clinics"* (P4), or asynchronously, remotely shipped.

However, demos are complicated and need an experienced handler like a sales rep. Once set up, demos are often adjusted, but this is easier than the initial setup: *"From the moment the actuation module was working…it was just cranking up the maximum current or reducing the maximum current"* (P4).

Demos are often collected into groups. P5 describes downloading apps that use his technology and *"sticking those in [their] demo suite"*. P1 and P2 talk about collecting examples for inspiration and guidance early in design: it's *'quicker to go out and buy examples'*, like '*15 or 16 appliances that had notably different feelings*' (P1). P2 instructed his student to *"collect physical push buttons just to get in contact with all the diversity of stuff."* He ended up with a *"button board"* to guide design. He also talks about company guidelines:

> "*When I was at [a major automotive company] 3 years ago…they had this guideline book…they had guidelines on the design of physical widgets like sliders, physical sliders, push buttons, rotary things…they defined thresholds basically where these forces have certain thresholds and if you get over the threshold something is happening*" (P2).

Demo setups can thus be stored long term for internal documentation (button board, guideline book), but they can also be ephemeral (tech days). In both cases, they can help to articulate the value, especially now when most people do not yet understand haptic technology.

#### 3.2.4. [Theme Em] Design is embedded in current technological culture: "A standard feature, in the future"

Haptic technology has yet to fully penetrate the public consciousness. Participants reported major difficulty when working with both customers and users, including a limited understanding of what haptic technology is and how to work with it:

> "*People really don't know what to do with [haptics] and I think within the haptics community we need to…continue to push it into the market, but once it's there I think it's going to add to the user experience and will be a standard feature in the future*" (P3).

Specifically mentioned were the difficulty in understanding customer requirements (Em1), and knowing how to appropriately evaluate haptic experiences (Em2). As in many technological fields, secrecy and intellectual property are important concerns for both designers and customers (Em3). Designers had ways to pitch the value proposition of haptics, often tied to UX and branding (Em4), but risk and cost of adopting the technology often make it a hard sell (Em5).

**Em1: Understanding requirements:** "*Hard to express what they need*". Customers found it difficult to both understand and request their needs. Our participants focused on the end result because it gives them and their colleagues the ability to solve problems: 'Don't specify elements. Only give end product. Don't tell how to restrict; can give hints' (P6). However, requested end-results are often vague or confusing, like *"good variable feel"* (P4):

> "*The customer only came with a question, yeah, how [can the design] feel variable? Here it did not really describe how it should feel variable*" (P4).

To make these impressions concrete, customers initially give engineering parameters as their best guess. P4 in particular talks about his customers, who might point to a *"reference button which is available directly on the market, from companies like [company 1] or [company 2], and they say it has to feel exactly like this button"*, or request *"a surface acceleration of 10–20 G perpendicular and a travelling distance* of 0.2–0.3 *mm"* (P4). This might have little relation to the final result, after the designers iterate with the customer: *"we ended with an acceleration of 2 G and a travelling distance of 0.4 of a mm, so, due to the size of the module, simply, the high accelerations were too high for a good variable feel"* (P4). The goal function of good variable feel was achieved, but the initial engineering-level specification was completely off.

Other participants showed this duality between high-level affective goals and low-level guesses. P1 especially used affective and psychological terms when considering design, such as semantic differential scales: '*good/bad; gender (robust/delicate; size); intensity (sharp/dull; bright/dim, fast/slow); novelty*' (P1). Haptic designers often connected low-level/high-level terms through iteration, or with their own way of representing features like quality: *"[audio click gives] quality, and, consistency across the whole dashboard"* (P5), '*mass is big for quality…for the haptics, nice feedback w/ good snap gives a sense of quality*' (P6).

**Em2: Evaluation:** "*It feels right*". Our designers all evaluated their designs but demonstrated different methods of evaluation, consistent with our workshop survey (Section 4). P2 explicitly evaluates both low-level, pragmatic concerns (e.g., task accuracy and speed) and high-level affective concerns like feeling personally involved using the AttrakDiff questionnaire (Hassenzahl et al., 2003, http://attrakdiff.de). P5's user experience team conducts validation, but P5 was unable to share details. Small-scale acceptance testing was employed by both P2 and P4: when iterating in-person with the customer, P4 kept iterating until the customer said it *"felt right"*; P2 only had himself and his student evaluate their designs in an academic context, despite indicating a desire to do a more thorough evaluation. P3's group doesn't create content, but indicated a desire to look into that and investigate it with studies.

