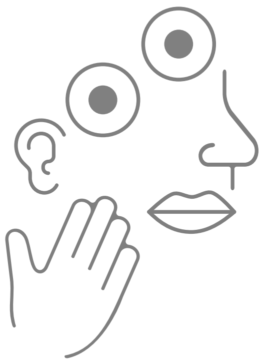

DESIGNING FOR A MULTI-SENSORY EXPERIENCE BEYOND VISION

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Humans are multi-sensory beings who make sense of the world via multiple sensory modalities. However, most everyday technologies, including smartphones, tablets, and personal computers, often fail to engage all the senses effectively. Instead, vision is heavily relied on to interface with everyday technologies, and as a result, it is disproportionately stimulated when compared to the rest of our senses. This hegemony of vision in design not only excludes the visually challenged but imbalanced sensory experiences also create sensory overload and fatigue in those who are not.

Limiting the senses that are engaged while interfacing with digital devices also increases the cognitive burden placed on the user. When complex information is conveyed unimodally in highly stimulating environments, people must expend a large amount of energy and cognitive resources to attend to and grasp information to commit it to memory and recall it.

This thesis aims to address contemporary sensory imbalance challenges by investigating and hypothesizing effective and accessible multimodal interfaces for everyday technologies and providing considerations for designers who seek to leverage multiple senses to convey information. Given the fact that taste often requires people to consume substances, the effects are difficult to control when designing for larger populations. Therefore, this thesis intentionally focuses on designing for touch, smell, hearing, and vision as a means of creating experiences that effectively disperse the intake of information across multiple senses. In particular, it aims to investigate how interactions with everyday technology can be designed to effectively engage the senses beyond vision to create balanced, immersive, and inclusive experiences.

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INTRODUCTION

Humans are multi-sensory beings that make sense of the world via multiple sensory modalities. Each of the senses has its own affordance that lends it to various everyday tasks with digital technology. However, currently most everyday technologies, including smartphones, tablets, and personal computers, often fail to engage all the senses effectively. Instead, vision is heavily relied on to interface with everyday technologies, and as a result, it is disproportionately stimulated when compared to the rest of our senses. Among the tasks we accomplish with everyday technology navigation has been heavily impacted by an over-reliance on vision and hearing. Overloading these senses, which we naturally use for navigation and spatial knowledge acquisition, can lead to diminished attention and even fatal accidents. Although the human touch sensation can be directional it is currently underutilized for this purpose. This thesis argues that the design of tactile directional instructions, provided to people to assist their pedestrian wayfinding while navigating unfamiliar routes outdoors, can enable them to acquire pertinent spatial information while maintaining attention and awareness of environmental surroundings (Figure 1). The study also explores the design of interactions with digital technology to honor the entire human sensorium and create experiences that facilitate the efficient consumption of information.

Figure 1: *This figure illustrates the urban environment that people navigate everyday are normally filled with various stimuli that flood our senses. Photo by Artur Kraft on Unsplash.*

RESEARCH QUESTION

How might the design of tactile directional instructions, provided to people to assist their pedestrian wayfinding while navigating unfamiliar routes outdoors, enable them to acquire pertinent spatial information while maintaining attention and awareness of environmental surroundings?

Sub questions

How might tactile directional information influence the confidence level of pedestrians during navigation?

How might the pacing and intensity of a tactile stimulus convey a sense of urgency?

How might a tactile stimulus, presented to a particular point on the human body, correlate to a specific direction in the surrounding environment?

How might tactile directional information influence a pedestrian's spatial attention and landmark knowledge acquisition?

SIGNIFICANCE

People increasingly recognize the importance of Inclusive Design and the benefits it can have not just for people who are disabled in various ways but for businesses as well. Designing for a multi-sensory experience has the potential to enable all people to participate meaningfully in interactions with digital technology regardless of their disabilities.

Smartphones currently have haptic feedback systems that mostly rely on built-in vibrotactile feedback to create engaging experiences. For example, Apple's Taptic Engine in the iPhone provides seven basic haptic feedback patterns by default. The different types of haptic feedback include notifications (success, warning, failure), impacts (light, medium, heavy), and selections (*Haptics - User Interaction - IOS - Human Interface Guidelines - Apple Developer*, n.d.). Prototyping tools for digital interaction design are also evolving to enable designers to incorporate haptics into their concepts. However, gaps still exist in incorporating haptic feedback into most daily digital interactions as a part of common experiences. Furthermore, those responses that are present only exist as supplements to visual feedback. For example, although possible, scheduling an event on a calendar application currently does not offer users haptic feedback during the process to notify them that they have successfully completed the task. As a result, there is no closure on the task that functions like the click of the headphone jack on an iPod. Given that the vast majority of daily tasks solely engage the eyes and deprive other senses of engagement, there is a high risk of disadvantaging people who are visually challenged and overwhelming those who are not. For these reasons, it is critical that research be conducted to realize multi-sensory experiences in the context of everyday tasks.

SCOPE

People use navigation apps on their smartphones and other GPS systems to aid their wayfinding in various scenarios that involve driving, using transit systems, walking, and cycling. Given that the over-reliance on vision and hearing in navigational systems in all of these modes of transport has negatively affected our ability to attend to our environment while navigating, in this thesis I explored the use of haptics to convey directional information intended to assist pedestrians in their wayfinding while navigating simple outdoor environments. Further, there are multiple populations that could benefit from a touch-based navigation system such as the visually challenged and those with hearing impairments. Nonetheless, I focused on a young adult population with no sensory disabilities since this is a large population that frequently uses navigation applications on everyday technology for assistance.

There have been several advancements in the field of haptic design and touch-based interfaces, including the development of several niche devices, vests, belts, rings, wrist bands, oral haptic interfaces, and canes. However, most of these devices exist separately from the technology we use every day such as smartphones, tablets, and personal computers. My focus in this thesis was to explore a touch-based interface that is ancillary to the technology people already use in their daily lives and that assists them in pedestrian navigation. I actively approached the challenge by augmenting existing navigation applications on people's devices to convey directional information effectively while respecting the user's need to attend to their surrounding environment.

Humans naturally possess five fundamental sensory capacities, namely vision, hearing, touch, smell, and taste. Taste involves the consumption of substances, the effects of which are hard to control when designing for large populations. For this reason, I limited my exploration of vision, hearing, touch, and smell in this thesis.

LIMITATIONS

I strongly believe that evaluating design prototypes with a variety of different populations is essential to surface insights that aid in the iteration of a prototype. However, for the scope of this thesis, I conducted my prototype evaluation study with young adult participants who were university students since that was the population that was accessible during my study. Prototyping techniques that assist the design for haptics is less developed than the extensive design tools available for visual design. The prototyping techniques I explored in this thesis were limited to the tools and knowledge I had available through the university resources, which in turn, determined the resolution of the prototype.

OVERVIEW OF THE STUDY STRUCTURE

The initial phase of this thesis involved formulating my research question and identifying existing gaps in the design of interactions with everyday technology and highlighting the benefits of multi-sensory design. The research question I posed warranted developing an understanding of human sensation and perception. Therefore, in the exploratory phase, I investigated literature from psychology and cognitive science. An audit of the current applications of sensation and perception research in multi-sensory design was also conducted to gain an understanding of the existing gaps in the design of interactions with digital technology. In the generative phase, I explored techniques that aid prototyping for haptics and subsequently I investigated methods for evaluating the design of a haptic prototype. During this phase, I also further refined the scope of this thesis and identified navigation as an everyday task that would likely significantly benefit from multi-sensory design and serve as an opportunity to hypothesize the broad application of findings to other common tasks. In the prototype design phase, I designed and created a haptic prototype to assist people in navigation and conducted a study to evaluate its effectiveness. Lastly, I used my analysis of the study outcomes to inform design recommendations for haptic and other multi-sensory interactions with digital technology.

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EXPLORATORY RESEARCH

This phase involved the review of basic science research on human sensation and perception that served as foundational knowledge for the design of multi-sensory interfaces. It also included a review of the application of foundational research in the field of design.

HUMAN SENSATION AND PERCEPTION

In order to design interactions with digital technology that effectively distribute information across our senses, it is crucial to first understand the natural sensory and perceptual capacities people possess. This involved a review of psychology and cognitive science literature.

In the book *Sensation and Perception*, authors Goldstein and Brockmole define key terms involved in human sensation and perception that aided my understanding of the human sensorium. They are paraphrased as follows (Goldstein & Brockmole, 2017):

Sensation: The process that involves the rudimentary process occurring at the beginning of the sensory pathway as in the case of sound vibrations stimulating the auditory receptors.

Perception: A more complex, “higher-order” process involving processes like interpretation and encoding accompanying activity in the brain.

Distal Stimuli: Stimuli that are distant from us in our environment. The light reflected from an object in the environment around us is an example of a distal stimulus.

Proximal stimulus: Stimuli that directly stimulate our sense organs. Feeling the texture of an object, for example, is a proximal stimulus as it directly stimulates the receptors in our skin.

Based on prior studies, authors Goldstein and Brockmole describe psychological methods used to measure perception and define thresholds used to measure the limits of our sensory capacities. Their approaches are paraphrased as follows (Goldstein & Brockmole, 2017):

Absolute threshold: The minutest level of a sensory stimulus that can be just detected.

Difference threshold: The smallest difference between two sensory stimuli needed to distinguish between the two stimuli.

Habituation: Habituation refers to the continued decrease in response to a stimulus on repeated exposure.

Our perceptual system doesn't just involve a stimulus stimulating our sensory system, but it also requires our attention. Significant stimuli capture our attention faster than less significant ones in our surroundings. However, sometimes there are stimuli that unintentionally catch our attention. Goldstein & Brockmole describe these stimuli as "task-irrelevant stimuli" or distractions. These can take the form of large billboards on the road, a call or notification on the phone while driving or a conversation with a co-passenger while driving. The authors describe attention and perceptual load using Lavie's definitions from the load theory of attention which proposes that when a task has high perceptual demands, distractions or task-irrelevant stimuli are easily filtered out and all attentional resources are directed towards the target task. However if a task has low perceptual demands, then more task-irrelevant stimuli or distractions will be processed Lavie's definitions are paraphrased as follows (Lavie, 2005):

Perceptual capacity: The capacity a person has available to carry out perceptual tasks.

Perceptual load: The amount of perceptual capacity required to carry out a specific perceptual task.

Low-load tasks: Refers to the perceptual tasks that take up only a small amount of a person's available perceptual capacity.

High-load tasks: Refers to the perceptual tasks that take up a significant amount of a person's available perceptual capacity.

Therefore, in the context of this thesis, a target task is defined as something a user would do using everyday technology, such as navigating a physical space and using a maps application on a smartphone, and task-irrelevant stimuli refer to input from the surrounding environment.

Multi-sensory design necessitates an understanding of the structure, resolution, and range of our sensory systems. *Sensation and Perception* by Goldstein & Brockmole provides useful detail in its description of our five fundamental senses, vision, hearing, touch, smell, and taste.

Vision: The eyes are responsible for the sense of vision and the receptors in the eye respond to light energy. Humans possess bilateral vision and are capable of perceiving color, brightness, shapes, edges, and volume that aids us in identification. A significant portion of sensory processing is dedicated to vision and it dominates our other senses. Since our eyes are capable of perceiving depth, motion, and volume perception, our sense of vision is involved in spatial perception and navigation.

Hearing: The ears are primarily responsible for detecting sound energy, which is carried in the air around us, the stimulus for hearing. The human ears are capable of sensing a range of sound frequency and amplitude. The presence of two ears enables us to have a binaural hearing capacity. Human hearing is also capable of localization or determining the source of the sound. This makes hearing another essential sense for spatial navigation.

Touch: The skin is the organ responsible for the sense of touch. The skin has specialized mechanoreceptors that can detect variables like movement, pressure, vibration, temperature, moisture, pain among others. Touch requires the source of the stimulus to be in close proximity to the body, making it a proximal sense. The epidermis or the upper layer of the skin has two kinds of mechanoreceptors, the Merkel receptor, and the Meissner corpuscle. The former is a slowly adapting fiber (SA1) and is responsible for the perception of details, shape, and texture while the latter is a rapidly adapting fiber (RA1) and is responsible for the perception of hand-grip and movement across the skin. The deeper layer of the skin, the dermis is also equipped with two kinds of mechanoreceptors. First, the Ruffini cylinder is a slowly adapting fiber (SA2) that respond to continuous stimuli such as the stretching of the skin. Second, the Pacinian corpuscle is a rapidly adapting fiber (RA2) that responds to rapid vibration and fine texture and has a large receptive field. The Pacinian corpuscle is one of the most sensitive mechanoreceptors.

Smell: The sense of smell is a chemical sense that is closely associated with primal parts of the brain, making it closely linked to emotion and long-term memory. Smell is also capable of eliciting strong responses such as repulsiveness more readily than vision or hearing.

The attention and distraction insights gleaned from this helped me identify the problems that have arisen in technology due to the improper distribution of information across our senses. The findings gained from the audit of the human senses reinforce the decision to further investigate touch as an effective means of conveying directional information, which is currently conveyed primarily through the eyes and ears in everyday technology. The highly specialized mechanoreceptors in the skin enable us to locate the source of the touch stimulus, which affords the mapping of objects in our surrounding space successfully onto the skin. This renders the sense of touch suitable for the offloading of directional information to assist in wayfinding. The psychological methods for measuring perception highlighted in the book guide the appropriate design of sensory stimuli to be effective and easily interpretable by the user with a minimal perceptual load. The insights from this book also informed my work while designing the haptic feedback prototype in that it helped me determine the distance between the actuators and the number of actuators needed to create discernible haptic patterns.

Our mental model of the surrounding environment is created through the processing and integration of sensory information from different modalities. *Crossmodal Space and Crossmodal Attention* by Driver and Spence examines how multimodal representations of the environment are created and how they might affect attention. Each sensory modality helps people perceive different aspects of the environment. Sometimes two or more of our senses respond to the same external stimulus, “enriching our overall experience” as in the case of lip-reading while listening to a person speaking in a noisy environment such as a cocktail party. In *Crossmodal Space and Crossmodal Attention*, the authors focus specifically on the spatial aspects of multi-sensory integration and the aspects that have recently found to relate to spatial attention. They highlight the challenges that come with multi-sensory integration for the nervous system. Each of the sensory signals is perceived from senses that are on different parts of the body, and the external stimulus is localized with respect to the position of the various senses it is stimulating. Previous research by the authors also shows that when one sensory modality focuses on an external stimulus, selective attention is directed towards the same stimulus within other sensory modalities as well (Driver and Spence 1998).

Multi-sensory integration has profound implications for multi-sensory design. Approaches from neurophysiology, experimental psychology, and neurological work leveraged in this book provided the necessary theoretical rationale for the design recommendations I made. The experiments and research described in this book offered insights into how information is selectively processed across the senses while filtering out distracting stimuli, which was useful for my thesis as I explored ways to use multi-sensory design as a means of allowing the user to complete their tasks efficiently and with ease.

THE GAP BETWEEN SCIENTIFIC RESEARCH AND DESIGN

Basic science research has shown that each of the human senses has evolved with specific capabilities, making them highly specialized to aid us in different tasks. However, there hasn’t been a smooth translation of the research into the design of digital interfaces. As a result, there has been an imbalanced distribution of information across our senses. The disproportionate stimulation of the senses while interfacing with digital technology has undesirable effects on the user such as:

Sensory overload and decreased responsiveness and habituation

Sensory fatigue and adaptation and potential impairment of the sense

Exclusion of those who are visually challenged due to over-reliance on the eyes to interface with technology

MULTI-SENSORY DESIGN

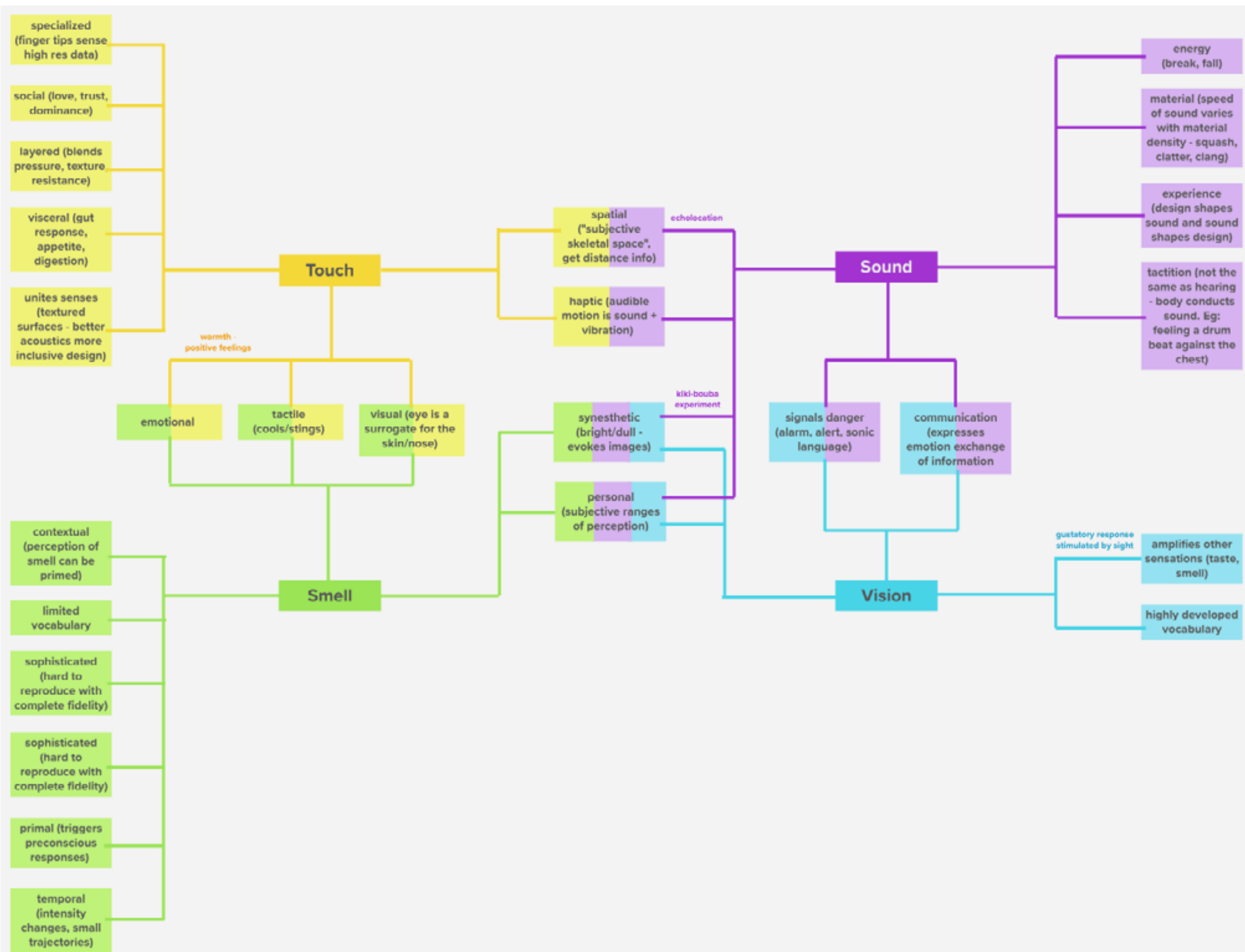
Although there is still a significant gap between basic science research on human sensation and perception and its application in the area of digital interface design, some promising work has arisen in the area of multi-sensory design in recent years. To understand the current status of multi-sensory design research, prototyping, and evaluation methods, I reviewed literature on multi-sensory design.

The Senses: Design Beyond Vision by Lupton and Lipps brings to light the dominance of vision in current design practice, explores the multi-sensory design, and highlights the value of it in enhancing people's lives. Through a wide range of sensory design projects, the book describes the possibility of an accessible experience that includes people from a plethora of backgrounds and abilities. The book endorses a multi-sensory approach to design to facilitate the opportunity for everyone to receive information effectively. The authors describe bringing together ideas and principles that add to the "sensory richness" of products (Lupton & Lipps, 2018). Each sense has its own set of affordances that lend themselves to multiple applications that might be leveraged to improve daily life. For instance, touch is described to be "specialized" as specific parts of the body deliver information at different resolutions while sound is spatial and enables humans to create a map of the surrounding space through binaural hearing.

This book provides a useful approach to understand how to leverage the senses to convey information effectively in a multitude of contexts for a broad audience with different abilities. With an intentional distribution of information across the senses, experiences can be designed to feel comfortable, natural, and context-sensitive. Based on the information gleaned from this text, I created a diagram aimed at capturing the affordances of various senses (Figure 2).

Designing Across Senses: A Multimodal Approach to Product Design by Park and Alderman aims to bring psychology and cognitive science research insights into the context of digital interface design to enrich the experience of people in their interactions with technology (Park & Alderman, 2018). In the first half of the book, the authors describe the human senses and the capabilities of each sense. They explain the current state and limitations of interface design with regard to each of the senses. As expected, most of the interfaces today are vision dominated, which is reinforced by the strong influence of graphic design on interaction design. Auditory interfaces are also quite popular in the field of interaction design and most alert and alarm systems rely on this interface most likely because people perceive and process stimuli via hearing faster than any other sense. After visual and auditory interfaces, haptic interfaces are next in terms of advancements and adoption. Game designers have extensively used haptic interfaces in controllers to create immersive experiences. In fact, most smartphones and wearables like smartwatches today are

Figure 2: *Shown here is a diagram that captures the affordances of touch, sound, smell, and vision.*



equipped with haptic interfaces that can be customized according to the user's preference. The book guides designers who wish to design experiences that are multi-sensory by outlining means to discern potential opportunities for intervention based on user needs and available technologies. The authors outline multimodal design phases that are not dissimilar to current user-centered design processes that are followed by most contemporary design practitioners. They outline phases from discovering opportunities to deploying a product or service. The book emphasizes the importance of creating prototypes that are flexible and readily incorporate feedback from the evaluation of the prototype. The book defines four types of multimodal interactions: synchronous and asynchronous modes, and parallel and integrated modes, which are paraphrased as follows (Park & Alderman, 2018):

Synchronous mode: An experience that combines multiple modalities that are all synchronized. For example, the ringing of a phone accompanied by the vibration and the display of the caller ID on the screen functions as synchronous feedback.