Our participants expressed a clear desire for stronger evaluation, but reported mostly lightweight, *ad-hoc* acceptance testing. This is consistent with our workshop findings, which suggest little real-world or in situ evaluation. One reason may be that standard evaluation tools need to be adapted for HaXD. P2 describes having to *"throw out"* terms on the AttrakDiff questionnaire that did not fit, and iterate on the questionnaire. However, deployment seems to be a natural way to see if the design is good enough, as the ultimate acceptance test. P5 described the most memorable moment of his software project being when his product had been deployed and used by a software development team. Seeing a haptic-enabled app available for download, and feeling his creation in context, was impressive to him:

> "*I think the most memorable day was when we started downloading apps, and realized that, yes, in fact this does work, and not only does it work but it works pretty well for a variety of apps… we ended up just sticking those in our demo suite even though we had no relationship whatsoever to the developer. So, their app just worked, and it worked really well*" (P5).

**Em3: Secrecy and intellectual property:** "*Kept confidential*". Sometimes the customers do not know what they want; but in other cases, they do but also have important information they need to withhold. As mentioned in Section 3.2.2/Ex4, secrecy in haptics has major implications that inhibit design, especially given the verticality of haptic technology:

> "*Somebody wants to design a completely new gaming controller for a gaming console, so they might just have some CAD drawings or they might have something they don't want to share with us, so in that case we provide them an evaluation kit…we don't need to know what their design looks like, they can really work on it internally*" (P3).

P3's clients are able to receive an '*evaluation kit*' and create content with audio editors. P4 describes meetings with customers that preserve confidentiality: *"on these tech days it's usually only one customer and not that many suppliers at the same time, sometimes only the customer and us, to make sure our development is kept confidential"* (P4). Once technology of P4's company is on the market, it is no longer secret – rivals can copy or reverse-engineer the devices, so there are many demonstrations to customers before release of the tech. P4 wants to show their technology to potential buyers, not to competitors.

Secrecy can cause delays for software too. P5 delivers a modified Android kernel to his customers, who are software developers. However, P5 often has not been given an early release of new Android versions, which causes delays in delivering the modified kernel. P5's group thus *"always lags the market by two months at least…it's annoying because as soon as the OEMs get the source code they want to put it in their product right away"* (P5).

**Em4: UX and branding:** "*Articulating the value*". Our participants were all passionate about haptic technology and its benefits. The value of haptics can be connected to better performance on various tasks: P2 tried to *"support people interacting bimanually to find out if they are more accurate in drag and drop tasks, [or] faster"*, but also whether they would *"feel more personally involved in the interaction somehow"* (P2). This latter goal, of user experience or rich feedback, was seen as the primary value for haptics:

> "*It's like having a touchscreen now on smartphones which nobody expects any other way anymore…sometimes pull out my old, uh, tom-tom navigation device in my car, and that one didn't have a touch screen back then (P3 laughs) so I tap on that one [expecting it to respond to touch input], and so it's the same thing with haptics, at some point it's just going to expect that you get some nice haptic feedback, but getting there is still a couple of years out*" (P3).

Of course, *"a couple years out"* has already gone by as of the time of this writing; and indeed, haptic feedback is now normal and expected in many touchscreen products, although quality and range continue to be challenging.

As noted in Section 3.2.2, tailoring and customization are important for each implementation. This is also true for value: differentiable sensations are important to help distinguish overall user experience and provide branding. '*look for alarms that were different; effective, but different*' (P1). Companies and products need to have both a cohesive and differentiable feel. P2's company *"guideline book"*, which defined force profiles for buttons, was helpful to *"coin a trademark"* (P2).

> "*[We] provide differentiated tactile experiences to our customers, who are major mobile phone manufacturers. Since Android is pretty generic across the board, um, they like to have custom themes, which are sets of these 150 effects*" (P5).

With software libraries, themes are essential to the haptic design process. This desire for consistent output has a tension with customization and fine-tuning: *"it's also important to tune the experience depending on whatever kind of motor they decide to put in"* (P5). This is part of the persuasive capability of touch: '*improve comfort and differentiate based on branding*' (P6).

**Em5: Overcoming risk and cost:** "*A tough sell*". Despite its value, haptic technology is a risky, costly feature to add. Providing improved user experience requires *"high-definition haptics"*, not *"some rumble feedback that has been around a long time"* (P3). This often means *"going up in fidelity"* from a *"cheap, poor quality motor"* (P5). P5's company argues that *"the end-user is going to prefer this quality of experience"* with improved hardware, like a piezo actuator.

> "*[If we were to perform this project again,] I think we would spend a bit more time up front articulating the value, the specific value prop, of individual features*" (P5).