Asynchronous Mode: An experience that combines multiple modalities that are asynchronous. For example, in voice assistants such as Amazon's Alexa, the light ring on the device indicates waiting, beginning, and the end of an interaction.

Parallel Mode: In parallel mode, multiple modalities are designed to enable a user to choose a modality to accomplish their task. For example, interfacing using voice commands, gestures, or controllers to control the Xbox define the parallel mode.

Integrated Mode: In integrated mode, multiple modes are combined simultaneously to accommodate the needs or preferences of different subgroups. For example, a crosswalk signal uses both visual and auditory channels to indicate when it is safe to cross the street.

From the insights I gained from reviewing the current state of various sensory interfaces, I found haptic interfaces (after visual and auditory interfaces) to have the lowest barrier to entry in terms of prototyping and incorporating into everyday technology. This helped inform my decision of designing a tactile interface to convey directional information. *Designing Across Senses: A Multimodal Approach to Product Design* describes how basic science research can smoothly translate into the design of digital interfaces that combine multiple modalities to create experiences that are more inclusive than what currently exists. For this thesis, this book provides a starting point for designing beyond vision by introducing practical approaches for research, scoping, prototyping, and the evaluation of multimodal products and services.

04

GENERATIVE RESEARCH

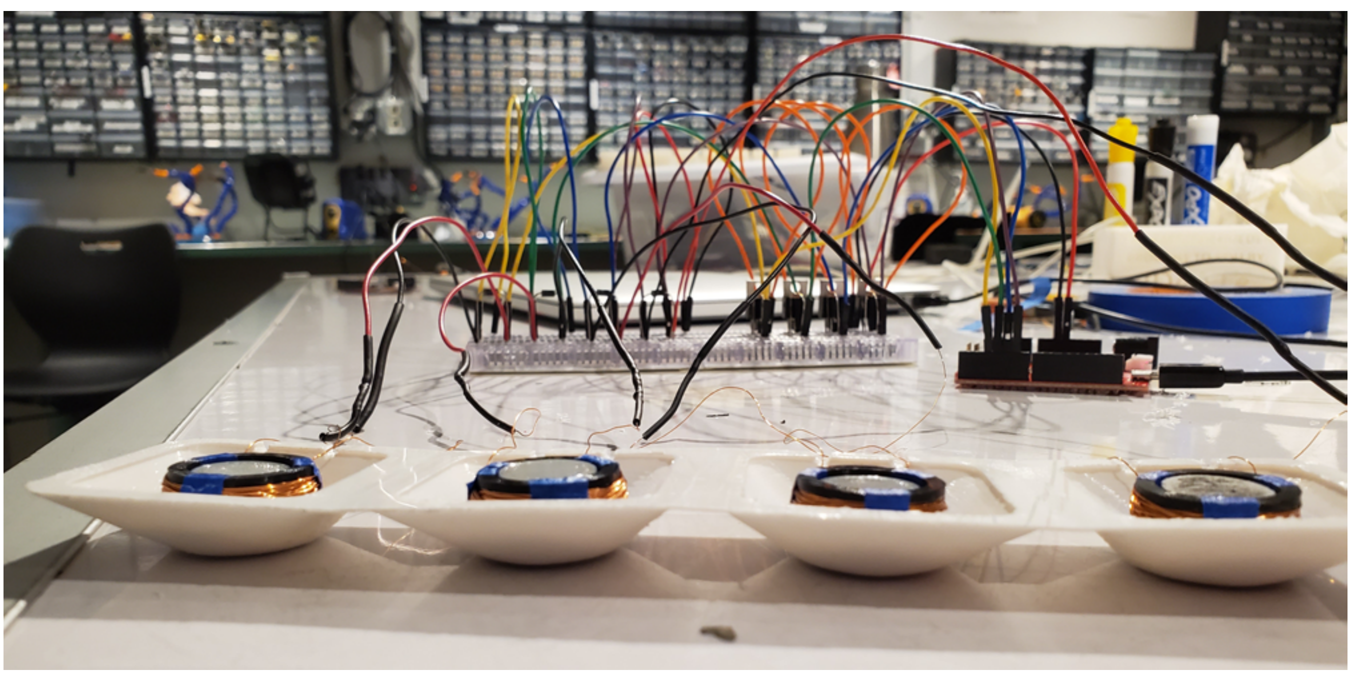
With the insights I gained from the exploratory phase, I explored ways of prototyping for touch. This phase involved investigating various tools and techniques available to prototype for haptics and to evaluate a touch-based design system.

PROTOTYPING

This stage primarily focused on investigating pressure-based human touch. The first step included learning how to build a prototype and render different touch sensations (Figure 3). A haptic feedback prototype, composed of a row of four solenoids was built to render various kinds of pattern stimuli to the forearm (Figure 4). The goal of this activity was to begin creating a rich vocabulary and a library of patterns that touch currently lacks in comparison to vision.
The hardware was primarily composed of four solenoids, a 3D printed case to house the solenoids, and an Arduino to control the actuation of the individual solenoids. The prototype was capable of simultaneous actuation from 0 to 100 Hz.

The inner forearm is a suitable site for haptic stimulation due to its relatively low threshold distance and therefore high sensitivity. Seven patterns namely frog jumping, light rain, heavy rain, calm heartbeat, racing heartbeat, smooth motor, and choppy motor were created by varying the pacing of the movement of each solenoid (Table 1). This was done by changing the on-time and the off-time for each of the cells.

Figure 3: *The prototype consisted of four cells each with its own solenoid that was capable of actuating independently.*



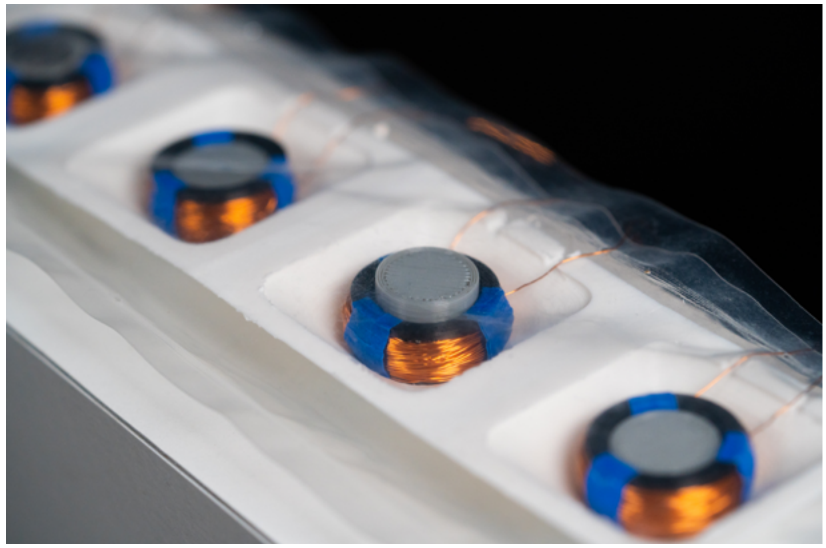


Figure 4: *Shown here is the functional prototype. Each cell is wound in enameled copper wire. The cell houses a neodymium magnet, with a spacer on top of it. The protruding piece, second from the right in this picture, shows an activated cell.*

Table 1: *Each of the 7 patterns, along with the parameters modulated for each of the three variants, can be seen in the table above. All parameters are in milliseconds. The first, second, and third numbers in parentheses next to each parameter correspond to the "bad," "moderate," and "good" variants of each pattern.*

Pattern	Description	Parameters (milliseconds)
Frog jumping	All cells turn on sequentially	On Time (500, 700, 100), Off Time (500, 100, 500)
Light rain	Random short sequential pulses in random locations	On Time (20, 240, 140)
Heavy rain	Random short simultaneous pulses in random locations, with random decay	On Time (15, 100, 50), decay Low (100, 50, 10), decay High (150, 100, 50)
Calm heartbeat	One cell turns on and off, repeatedly	On Time (200, 500, 500), Off Time (300, 500, 900)
Racing hearbeat	One cell turns on and off, quickly, repeatedly	On Time (100, 125, 167), Off Time (180, 225, 300)
Smooth motor	All cells turn on and off very quickly, repeatedly	On Time (off time is same) – (25, 20, 10)
Choppy motor	All cells turn on and off quickly, repeatedly	On Time (off time is same) – (200, 100, 50)

STUDY DESIGN

Study design

To evaluate the prototype I conducted a study with five participants. By rendering seven different patterns, I aimed to investigate the parameters that can be varied to relay impulses that are recognized as behaviors that are commonly felt, such as rain. Each pattern had three variants per pattern, designed to be "bad" (unclear), "moderate (somewhat clear)", and "good (very clear)" representations of the verbally-announced sensation. Participants were asked to rank each pattern on a 5-point Likert scale, noting how well a sensation corresponded to its name. Each participant completed two trials, separated by a 5-minute break (Figure 5). As a result, they ranked the 21 randomized pattern variants twice.

Figure 5: *Shown here is a participant engaged in the study. They wore noise-canceling headphones to minimize the interference of auditory stimuli on their rating of a pattern.*

Evaluation of the prototype

The results showed a general likability for most of the “good” variants of the patterns (Chart 1). Pattern likability increased between trials, indicating that increased exposure to this modality may increase the believability of patterns (Chart 2). The data also suggested that participants can distinguish accurate patterns from inaccurate ones. Additionally, when primed, participants can believe that certain stimuli represent “good” versions of their real-world equivalents (e.g. the “choppy-motor” pattern represents a real choppy motor”).

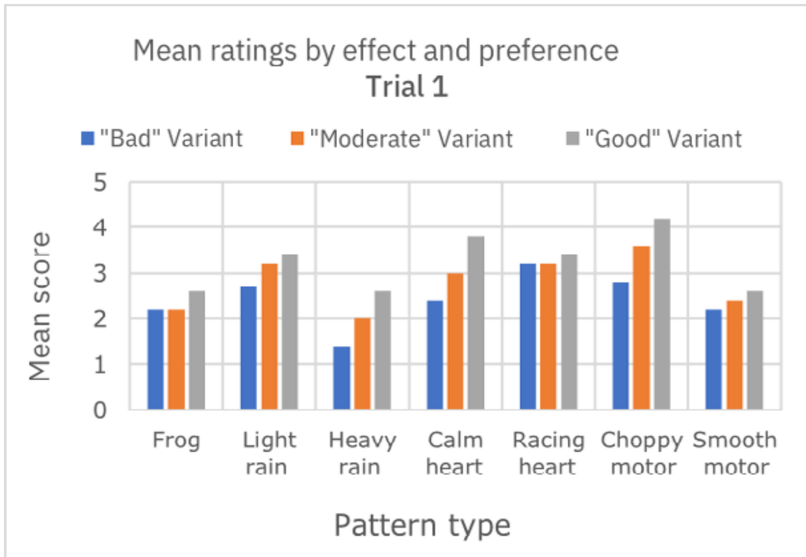


Chart 1: *This chart graphs the average scores for 3 variants of the 7 patterns, for Trial 1. Trial 1 favorites among participants included the “good” variants of choppy motor, calm heartbeat, and light rain.*

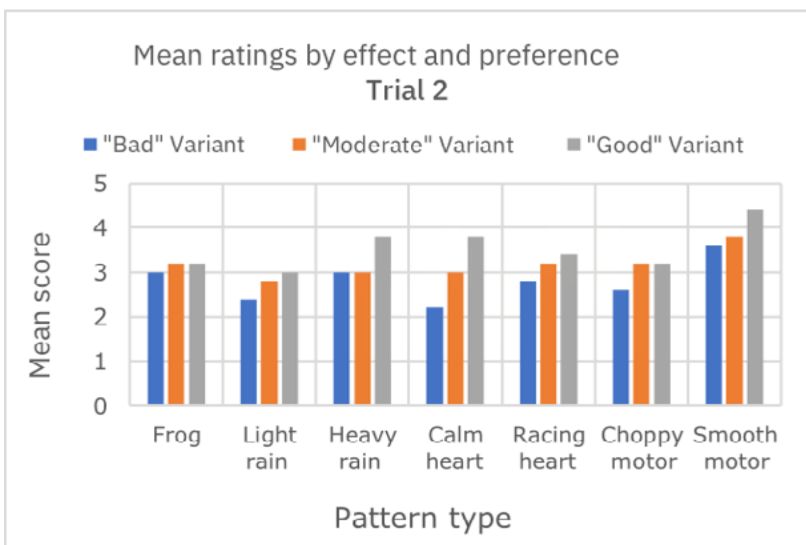


Chart 2: *This chart graphs the average scores for 3 variants of the 7 patterns, for Trial 2. In Trial 2, most participants favored variants of the smooth motor, heavy rain, and calm heartbeat.*

What I learned

From this study, I learned that pressure-based stimulation required hardware much larger than a small vibrating motor to produce a recognizable level of stimulation, making it less suitable to be incorporated into everyday technology. While evaluating a prototype of a haptic interface, novelty effects have an influence on the perception of the prototype and the interpretability of haptic patterns as task-relevant information because haptic interfaces are less common than visual and auditory interfaces. Touch-based interfaces can be quite emotive and may create a more immersive experience for users when paired with visual and auditory stimuli than interfaces that are solely vision- and audio-based due to their tangibility.

EVALUATING EVERYDAY TASKS WITH TECHNOLOGY

To determine which specific tasks with everyday technology would most benefit from multi-sensory interfacing, I evaluated everyday tasks according to different criteria such as the current scenario, existing challenges, potential approaches for multi-sensory interfacing, and the opportunities for this thesis. Some of the tasks I identified as benefiting from multimodal interfacing include capturing experiences, navigating spaces, receiving alerts and alarms, and timekeeping.

Capturing experiences

Currently, experiences are captured using audio and visual channels. Information such as depth of field, color, texture, and light are recorded, and current technologies support capturing pictures in high resolution and stereo audio. Additionally, sound and visual channels can be combined with time to capture experiences in motion as videos. Technology has also been developed to capture 360 photos and videos that can be viewed using immersive headsets.

Research explains that vision dominates the other senses to create an understanding of the environment around us and that audio can strengthen the visual stimuli. However, the lack of engagement of proximal senses such as touch and smell limits the immersiveness of reliving captured experiences. Combining multiple modalities as opposed to focusing on one or two of them results in a more accurate capturing of experiences, making them more believable and immersive.

Potential approaches to make interactions multi-sensory:

Tactile aspects of an experience can be captured with the help of an input device that can measure the force of touch that a user perceives during an experience. In addition, peripheral devices equipped with technologies such as those found in Headspace can be used to capture the olfactory signature of an experience (*Never Been Sniffed: Biotech Unlocks Mysteries of Scent – CNN Style*, n.d.).

Opportunities for this thesis:

Currently, VR and AR technologies are being used to capture experiences in increasing detail. Peripheral devices such as 360-degree cameras are easily accessible allowing users to capture their entire surroundings beyond the fixed resolution limited by smartphone cameras. Affordable head-mounted displays are also becoming popular, allowing users to view the content captured in an immersive environment. Given the richness of current visual tools, the addition of haptics might only marginally make the experience more immersive and may not have a significant impact on the user's ability to recall or revisit events accurately. As a result, this thesis will look to other everyday tasks to define significant opportunities for positive impact through the use of multi-sensory interfacing.

Timekeeping

Users currently rely on visual cues to check the time on their personal digital devices. Users can also use a voice interface to check the time and receive an audio response. Smartwatches, like the Apple Watch, can relay the time to users via haptics but this approach puts a high perceptual load on the user because it requires the user to pay close attention to a haptic pattern that consists of a number of distinct impulses that corresponds to the time. Research has shown that people's ability to recognize the time of day depends on numerous factors and they usually struggle to identify the time of day accurately without external aids. However, in contexts where users need to focus on their environment, such as when driving or navigating in a crowded environment, diverting their attention to check the time can be dangerous.

Potential approaches to make interactions multi-sensory:

People typically check or monitor the time throughout the day as a quick reference and to verify that they're on schedule. Various modalities can be used to not just communicate absolute time to users, but they can also convey a sense of urgency or the lack thereof with regards to users adhering to and tracking their daily schedules.

Opportunities for this thesis:

Although using multiple modalities for timekeeping purposes may be beneficial, only a few contexts where users have limited attention available may warrant the integration of multi-sensory feedback. Furthermore, telling the time via modalities that extend beyond vision and sound might require a significant amount of training. For these reasons, other everyday tasks were explored in this thesis as points that indicate the potential for significant benefit of multi-sensory interfacing.

Alerts and alarms

Everyday devices are capable of providing visual, haptic, and audio alerts and these alerts are customizable. For example, users can choose the volume and the type of an audio alert, they can choose to have strobing lights — produced by the flashlight on smartphones — and they can also elect to have haptic alerts with customizable haptic patterns. Although everyday devices currently engage a range of modalities, they are not context-sensitive because they are incapable of automatically providing less disruptive alerts when the environment is quiet. Research has shown that olfactory notifications are significantly less disruptive than auditory and visual notifications. However, currently, everyday devices do not use the smell modality to deliver alerts and alarms.

Potential approaches to make interactions multi-sensory:

There exist important opportunities to develop context-sensitive alert systems that respond to ambient sound levels and learn from the way users interact with their devices. Research also points to the potential benefit of portable peripheral devices that are able to deliver olfactory alerts from users' smart devices.

Opportunities for this thesis:

Currently, smartphones include features like Attention Aware on the iPhone, that detect when a user, who has picked up a device, is looking at it (*About Attention Aware features on your iPhone X or iPad Pro*, n.d.). In response, the volume of the alert is lowered on the phone. In contrast, smartphones currently do not have olfactory interfacing capabilities or the technology to support them seamlessly. In addition, incorporating an olfactory interface in smartphones would require quick removal from the air, which can be challenging to fit into a pocket-sized device. Given the current limitations in leveraging olfactory feedback as alerts and alarms in everyday devices, this thesis continues to investigate other everyday tasks as important areas for impact.

Navigation

Current navigation systems engage our vision with the use of maps and target hearing with the use of voice navigation, which are the senses we predominantly use naturally for navigation. Most current navigation apps on smartphones require users to direct their attention towards an app while navigating, which hinders spatial knowledge acquisition. Although research indicates that pedestrians who actively query the navigation system for instructions demonstrate high spatial knowledge acquisition, most current GPS navigation systems are highly automated and the system makes all the decisions autonomously without human participation. While conventional approaches may be beneficial in contexts like driving, where the system needs to give instructions with a low delay, ignoring users and making all decisions autonomously may undermine users' spatial memory and spatial knowledge acquisition.

Additionally providing directions via visual and aural modalities can distract users, can lead to a diminished awareness of their surroundings, and can even result in fatal accidents. Research has also revealed that divided attention between the "survey perspective" and the "route perspective" offered by the navigation application can hinder the user's ability to focus on their surroundings (Gardony et al., 2013).

Potential approaches to make interactions multi-sensory:

Haptic alerts can be incorporated into current navigation apps on everyday devices using peripheral interfaces. They could take the form of common accessories, such as a shoe, vest, belt, armband, glove, or ring. Existing smart devices like smartwatches may also be leveraged for this purpose. The device may be equipped with tactors that provide tactile feedback to users who are trying to navigate their environments. The device can also include a simple interface that users can leverage to actively query the navigation system. It's important to note that looking at a device may be dangerous while driving and the use of voice commands may be difficult for the system to decipher in noisy environments.

Opportunities for this thesis:

Current navigation apps on everyday devices can benefit considerably from multimodal interfaces. For example, the addition of haptics can help offload tasks that warrant visual and aural attention onto haptics. Although there are several niche devices that use haptics to aid in navigation, they typically are not easily accessible or not as ubiquitous as navigation displays that provide only visual and voice guidance. Since touch currently is not used as much as vision and sound in navigation tasks, leveraging current technologies to help users navigate efficiently with haptics has the potential to serve as a strong opportunity for an effective design intervention. Furthermore, the implication of reducing the burden on the eyes and ears while using navigation applications is salient because doing so may help users learn routes by being attentive to their surroundings, which in turn may prevent accidents. Therefore, for this thesis, I found navigation applications on everyday technology to benefit the most from the introduction of haptics as a modality to convey information.

RESEARCH QUESTION

How might tactile directional instructions in navigation systems affect spatial knowledge acquisition and attention to surroundings while navigating unfamiliar routes outdoors?

RELATED WORK

I surveyed several kinds of prototypes that offload information onto haptics to gain a clear understanding of existing related research and leverage discoveries gleaned from current efforts. The prototypes include devices that assist users in wayfinding and navigation, help the visually challenged to "see", and provide haptic feedback while users teleoperate a robot from a remote location. The goal of this inquiry was to gather insights on prototyping techniques and the technology used to convey information through haptics.

The BrainPort Vision Pro, designed and manufactured by Wicab, Inc is a sensory substitution device that aids the visually disabled in localization, navigation, and object recognition through electro-tactile stimulation. The device consists of a camera that is mounted onto an adjustable headset and comes in multiple sizes. The headset is equipped with controls for the user to operate the device and a rechargeable battery. The headset also has a tongue array attached to it that provides electro-tactile stimulation via hundreds of electrodes. The device enables its user to see by converting the video signal from the camera into electro-tactile stimulations that the user experiences on their tongue through the tongue array. White pixels from the camera translate into strong stimulations on the tongue array, grey pixels are felt as medium-level stimulation and black pixels are felt as no stimulation. This mechanism produces a pattern described as "moving bubbles" that is felt on the tongue, which enables blind users to “see with their tongue” (*BrainPort Vision Pro | United States | BrainPort Technologies*, n.d.).