P5 notes the challenge of convincing non-end-users to buy or deploy P5's technology: *"[our company] has the unique challenge that our customers are not the people who use our products"* (P5). Since the main benefit is to the end-user's experience, it is challenging to connect to the bottom line, especially compared to other haptics components. According to P3, designers need to

> "*…get up to the decision-making level and more on the business side…[business roles] know nothing about technology, I mean, they don't care, but we are trying to demo parts to them, present business cases to them, and show them what they can do in order to gain market share, or increase their retail price when they add our technology*" (P3).

P3 further commented on lack of knowledge among decision makers about haptics compared to other technologies.

> *"Let's assume we were to work on a completely different product like memory chips, so everybody understands what this is for, what it can do, and you probably have a memory chip that is faster or, whatever, smaller. Now for haptics, this approach is kind of difficult because the technology scouts themselves they kind of understand what this is for, but how it's going to add value to their device, and how much they can increase the retail price, or if they can increase it at all, or gain market share, that's completely open"* (P3).

Newer technologies are hard to explain: *"[Gesture-based haptic feedback is] a much more complex task to design, and also to explain, to the OEM"* (P5). It can also make persuading a customer difficult. P3 finds that *"there's always discussions on the cost"*, and proposes *"alternative business models"* to no avail. Cost concerns are perfectly captured by P5:

> "*[The customer says,] 'we love [the piezo demo], it feels great, we're building this phone that has a 10 cent eccentric mass motor in it, can you make it feel the same?' The answer of course is no*" (P5).

P5 notes that *"cost pressures are pretty extreme* [because mobile phones in the US cost] $*199 on contract, that's sort of a fixed price and you can add more features to the phone, but that just reduces the profit margin, right?"*, so *"the addition of haptic feedback technology…can be a tough sell"* (P5). Haptic technology is especially risky because of previously discussed challenges: it involves separate risk-adverse engineering divisions, and changes to the *"guts"* of a product. Designers need to set up complicated demos to persuade decision makers of the value of improved user experience: '*if [we] only compete on cost; then this is tough*" (P1). Of course, *"it's hard to get through to the right level"*, like *"C-level kind of persons, so, talking to the CTO of Sony, those kinds of people"* (P3). The combination of high-risk, increased cost, and indirect connection to the bottom line make haptics a very tough sell indeed.

## 4. Study 2: findings from a follow-up workshop

Our second study was conducted during a workshop on haptic experience design at World Haptics 2015, the largest academic haptics conference to date, held that year in Chicago, IL, USA (http://haptics2015.org).

### 4.1. Method

The workshop was organized by the first and second co-authors to initiate a conversation between researchers and industry practitioners about HaXD status and needs, and to complement our findings from the first study by connecting with a broader set of hapticians.

#### 4.1.1. Participants

We sought to augment our six participants from the first study with a larger set of hapticians. Over thirty people participated in the workshop brainstorm session and the panel discussion. Sixteen workshop participants responded to a questionnaire at the close of the workshop, which requested details about the respondents' roles, tools, and techniques. We sought to augment our six participants from the first study with a larger set of hapticians.

Of 16 questionnaire respondents, 5 self-reported as working in industry, and the other 11 as members of academia (one reported also working at "other: research institute"). For roles, 4 reported as graduate students, 4 as developers, 2 as designers, 2 as a combination of designer and developer, 2 as researchers, 1 as a business person ("product integration/commercialisation"), and 1 did not report.

#### 4.1.2. Procedure

The workshop had three parts. First, four leading haptic design experts – two from industry, one academic, and one with a foot in both worlds – gave short presentations on topics concerning both engineering and UX. These presentations set the stage for a hands-on brainstorming session about challenges to HaXD and desired tools to solve those challenges. After that, we had an expert-led discussion following up on the brainstormed ideas.

Brainstorming occurred in 6 groups of approximately 6–7 members. Each group was asked to identify challenges faced by their members and then brainstorm solutions. Brainstormed ideas informed the panel discussion, which was led by the four haptic design experts but included all workshop participants. At the end of the workshop, a questionnaire was distributed to all participants. The questionnaire was supplemented with researcher notes written during and after the workshop, and the participants' sheets used for brainstorming, which were collected afterwards. Details about the workshop activity and questionnaire are included in the supplementary materials.

### 4.2. Results

In the following, we report results from the questionnaire's quantitative and qualitative (open-ended) questions, along with findings from notes and brainstorming sheets.

#### 4.2.1. Quantitative data (survey): tools, evaluation, groupwork

Respondents reported a wide variety of hardware and software tools used to work with haptics (Fig. 3). Most used were popular general or technical programming languages like C/C++, Matlab, Java, and hardware hacking tools like Arduino and 3D printers. Force-feedback APIs for consumer hardware (Geomagic Touch CHAI3D, H3D) were moderately used. Very few respondents reported using scripting or web tools, like Python, HTML/CSS, JavaScript, or more specialized tools. This combination suggests needs for performance, technical or scientific software libraries, and an ability to access and control prototyping hardware at a fine-grained level; in contrast to many other media design domains, web tools use is notably low. The latter is not particularly surprising for HaXD that is, by itself, not primarily visual, and often comes with tight timing requirements.

Evaluation techniques were also varied (Fig. 4a); many respondents listed several. Most common were methods deployed in-lab or in-house (piloting, laboratory studies). Less common but still used were more externally valid evaluations (in situ studies and real-world deployment).

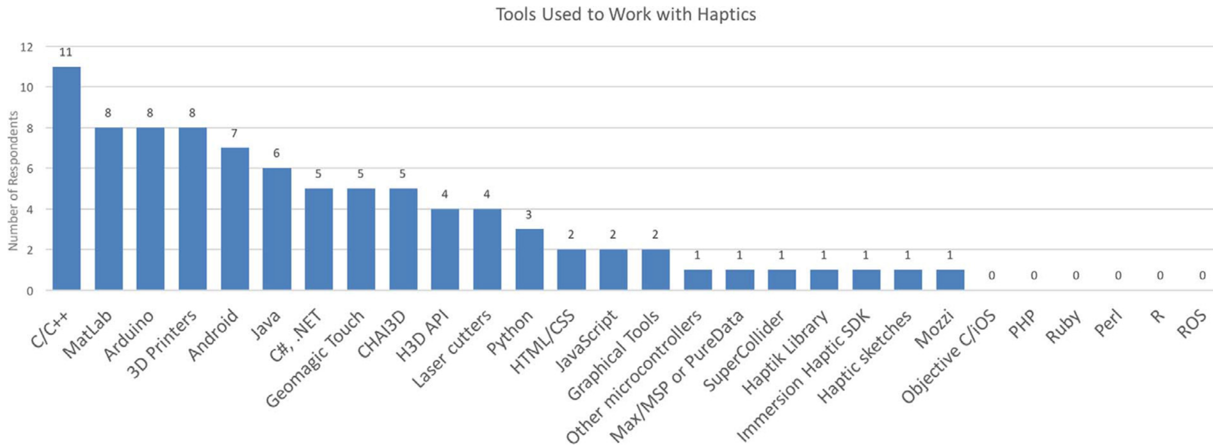
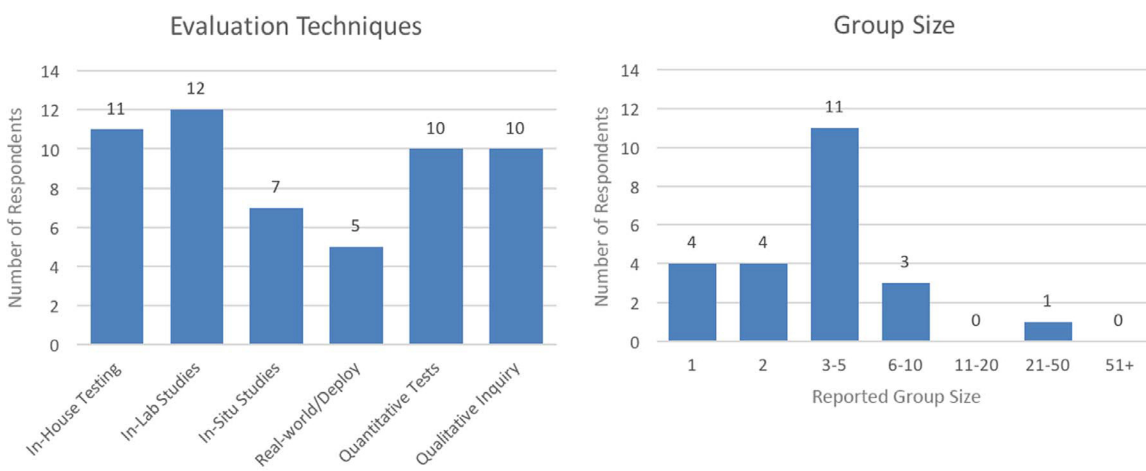



**Fig. 3.** Responses for tools used in haptic design (N=16, "*check all that apply*").




(a) Responses for evaluation techniques used (N=16, *"check all that apply"*).

(b) Reported group size for projects (N=16, *"check all that apply"*).

**Fig. 4.** Questionnaire responses for evaluation techniques and group size.

Quantitative and qualitative methods were reported with equal frequency: 8 respondents reported using both, i.e., a mixed-methods approach, and 4 respondents did not report using either, but did report conducting in-lab, in situ, or real-world evaluation.