Through its synesthetic system, the BrainPort Vision Pro demonstrates how we see with our brain and not our eyes. The eye is merely a source of information for the brain and can be a surrogate for other parts of our body. The skin, or the tongue, or tools like a camera can provide information to the brain, which then computes what is being seen. Using a camera for the eyes raises the question of body augmentation and human enhancement with technology. As a result, I asked are there multiple ways of constructing an image of the world, such as using each sense independently of each other (seeing the clouds in the sky), using them together to process information different kinds of information (feeling a smooth surface while simultaneously seeing the light reflected off it), using one sense as a surrogate for another (using the tongue to feel patterns that help the brain to see), augmenting a sense with technology (wearing night-vision goggles) or surrogating a sense with technology (using a camera as an eye)?

In the paper, *Interacting with Virtual Environments using a Magnetic Levitation Haptic Interface*, Berkelman, Hollis, and Sacludean report on their investigation of haptic feedback provided through the use of a magnetic levitation device (Berkelman et al., 1995). The approach enables computer users to interact with virtual environments in an engaging and intuitive way. The researchers argue that multiple modalities must be leveraged for humans to process information and interact with computers effectively. Through this paper, the authors emphasize that virtual reality displays merely provide a realistic appearance of the environment but they don’t allow users to feel the environment or manipulate objects. The paper cites tasks such as flight simulators, force reflecting teleoperation and telepresence, and simulated molecular docking, that currently use a haptic interface as examples of multimodal computer interfaces. In these instances, researchers speculate that CAD modeling systems or any computer task that involves an input device like a mouse, tablet, or joystick could be augmented with a haptic interface. In this work, the researchers provide users both realistic and responsive interactions with simulated environments. Nonetheless, haptic displays and devices have numerous challenges. One obstacle includes uniting haptic interface controls and physical simulations to render realistic interactions with virtual environments. Working with haptic devices, like manipulator’s arms, presents another challenge because their dynamic behavior includes parameters like back drivability, inertia, hysteresis, and friction that lead to inaccurate haptic feedback. However, using magnetic levitation technology enables these challenges to be overcome because it offers a high degree of control and the absence of cables and linkages.

Since haptic interfaces with magnetic levitation are compact enough to be placed on a desktop, they can be highly effective in augmenting visual feedback with appropriate haptic feedback. This approach may not only improve a user's perception of a virtual environment by providing realistic feedback via multiple sensory modalities, but it may serve to reduce the burden on the eyes while manipulating objects in a virtual environment. Haptic feedback from the magnetic levitation device along with realistic renderings of the virtual environment may be further augmented with synchronized audio feedback from a speaker, resulting in a rich sensory experience for the user.

The paper *Feel Effects: Enriching Storytelling with Haptic Feedback* by Israr et al., aims to lay the groundwork for a usable haptic vocabulary with a framework that allows additions to the library in a systematic manner. The researchers point out that although haptic technologies can be used to enhance the experience of storytelling and make it more immersive than current approaches, there still exists a lack of vocabulary and a means to create realistic and convincing haptic patterns that correspond to the content (Israr et al., 2014). The researchers rendered the haptic patterns using a vibrotactile array embedded in a vest that would stimulate the receptors onto the back of the user. Their work suggests potential use cases such as gaming chairs, theater seats, and ride vehicles. The researchers produced a set of 40 "feel effects" that range from precipitation to animal locomotion. They define a "feel effect" as mapping a "meaningful linguistic phrase" to a "rendered haptic pattern." Parameters such as the number of actuators activated, time delay, duration of activation, and intensity were varied to produce the different feel effects. The participants were also provided an interface that they could use to tweak the haptic sensation to best correspond to the language phrase.

Given the lack of haptic prototyping and testing tools that currently exist, this work successfully demonstrates a way to prototype and test a haptic feedback device that informed the testing of my haptic prototype in this thesis. Inspired by the experimental interface that the researchers created that allowed participants to experience different versions of the haptic pattern, I create variations of predetermined haptic patterns that my participants could experience and rate based on their appropriateness. Israr et al., also suggest a method for making haptics accessible to designers via a library of haptic patterns corresponding to language phrases. Through my thesis I aimed to extend their work, further aiding the design for haptics.

The use of haptics in providing assistance in indoor and outdoor pedestrian navigation has been successfully demonstrated in research. However, as researchers Satpute, Canady and Klatzky have identified, considerably lesser work has been done in applying haptics to accessing targets in the peripersonal space or the space that immediately surrounds the body. In their paper *FingerSight: A Vibrotactile Wearable Ring for Assistance with Locating and Reaching Objects in Peripersonal Space*, they prototyped a finger mounted haptic feedback device and used it to aid visually-challenged people in accessing targets within arms reach. The prototype consists of four vibrating tactors that are placed in the two perpendicular axes (up-down, left-right) embedded on an elastic Velcro band, which is placed on the forefinger of the dominant hand of the user (Satpute et al., 2019). A small camera mounted on top of the band was used to collect input from the user's surrounding environment, which was then analyzed using a computer vision algorithm. Through repeated testing, the researchers determined that the user receives two vibrotactile feedbacks per second for optimal performance, which could be increased with the user's proficiency. Studies were also carried out to determine the appropriate strength of the vibrotactile feedback that sought an impulse that was just enough to provide sufficient stimulation but prevent unintended transmission across the rest of the ring. The prototype enabled blindfolded participants to successfully localize objects in their peripersonal space by guiding them to the target with vibrotactile feedback.

The research done for FingerSight proved beneficial for this thesis in that it aided the exploration of how haptics can guide people in their environment. As the researchers point out, this device does not depend on audio/sonic feedback. Therefore, it would not cause any disruptions or interfere with the users' ability to attend to sounds in their environment. Additionally, this prototype consists of a ring form, which causes the area of the user's body that receives vibrotactile feedback to be smaller than if the device were a glove, sleeve, or vest form and therefore is minimally obtrusive.

Several vibrotactile belts have been developed that have shown strong potential to assist users in wayfinding. A tactile belt was developed by Van Erp et al. that consisted of eight vibrotactile actuators (Erp et al., 2005). The actuators were placed at equal intervals and represented the cardinal directions. They had a contact area of 1.5 by 2 cm and vibrated at a set frequency of 160 Hz. The hardware consisted of a minicomputer, a digital compass, batteries, a GPS, and a tactile display. The prototype conveyed both the direction and the distance to a waypoint. The directional information was conveyed by the location of the vibrating actuator and the distance information was communicated using the rhythm of the vibrations (i.e. the smaller the distance, the quicker the rhythm of the vibration). The evaluation of the prototype was conducted with 12 sighted pedestrians on routes that were between 360 and 390 m in length, and the routes had the first two waypoints in common. The results of the evaluation indicated that distance information may not be crucial for efficient wayfinding assistance. However, a confounding variable was the lack of statistical power of the study to confirm the hypothesis. Another possibility for the discrepancy may have been that the participants were unable to clearly interpret the information.

Similarly, Heuten et al. developed Tactile Wayfinder, which consisted of a belt with six vibrational motors. The design of the belt was developed to use as few motors as possible to maintain optimal flexibility in the belt and six was found to be ideal (Heuten et al., 2008). The placement of the vibrational motors allowed for a precision of 60º. Two adjacent motors indicated an in-between direction to increase the resolution of the tactile interface. Pielot and Boll developed another iteration of the Tactile Wayfinder that consisted of 12 vibrational motors and provided the direction of the next two waypoints (Pielot & Boll, 2010). The design system of the belt consisted of two tactile outputs that were presented to the user every 4 seconds. The first output was a pulse like a heartbeat and represented the waypoint that was immediately next. This output was repeated five times by the appropriate tactor corresponding to the direction of the waypoint. The second output in the sequence was represented by a single pulse and indicated the “look-ahead waypoint”.

From this audit, I found that most of the haptic navigational guidance systems used vibration as a means to convey directional information. I believe they took this approach because vibrational motors are compact and consume less power, which makes them well suited for wearables. The vibrotactile actuators were positioned mostly in cardinal directions and the location of the actuator indicated the direction of the waypoint. Furthermore, Pacinian corpuscle, the mechanoreceptors in the skin that respond to vibration, is the most sensitive mechanoreceptor in the body, rendering vibration as an ideal choice of haptic feedback. Vibrations are also typically easier to distinguish from other touch-based stimuli the user may encounter in everyday life.

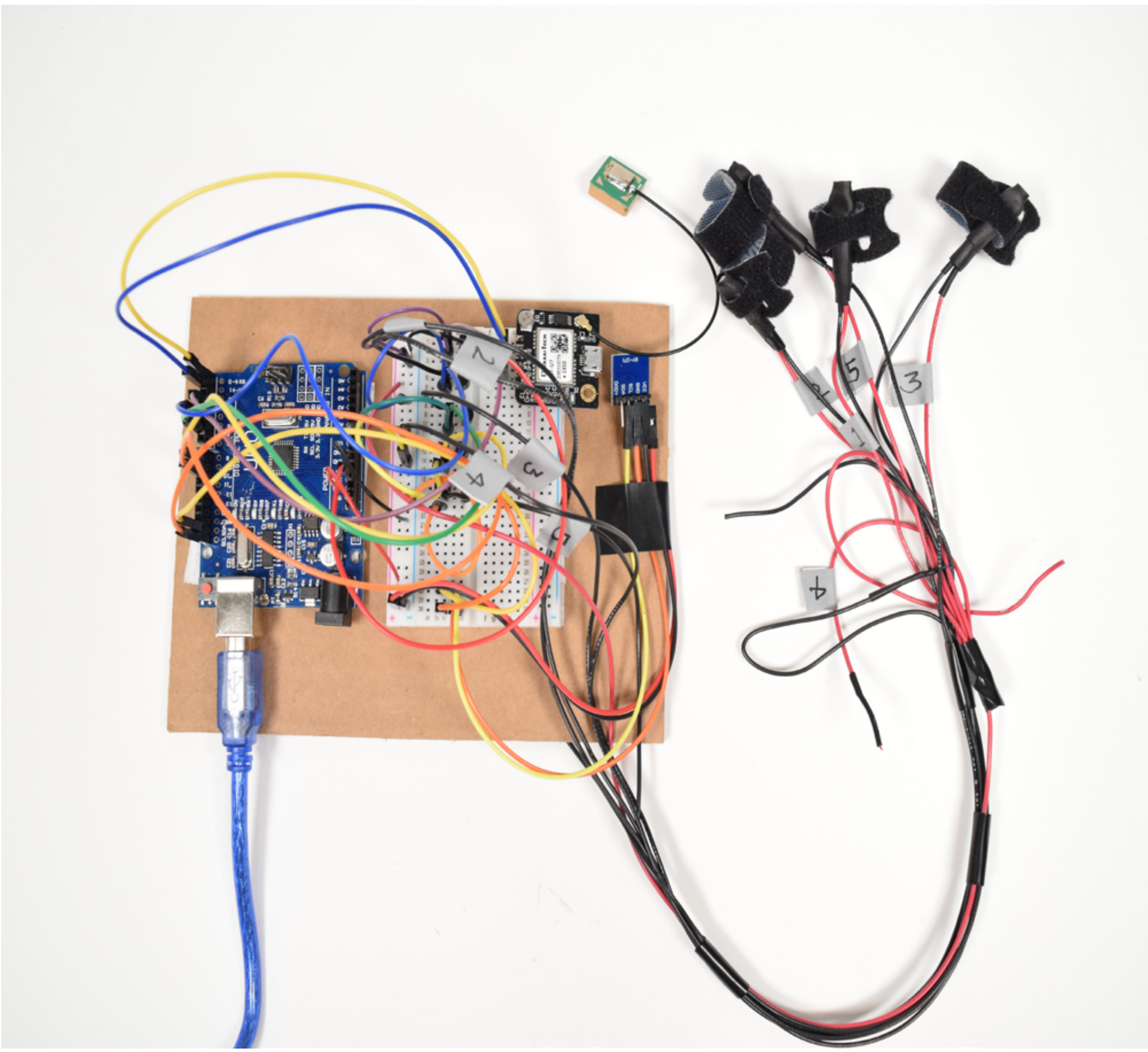
05

PROTOTYPE DESIGN

Based on discoveries gleaned from my generative research, I sought to investigate the influence of various parameters of the tactile stimuli on people's perception of information being conveyed in the context of simple outdoor navigation. As a result, I created a prototype device that enabled this study.

The hardware was comprised of an Arduino Uno, 4 DC 3V-5V ultra-thin button coin vibration motor, 4 size adjustable Velcro rings and a power bank to supply power (Figure 6). The vibrotactile motors were mounted onto the adjustable Velcro rings so that the prototype could be worn easily by multiple participants easily.

Figure 6: *Shown here is the prototype tactile device comprised of an Arduino Uno, 4 vibration motors, 4 size adjustable Velcro rings and a power bank to supply power.*



STUDY QUESTIONS

I built a haptic prototype and conducted user-testing of the device in an effort to develop a clear understanding of how people interpret stimuli in the context of navigating physical spaces. Based on the analysis of findings, I also aimed to identify patterns of interpretations that would inform the creation of a tactile language that would prove useful to other designers who strive to build effective multi-sensory tools to aid task completion. Therefore, I investigated:

Interpretability of the tactile design language

How might the design of the tactile language affect the interpretability of the tactile stimuli as directional instructions?

More specifically, I probed questions related to facets of navigation as follows:

Position of tactile stimuli

How might the position of the tactile stimuli convey the direction in which the user is instructed to move?

Given that it is critical for people to grasp their location in space and steps they need to take to reach desired waypoints, I deeply explored the use of vibrotactile stimuli to aid their understanding. In an effort to investigate the question I posed, I leveraged existing research by Van Erp et al. that describes people's common interpretations of direction and used it to frame my hypothesis (Erp et al., 2005). Thus, in the prototype, the vibrotactile motors were mounted onto 4 adjustable rings that were placed on the user's index finger, middle finger, ring finger, and little finger of the dominant hand. The position of the rings corresponds to spatial positions in the user's surrounding environment. For example, the ring on the leftmost finger of the hand corresponds to a left turn from the user's frame of reference, the ring on the rightmost finger corresponds to a right turn from the user's frame of reference, and feedback on the middle finger and the ring finger correspond to continuing straight on a path.

Time delay of tactile stimuli

How might the time delay between consecutive tactile stimuli in a tactile feedback pattern influence the perception of urgency of the information being conveyed?

Although people may grasp what stimuli mean in isolated instances, in real scenarios they will receive them in succession as they move through spaces. Therefore, the pacing of stimuli must be studied to ensure that people understand individual impulses that are intended to be separated and distinct. To study the effects of time delay on navigational understanding, I created a series of tactile patterns—each having a different time delay between consecutive stimuli. Therefore, a pattern with a fast rhythm was created with a small time delay between two consecutive stimuli within the pattern, and conversely, a pattern with a slow rhythm was created with a large time delay. I hypothesized that a fast rhythm pattern would convey a sense of urgency and time sensitivity with regard to the information being conveyed when compared to the slow rhythm pattern.

Intensity of tactile stimuli

How might the intensity of tactile stimuli affect the perception of the criticality of information being conveyed?

A hierarchy of alerts needs to be established so urgent alerts that warrant immediate attention can be easily distinguished from alerts that might not be as critical. I used the intensity of vibration as a parameter to establish a hierarchy where critical alerts are accompanied by tactile stimuli that are more intense than the ones that accompany a less critical alert. I varied the intensity of the pattern by changing the intensity at which the vibrotactile motor vibrated. I achieved this goal through pulse-width modulation and varied the power supplied to the vibrotactile motor.

Aiding Spatial Knowledge Acquisition and Attention

How might tactile directional instructions affect spatial knowledge acquisition and attention to the surrounding environment?

Navigation systems are widely used to assist wayfinding and have improved people's navigation performance in recent years. However, studies have shown that navigation systems hinder spatial knowledge acquisition and the ability to attend to the surrounding environments while navigating. Therefore, I investigated the benefits that offloading directional information to touch might have on spatial knowledge acquisition and attention to the surrounding environment. For this purpose, I prepared a questionnaire to evaluate spatial knowledge and attention.

User's Perceived Confidence and Clarity

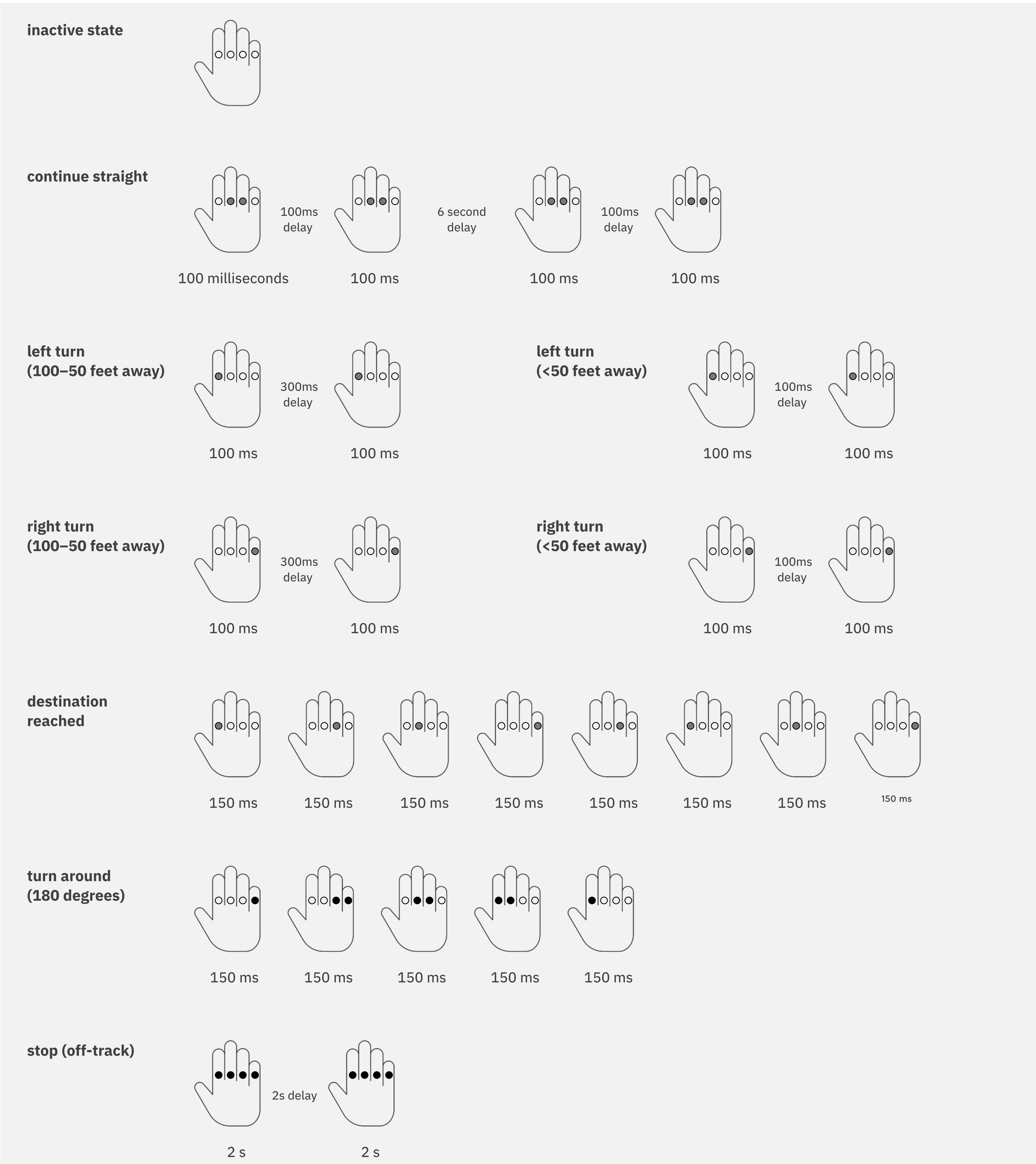
How might the nature of tactile directional instructions affect people's perceived confidence in their ability to follow directional instructions and reaching an intended destination and their perceived clarity regarding those instructions?

In addition to providing strong navigation performance, it is also important to understand users' perceived level of confidence and their perceived clarity of directional instructions provided by a system to ensure they are comfortable using the navigation system and the system feels natural to them. A Likert scale was devised to assess the participants' confidence level in their ability to orient themselves in space and find their way and another Likert scale was developed to assess the participants' perception of the clarity of the instructions provided.

TACTILE INTERFACE DESIGN

Based on my inquiry of sensation, and perception, design methods, and my research questions and hypotheses, I developed a tactile design language to assist pedestrians in the context of simple outdoor navigation. Several vibrotactile patterns were created using the prototype described in an earlier section. These patterns were then evaluated with ten participants in a study described in the following section. The vibrotactile patterns were created by manipulating the number of vibration motors that were activated, the intensity of vibration, the location of the vibration motor activated, and the delay between each successive tactile stimulus. The vibrotactile patterns aimed to communicate various information to assist a pedestrian in wayfinding such as the direction and distance to the next waypoint, the urgency of the information being conveyed, and system notifications such as 'stop' and 'destination reached'. As a result, the following patterns were created: continue straight, left turn in 50–100 feet, left turn in less than 50 feet, right turn in 50–100 feet, right turn in less than 50 feet, stop, turn-around, and destination reached (Figure 7).

Figure 7: *The figure shows the tactile patterns created with the prototype as part of a tactile design interface that communicates directional instructions.*



STUDY DESIGN

I formulated a four-part study protocol to evaluate the efficacy of the prototype and investigate the research questions I posed. 10 sighted participants between 24 and 34 years-of-age who were university students were recruited for the study.

Perception and training

In an effort to understand their perception of various stimuli and train them to use impulses as navigational instructions, study participants were introduced to tactile stimuli outside the context of navigational tasks at the start of the study. They were shown the prototype and it was positioned on their dominant hand (Figure 8). Participants were presented with the various tactile patterns at random and were asked to interpret them as navigational instructions. They were presented with the tactile patterns for an upcoming left turn, an immediate left turn, proceeding straight ahead, an upcoming right turn, an immediate right turn, and stop. After each pattern, they responded with their interpretation of the pattern.