Group size reports suggested that hapticians work in groups with varying sizes (Fig. 4b). Few work in large groups; just one person (the designer / developer for a research institution) reported a group size of 21–50. No one reported a group of size of 11–20, and most reported working with 3–5 others. Five participants reported varying group sizes (combinations of 1, 2, and 3–5 people). Because our question did not precisely define the meaning of a "group," we note the possibility of interpreting it with differing degrees of collaborative closeness.

*4.2.2. Qualitative data (survey & brainstorming): consistency, quality, value*

Qualitative responses from the survey's first open-ended question, which asked for the largest challenges participants faced in haptic experience design, highlighted three themes:

1. **Universal design**: *"universal experience", "adopting wide spectrum of users", "optimal and consistent delivery of haptic cues to large number of people", "users variations in terms of subjective analysis", "common haptic experiences, any person/any device", "the spectrum of perception".*
2. **Evaluating quality**: *"what is 'good enough'?", "modeling haptic quality of experience", "appropriate fidelity force feedback", "optimal and consistent delivery of haptic cues…".*
3. **Value**: *"getting people to realise the benefits of good haptics. Finding new ways to use hi-fidelity (wide bandwidth) haptic feedback to enhance UX", "Bringing haptics to mainstream/consumer electronics", "merging the technologies, make safety and pleasure experiences", "convincing it's useful".*

Other responses include emotion (*"transfer emotion through haptics"*) and language (*"haptic language; no simplicity in generating new sensations"*). In the second open-ended question, which asked what participants would like to see in a design tool to overcome these challenges, respondents suggested ways of handling variability or definability, such as automatic configuration:

> *"mapping", "automatic evaluation of systems and actuators", "quatification [sic] of haptic perception", "autoconfiguration, calibration and prediction of results with the users", "accessible to all, supported by standards", "autoconfigure depends that perception [sic]", "bigger testing pool".*

Many of the challenges identified during brainstorming mirrored questionnaire results. Three groups (G1, G2, and G6) focused on the *value* of haptics: what is the point or benefit in certain situations; as well as how to market that advantage to either a client or end-user. One group (G3) tackled the problem of *examples of good design*, including hardware and software architecture, suggesting a repository like GitHub or software engineering patterns. Three groups (G4, G5, and G6) talked about *meaning* – and subjectivity therein, including the possibility of a shared or useful language.

Discussions at the workshop suggested that haptics is not well marketed and that touch is taken for granted. The word “haptic” might be too “jargonny” or poorly understood; perhaps other terms such as “tactile effect” or “physical effect” could be more useful. Curated examples and an on-line repository were offered as valuable goals.

Our findings from this second study align with those from the first. Hapticians face barriers from many sources. Communication remains difficult, especially when stakeholders have a limited understanding of the value of haptics. In addition, hapticians must overcome variability in used tools, targeted hardware, and individual perception. To remedy these challenges, there is a desire for more powerful tools that can automatically create or evaluate haptics, or use and share examples.

## 5. Discussion

As a first step in further exploring the findings from our two studies, we examine in more detail the critical activities practiced by hapticians. This inventory confirms that HaXD is a field of design with familiar processes, but also one that is developing its own identity distinct from general UX design. We then identify major challenges encountered in HaXD that are unique to or exaggerated when the experiences being designed are haptic. We conclude with several concrete recommendations to support HaXD in the future and a vision for what this might look like. These findings can inform future efforts to understand and support hapticians.

We note that our interview results were generally applicable to professional haptic design in 2012. Based on recent interactions with designers in comparable roles (including those in the workshop), and our experience as hapticians ourselves, we believe our findings continue to hold at the time of writing (2016) with three caveats: (1) hardware has improved and become more diverse, (2) haptic feedback is more prevalent and more expected in the consumer culture, and (3) in a limited number of sub-disciplines, such as gaming environments and movie special effects editing, specialized tools have begun to appear to solve very specific designer problems where the cost/benefit equation merits their use. However, the design pressures shaping practices and tools themselves have changed little over that time, as shown by our findings from the more recent workshop (2015, Section 4).

### 5.1. Activities of haptic design

Based on our observations, we report the following activities that haptic designers conduct, all of which will be familiar to designers in other fields.

**Develop and communicate vision**. Hapticians must articulate the value that their designs can bring to both end-users and customers. They must communicate value to their team and others and, crucially, they must *persuade external stakeholders* that their product will contribute to the bottom line. To do this, they must *collect, run, and tune demos*, a critical part of the communicative toolkit for haptic designers.

**Prepare for design**. Hapticians need to *divine requirements* from customers, which customers often do not understand themselves. Hapticians also *gather examples*, both to provide inspiration and facilitate communication. Hapticians need ways to capture, modify, manage, find, use, and share examples and ideas, both ones they develop themselves and ones they seek out for inspiration.

**Iteratively develop, communicate, and evaluate multiple concepts**. Our participants needed to iterate, often with their clients' and users' feedback, to find the best designs. *Design thinking* and *user-centered design* are both important to apply to haptics, especially because requirements are difficult to communicate and understand. Additionally, hapticians must either *communicate with engineering*, articulating requirements to receive new physical prototypes, or *have engineering skills* to create demos and prototypes themselves. During iteration, hapticians must also *evaluate designs and collect feedback*, both with informal feedback from colleagues, and formal studies, typically run by a UX/research division. However, this practice is currently constrained both by industrial concerns (confidentiality, cost, end-user access) and the hard-to-share nature of haptic technology itself.

**Interface with research**. Hapticians need to *hand off* prototypes or stimuli to their UX or research division, and communicate study goals. They must also *monitor the academic research* in this rapidly changing field, interpreting data emanating from multiple sources: marketing research, psychophysics studies on hardware and stimuli, and interaction design of applications. Alternatively, they might *plan, run, and analyze studies* directly.

**Manage IP**. As in other technological fields, hapticians must be sensitive about intellectual property, both that of their own company's technology, and of the many companies and divisions with which they interact. Because haptic technology is very vertical, this can be quite constraining.

### 5.2. Challenges for haptic experience design

From our two studies, we identify several challenges facing hapticians that are unique to HaXD or are exacerbated when working with haptics compared to non-haptic UX design.

#### 5.2.1. Context is largely unknowable

Haptic experiences are examples of multisensory HCI. They are multisensory and holistic, interacting closely with physical hardware, grip, and orientation. When our participants knew the haptic experience's physical context, like the dashboard of a car, and had access to other technical and requirements aspects of a multisensory experience, e.g., specifics of auditory and graphical media, and computational architecture such as the smartphone operating system on which multiple modalities must be delivered in synchronicity, they were able to use tricks to improve designs and circumvent constraints. However, when context is unknown, e.g., due to confidentiality, diverse environments, application-specific nuances, and a wide variety of means of handling an interface, hapticians are often hampered in their attempts to create consistent experiences.

#### 5.2.2. Applications and individuals vary extremely

There is no “one size fits all” in haptic experience design. Each customer's design challenge has new properties. Hapticians must continually adapt their practice to changing conditions (Schön, 1982), and cannot simply design once and deploy. Companies use haptic sensations to brand their products, and individuals might want to customize effects for their preferences: users perceive, understand, and respond affectively in different ways to a haptic experience.

#### 5.2.3. Demos are complex, costly, and crucial

Essential in eliciting requirements, communicating vision, and persuading customers, demos are hard to manage. With many moving parts and ways to fail, demos often require a dedicated assistant; latency is a special challenge for early prototypes, and can defeat carefully synchronized multisensory effects. Because HaXD takes place over global distances, and across organizations and disciplinary boundaries, it is often difficult to have a handler onsite, send proprietary hardware, or divulge enough detail for clients to run them on their own.

#### 5.2.4. Iteration is painful

Every change to a haptic experience results in a change to the “guts” of the system, including reinforcing modalities and physical setup; technical constraints are tight and unyielding. Hence, even early "sketching" iterations to understand requirements can be slow and difficult, limiting playful exploration of a design space and disrupting communication with customers and users.

#### 5.2.5. *Collaboration required for haptics is difficult*

Hapticians either need to fill many roles or work in groups that include hardware, software, design, business, and psychology. Furthermore, haptic design teams must interact with many external stakeholders stratified across different international companies, and must encourage remote, asynchronous collaboration with physical, synchronous designs.

#### 5.2.6. *Evaluation methods are constrained*

Quality of experience, usability, and branding are difficult to study with physical systems. Although many of our participants mentioned evaluation methods as important, time and cost constraints limited it in practice; acceptance testing seemed to be the primary tool. Hapticians use both qualitative and quantitative methods, but in-situ evaluations are difficult to come by, suggesting that haptic designers primarily conduct evaluations in-lab and do practical deployments.

#### 5.2.7. *Value of haptics is hard to quantify*

The benefits of haptic technology are often intangible: better user experience, usability, branding, perception of quality, or even improved perception of another modality which the haptic sensation enhances. Product manufacturers (phones, cars) must be convinced of the contribution to the bottom line, and are all too aware that improving haptics comes with increased cost and risk. Haptic design teams reaching out to customers through risk-adverse engineering avenues face additional push-back.

### 5.3. *Recommendations for haptic and multisensory experience design*

Based on these challenges, we identify in this section three main directions for development that could lead to better haptic design by recognizing that haptics is fundamentally a multisensory experience and thus haptic design is always multisensory design. While we have tried to elucidate challenges that are particular to haptics or at least are exacerbated when haptic technology is part of the designer's palette, most apply at least to some degree to design in other modalities, especially to joint design to create a holistic multisensory percept (Haverkamp, 2014). We therefore discuss our findings using evidence from HaXD, but suggest that our recommendations apply generally to many other types of multisensory experience design.