Figure 8: *Shown here is the prototype mounted on a participant's dominant hand.*

Two navigation tasks

After assimilating to stimuli used as navigation cues, participants engaged in two navigation tasks. One task asked participants to navigate spaces using a visual tool that was provided to them, whereas the other task called for them to use the prototype I created. Half of the participants navigated the space using the visual tool before the prototype and the other half used the prototype first. In the visual navigation assistance task, the participants received directional instructions via Google Maps and in the tactile navigation task, the participants received directional instructions via the haptic prototype.

The participants watched one of two pre-recorded point-of-view videos of a pedestrian navigating along a simple route outdoors for five to seven minutes. The videos were played on two large displays to simulate an immersive environment of navigating an outdoor route (Figure 9). The routes involved three-to-four waypoints between the origin and the destination and had a number of visual and wayfinding cues such as a passersby and significant landmarks. While each participant watched the video they walked in place. At the same time, the participants received directional instructions that assisted them in navigation. The participants were asked to respond to the directional instructions at every waypoint by making the navigation decision as they would if they were navigating in the real world and each of their responses was noted. For example, if the navigation system directed the participant to turn left, then the participant would turn to their left by rotating their body in place. The study setup ensured that participants

Figure 9: *Shown here are participants engaged in the navigation tasks—tactile navigation task (Left); visual navigation task (Right).*

would always have an egocentric view that would prevent mental rotation transformations interfering with their spatial navigation performance. While performing the task, the participants were asked questions regarding their interpretation of the directional instructions and encouraged to think aloud. Conversations with the participants were framed to mimic real-world distractions that are irrelevant to the task in an effort to understand the perceptual load on the participants while using the two different navigation systems. A navigation system that has a high perceptual load would consume attentional resources faster than a navigation system that has a low perceptual load making it more challenging to focus on task-irrelevant stimuli.

After each of the navigation tasks, the participants were asked to rate their confidence in their ability to follow directional instructions on a Likert scale where 0 meant they were not at all confident and 10 meant they were extremely confident in following directions from the navigation system. The participants were also asked to rate the clarity of the instructions provided by each of the navigation systems on a Likert scale where 0 meant the instructions provided by the navigation system had no clarity at all and 10 meant the instructions were extremely clear without any ambiguities.

Post-navigation task questionnaire

After each of the navigational tasks, the participants completed a questionnaire in which they were tested on their attention to the visual cues in the videos and their spatial knowledge acquisition—particularly landmark and route knowledge. Siegel and White put forth a framework for spatial knowledge acquisition in which they describe three stages of spatial knowledge acquisition namely landmark knowledge, route knowledge, and survey knowledge (Siegel and White, 1975), which I used to inform the structure and analysis of participants' discrete understanding of spaces. They describe landmark knowledge as the knowledge of salient features, scenes, or locations specific to the environment a person is navigating. Route knowledge refers to the stage where decisions pertaining to navigation are made in relation to landmarks in the environment—for example, turn left at the church.

The questionnaire asked participants to recall the navigational decisions they made at various landmarks in the environment shown throughout the video (Figure 10). The participants were also prompted to recall and correctly identify the landmarks that were present in the video that they saw during each navigation task.
To evaluate the participants' ability to attend to other tasks while navigating, they were asked to describe a detail of the conversation they had during each navigational task.

Evaluation

The participants' ability to follow the directional instructions correctly was evaluated based on the number of correct responses to the directional instructions they received during the navigational tasks that were during the task. For example, if the navigation system directed the participant to turn left, a correct response was recorded when the participant turned to their left by rotating their body.

Visual attention to the environment was judged based on the time the participants spent looking at the point-of-view video during the navigation tasks. The time spent looking at the video was considered to be directly proportional to the participants' visual attention to the environment. The participants' spatial knowledge acquisition was evaluated based on how many environmental details they were able to correctly recall in the questionnaire. The number of questions correctly answered was considered to be proportional to the participant's spatial knowledge acquisition. That is, the higher the number of correct recalls, the better is the spatial attention and landmark knowledge acquisition.

Figure 10: *Shown here is a still frame from one of the navigation videos that participants saw during the study. In the post-navigation questionnaire, the participants were asked what turn (if at all) they made at this junction to test their attention.*

Tactile pattern co-design

After the participants completed each questionnaire, they were given the opportunity to tweak the different tactile patterns to make them more intuitive and effective for them. The participants made adjustments by verbally describing changes they might like to make to each of the patterns, I then tweaked the patterns, the participants felt the new changes, and then verbally responded with their perception of the adjustments.

STUDY OUTCOMES AND ANALYSIS

Interpretability of directional instructions

During the initial perception analysis and training period, when the participants were first introduced to the haptic prototype and the tactile patterns, most of them were able to correctly interpret what the patterns were conveying in the context of navigation. Furthermore, all the participants were able to follow all directions by the navigation systems and respond correctly during both the tactile and visual navigation tasks.

Position of tactile stimuli

Although 6 participants were able to interpret the position of the tactile stimulus as the direction to the next waypoint (for example, a vibration on the leftmost finger representing a left turn), there was confusion among 4 of the participants with regard to this piece of information. Since none of the participants had used tactile navigation systems prior to the study, novelty effect could have had an influence on the participants' interpretation of the tactile patterns.

Time delay of tactile stimuli

The participants successfully discerned the different levels of urgency through changes in the rhythm of the patterns. 7 out of 10 participants correctly identified a fast-paced tactile pattern as more urgent than a slow-paced tactile pattern.

Intensity of tactile stimuli

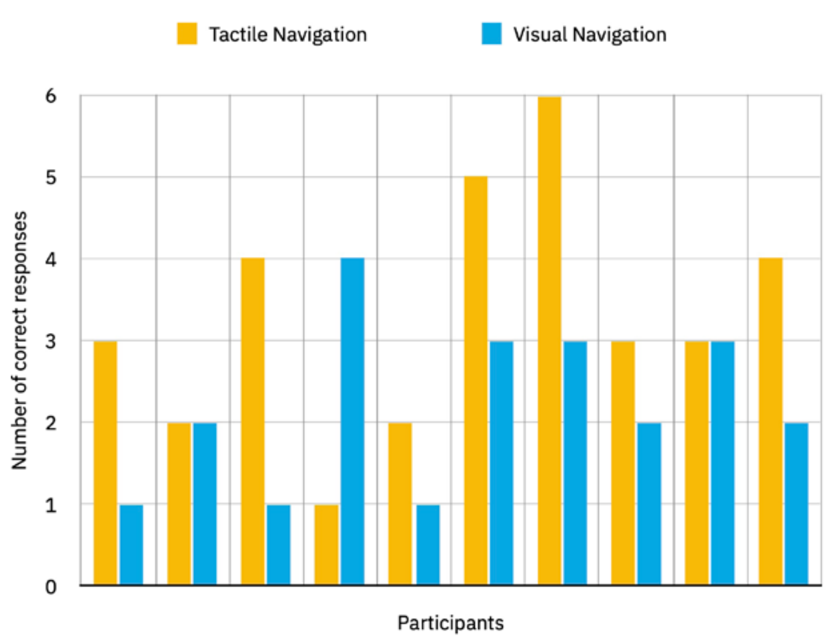
The participants also correctly responded that a tactile stimulus of higher intensity conveyed more critical information than a tactile stimulus of lower intensity. All participants were able to interpret the intensity of the tactile stimulus as the criticality of the information being conveyed.

Aiding spatial knowledge acquisition and attention

In order to evaluate the degree of spatial knowledge acquisition in the participants after each navigation task, I referenced the data collected from the post-task questionnaire. The participants' responses indicate that they were able to correctly recall the landmarks and route details 55% of the time post the tactile navigation task and 36.6% post the visual navigation task (Chart 3). In addition, participants were able to visually attend to the pedestrian navigation video for the entire duration of the tactile navigation task. On the contrary, they spent an average of 24% of the task time looking at the map on a phone screen for directions in the visual navigation task (Chart 4). This finding is in accordance with my initial hypothesis that tactile navigation systems effectively promote spatial knowledge acquisition because the participants' visual attention is not occupied by the tactile navigation system, and therefore would not hinder the participants' ability to visually attend to their environment. Furthermore, participants also reported that the tactile navigation system was less demanding cognitively when compared to the visual navigation system.

The participants were also evaluated on their ability to attend to tasks that were irrelevant to their main goal of navigating. Their ability to recall a detail of the conversation they engaged in during the navigation tasks in the post-task questionnaire was assessed. 8 out of 10 were able to successfully recall a conversation detail after performing the tactile navigation task. In comparison, 7 participants correctly recalled the conversation detail after the visual navigation task. The slightly higher recall rate of a task-irrelevant detail while

__Chart 3:__ This chart graphs the number of correct responses each of the participants provided in the post-task questionnaire. Most participants provided a greater number of correct responses to questions after the tactile navigation task than they did after the visual navigation task.



using the tactile navigation system indicates that the participants' ability to attend to other tasks while using the navigation system is higher than while using a visual navigation system. This finding confirms that the participants indeed had a higher ability to engage in their surrounding environment when assisted by a tactile navigation system to navigate unfamiliar routes which further confirms the lower cognitive load of the tactile navigation system compared to the visual navigation system.

User's perceived confidence and clarity

A user's confidence level in their ability to navigate without losing their way was assessed using a Likert scale in which a high rating corresponded to a high level of confidence. Another Likert scale was developed to assess a user's perceived clarity of the directional instructions provided by the navigation system. The rating on the scale was directly proportional to a user's perception of the clarity of the instructions provided.

The mean rating of the participants' confidence level in their ability to follow directions in the tactile navigation task using the Likert Scale was found to be 8.5 and in the case of the visual navigation task, it was found to be 7.5 (Chart 5). The higher confidence rating for the tactile navigation system indicates that the participants felt more confident in using the tactile directional instructions than the visual tool. This finding may result from the reduced informational load evident in the tactile navigation system when compared to the visual navigation system that provided more information to the participants such as contextual information, numeric distances to the waypoints, survey and first-person perspectives, and street names.