#### 5.3.1. *Enable adaptable haptic interfaces*

Many of the challenges facing hapticians are a result of uncertainty or variability in physical context. One solution is to let physical haptic interfaces adapt to their context, either automatically or with help from a designer, customer, or end-user.

One automatic approach to mitigate variable physical context is to employ *closed loop control*: adapt actuator output to desired levels with sensors. For example, a microphone could sense the external vibrations of a VT actuator, whose output can then be modified to overcome the effect of external factors such as material, orientation, and grip to achieve a specified frequency, amplitude and responsiveness. This might be deployed as needed in products during use, or just once during manufacturing as a quality assurance step to adapt for different product materials.

Another approach is to let the customer or user adapt the experience through *customization*, which takes into account both physical context and individual differences in perception and preference. This might be a simple volume control, or a powerful menu of settings. Customizable infrastructures that support fine-tuning can also help speed iteration once demos or even fully-fledged applications are set up, letting designers and customers try variations of a haptic experience more easily.

Finally, *efficient calibration* of demos, using either sensors or a person's manual input, could improve collaboration by providing easier demo or product setup. Devices that are self-assembled or operable by non-experts must have an easy way to troubleshoot and ensure correct rendering. Doing this could engage the DIY community to explore haptic technology, and improve the efficacy of sending evaluation kits to potential customers.

#### 5.3.2. *Exploit virtualization*

The unique problems of haptic design stem from the combination of physicality and the software engineering necessary to integrate the hardware into a solution. Some of these challenges may be offloaded through virtualization: certain types of iterations or tests can be done more efficiently with software simulations or crowdsourced evaluation – once this capability exists.

*Proxies* are one way to virtualize complex physical setups, e.g., using low-fidelity feedback like phone vibrations when high-fidelity feedback is unavailable (Schneider et al., 2016). Low-fidelity previsualization of haptic sensations (or "pre-feels") (Schneider et al., 2015b) can improve iteration speed, by allowing the designer to experience an approximation of an iteration before committing resources to building it, and/or to compare with a reference starting point. Visual or audio proxies can easily exploit existing infrastructure.

*Software simulations* of hardware can explore how different electronic or mechanical components could be rearranged to preserve or enhance dynamics, reducing physical prototyping. Even more advanced might be the use of simulations to develop "perceptually transparent" sensations (Ryu et al., 2007), allowing actuators or other components to be swapped in and out if upgrades or cheaper models are available, while software components are automatically updated to achieve a consistent end result. This virtualization technique dovetails nicely with closed-loop adaptable interfaces by establishing models and correcting for errors.

Software has enabled immediate, efficient deployment of visual and audio stimuli through the Internet. Analogous infrastructure could help haptic technology catch up to other modalities more quickly, e.g., developing modular systems, data structures and protocols, and large on-line repositories of examples. *Broadcast* haptics remains an important and unrealized goal, which can help both with potential customers and end-user experiences (O'Modhrain and Oakley, 2003).

#### 5.3.3. *Establish richer conceptual infrastructure*

Several measures can help to address communication and cultural barriers to haptic design.

*Outreach and education* might be able to improve the perceived value of haptics and facilitate interdisciplinary communication. Public haptic portfolios, accessible haptics education (Jones, 2014) such as online tutorials, support for DIY and maker cultures, and events such as haptic hackathons (Madelska, 2015) will help to establish haptics as a known technique in designers' toolkits, spread the word about its value, and most importantly help more people join the conversation that will articulate the value in touch-based technology. It will help provide different stakeholders with common reference points, language, and understanding, both lowering the bar to conduct haptic design as a team member, and providing a voice to external stakeholders.

A *haptic design language* is needed for multidisciplinary team member and client communication. A design language, such as Google's Material Design (https://material.google.com), is a defined set of aesthetic and interactive rules to ensure a consistent look and feel. Much like graphic design, where non-experts might be aware of some concepts (symmetry, contrast, hot/cool colours) while experts know much more (colour combinations, concept of weighting in a visual design), a shared, objective and teachable language will help teams communicate across divisions and with clients, users, and customers. It remains to be seen whether this will be a formal lexicon of terms, or ideas that emerge organically; either way, we suggest paying careful attention to the language used when doing haptic design, to share the language alongside the sensations and their components, and to closely consider multisensory interactions when developing that lexicon.

Hapticians have limited access to *evaluation techniques* that are taken for granted in other modalities, especially in situ tools. One promising way of mitigating this handicap is application of remote analytics to haptic design, e.g., logging, machine learning, or qualitative contextual inquiry. This may require development of new batteries of haptics-suitable tests, especially ones which target its less objective benefits (e.g., quality and branding). That might in turn help to study perceived value and risk.

### 5.4. Future of haptic design

Hapticians follow an observable, defined process. They collect requirements, develop multiple concepts, and iterate until they arrive at a final experience, which is then evaluated with varying amounts of rigour. We saw evidence of libraries, examples, and our participants' own craft and experience; we also saw a diverse, international, collaborative ecosystem. Some deliberately applied user-centered design techniques.

However, we also saw that haptics *"might be 30 years behind graphics"* (P3), or at least *"really new"*, i.e., in an early stage of development. We believe that HaXD can draw from both newer fields like experience and interaction design, as well as more established ones like graphic design. How might this look?

Hapticians might work in teams, interacting with other relevant units. From our research, it is likely that hapticians will need to communicate with everyone from mechanical engineers, software developers, and expert designers of other media modalities, to people conducting business and user research. As with graphic design schools, there may be formal education available for haptic designers. However, because haptic technology needs to be tailored to each specific problem, these will likely be generalized professional programs that train diverse skills, or focus on certain sub-categories of haptic technologies, e.g., tactile artists or animators (Schneider et al., 2015b), friction designers, or 3DOF force-feedback developers. As hardware becomes more affordable, we also expect the recent Maker movement (Dougherty, 2012) will encourage hobbyists and artists to explore haptic technology and push its limits.

As with other emerging media, such as the web browser wars of the 90 s, standardization of HTML/CSS, and Blu-Ray versus HD DVD, we expect diverse file formats and infrastructures to emerge and then coalesce. Given the diversity of haptic technologies and experiences, we expect these to be centered around *paradigms*, mental models of how to work with a haptic experience. For example, haptic icons (Maclean and Enriquez, 2003) are one paradigm: display-only, temporal and meaningful entities rendered on a single body location. These might be designed, distributed, and experienced similarly to audio files. Tactile animations (Schneider et al., 2015b) are another: generalized spatio-temporal entities that can be rendered continuously on different grids. Multi-DOF force-feedback displays are often programmed with a third paradigm: a virtual environment and a single manipulator; this is most analogous to 3D virtual worlds. Paradigms can be applied to multiple devices in a class (e.g., tactile animations on grid displays), or multiple paradigms might apply to a single device (such as a Haptuator (Yao and Hayward, 2010)) that can display a haptic icon (temporal only), or that can produce a directional force (Culbertson et al., 2016) (spatio-temporal).

We expect design dimensions to be further developed, and eventually encapsulated into best practices, just as alignment, contrast, and weighting are used for graphic design. Other design languages, like musical notation, will facilitate recording and communication amongst experts. Meanwhile, more developed aesthetic theories, like musical or colour theory, will help guide people to effective, pleasing, differentiable haptic designs. Intellectual property law will need to be adapted – much like a logo can be trademarked, how might a certain button click? Whether a haptic icon set should be protected, and how to set an appropriate level for burden of proof, remain open questions.

We hope that these questions and more will be answered during this exciting time in which there is so much activity focused on technology to engage one of our most essential senses. The more guidelines we develop, the more we can support hapticians in their practice. In the future, we hope to extend our description of HaXD into a set of best practices to guide people who wish to design haptic and multisensory experiences.

### 5.5. Limitations

Like any investigation, this work has its limitations. Because hapticians who can discuss their work are relatively difficult to find, our participants for Study 1 were recruited using our professional network. Most of our Study 1 participants were male, and were involved with only a handful of possible haptic technology or application domains – in fact, many applications that exist today did not in 2012. For Study 2, participants were self-selected from the World Haptics community; this group involved both academic and industry practitioners. As such, in contrast to Study 1 participants (entirely from industry), two thirds of Study 2 participants were from academia. The interviews for Study 1 were conducted in 2012, and our Study 2 workshop occurred in 2015, so even that may soon be dated. Haptic technology has continued to improve; we have tempered our conclusions accordingly but strongly believe the insights from our two studies still apply.

## 6. Conclusion

We have provided a first exploration of how haptic experience design (HaXD) is being practiced in industry. We report findings from interviews with six hapticians, finding observations about designer process and themes about the holistic nature of haptic experiences and the collaborative ecosystem and cultural context of our participants. We supplement this with broad follow-up data from a recent workshop at a major haptics conference.

We identified the various activities hapticians practice, similar to other fields of design. We also note specific challenges facing designers who work with haptics, and recommend both high-level priorities and low-level tactics for conquering those challenges. This is a first step in understanding HaXD outside of the research lab. We look forward to when physical, interactive technology can be designed with creativity, passion, and panache.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ijhcs.2017.04.004.

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