Chart 4: *This chart graphs the percentage of the task time the participants spent looking away from the point-of-view video and at the navigation system in the visual navigation task.*

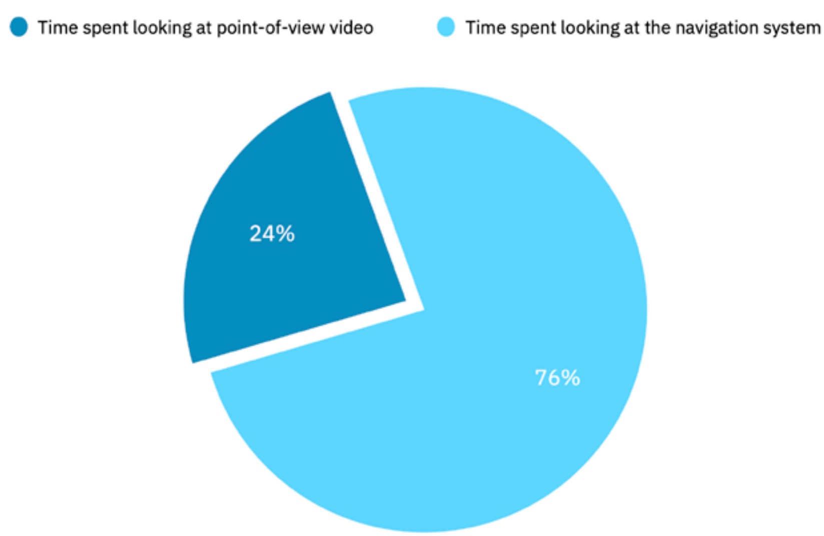
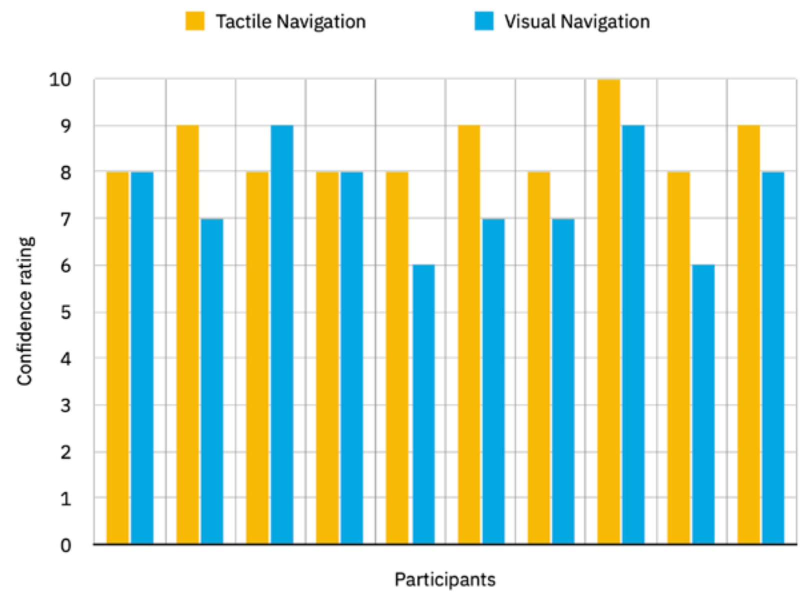
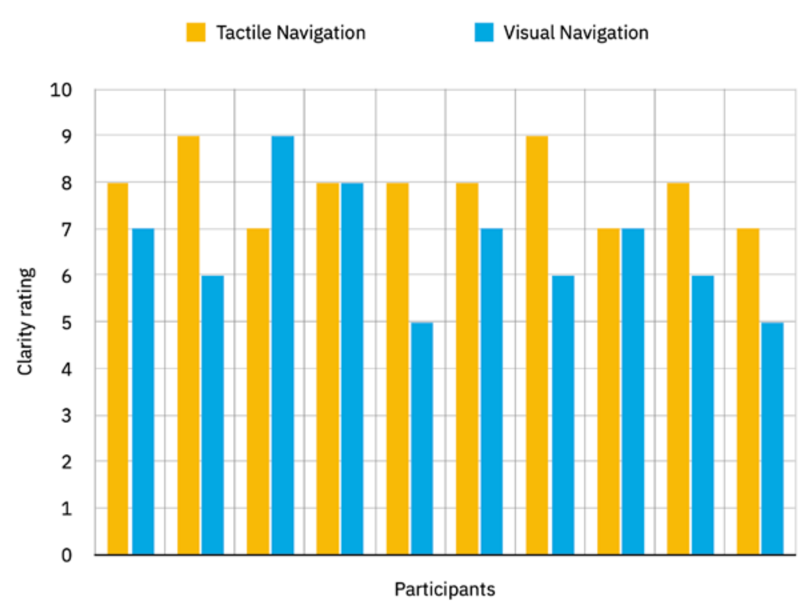


Chart 5: *This chart graphs the participants' rating of their confidence in their ability to orient themselves and navigate in space using the tactile and the visual navigation systems.*



A similar trend was seen in the case of the Likert Scale ratings of clarity levels of the directional instructions provided by the tactile and the visual navigation systems. The mean rating for the clarity of the instructions provided by the tactile navigation was found to be 7.9, and 6.6 in the visual navigation task (Chart 6). The participants indicated that the simplified directions provided by the tactile navigation system were more clear and easier to follow than the instructions provided by the visual navigation system because of the constant perspective shifts in the visual map that may give rise to mental rotation transformation challenges that may impact navigation performance. Additionally, any lag in the updating of the first-person perspective that was caused by the GPS and accelerometer could also have exacerbated this issue.

Chart 6: *This chart graphs the participants' rating of the clarity of directional instructions provided by the tactile and the visual navigation systems.*



06

DESIGN RECOMMENDATIONS

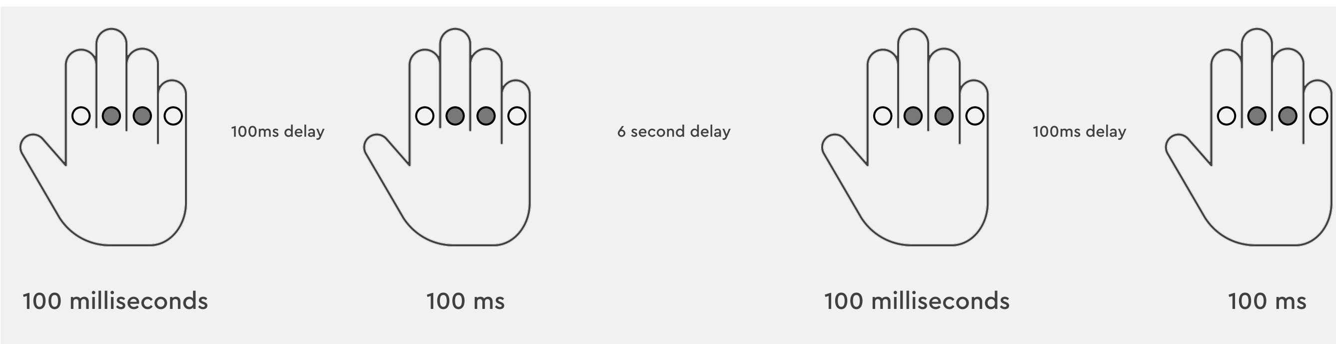
BUILDING A TACTILE DESIGN LANGUAGE

Based on insights gleaned from the study I conducted, I established a set of design recommendations that aim to guide others in their design for haptics as a modality to convey information in everyday technology that assists users in their completion of daily tasks.

Use an appropriate intensity for tactile alerts

High-intensity alerts that appeared frequently or that lasted for a long duration of time were perceived by users to be intrusive and distracting. For example, from the study, I found that when the stimulus intensity was high in the 'continue straight' tactile pattern that provided confirmation to the participant that they were on the right track, the participants found it uncomfortable since the alert was repeated frequently (Figure 11). This harmful effect could be mitigated by ensuring that alerts that appear frequently have a lower intensity than those that don't appear as often.

__Figure 11:__ Shown here is an illustration of the 'continue straight' tactile pattern that had a 'medium' intensity of 125 Hz.



Use an appropriate rhythm for tactile alerts

Persistent, fast-paced tactile patterns were perceived among users to be more time-sensitive than tactile patterns that had a slower pace, which caused participants to immediately attend to the alert (Figure 12 and Figure 13). Users' strong perception and response to rhythmic stimuli can be leveraged to successfully convey the time-sensitivity of an alert to users, which can help them distinguish between high- and low-priority messages.

__Figure 12:__ Shown here is an illustration of 'left turn in 50–100 feet', a slow paced tactile pattern that had a delay of 300 ms between successive tactile stimuli.

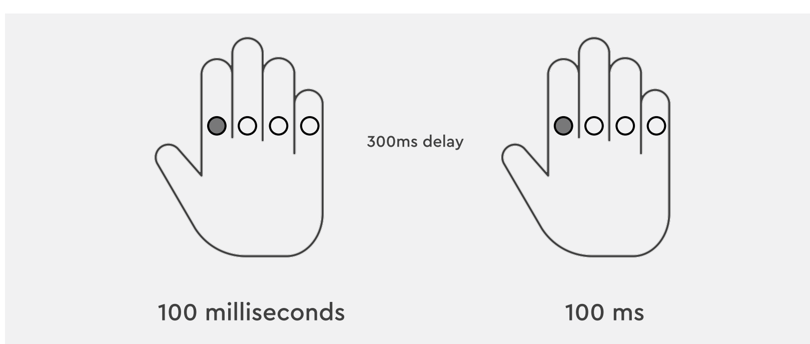
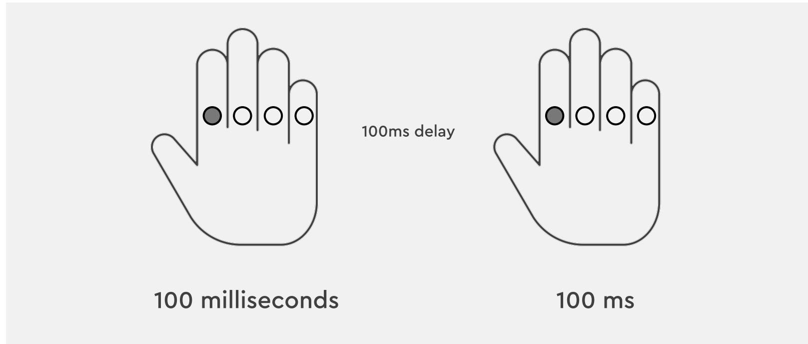


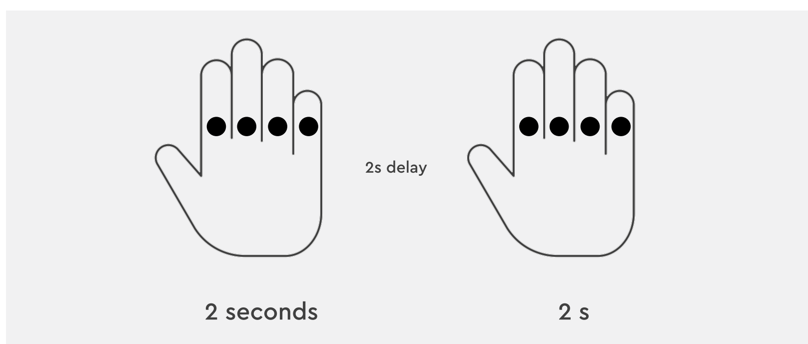
Figure 13: *Shown here is an illustration of ‘left turn in less than 50 feet’, a fast paced tactile pattern that had a delay of 100 ms between successive tactile stimuli.*



Make distinctions between different kinds of tactile alerts clear

Subtle changes in tactile patterns lead to ambiguities in their interpretation among users. This effect was seen to be exacerbated by the increase in attentional demands placed on users when engaged in multiple tasks, such as following directions while attending to a conversation. Creating clear distinctions between different alerts could help reduce the cognitive demand placed on users and minimize confusion in the perception of their meaning. For example, the ‘stop’ tactile pattern was designed to be distinctly different from the ‘continue straight’ tactile pattern since the former was intended to alert the participant when they were on the wrong track while the latter was intended to provide confirmation to the participant that they were on the right track (Figure 14).

Figure 14: *Shown here is an illustration of the ‘stop’ tactile pattern that had a ‘high’ intensity of 250 Hz designed to quickly grab the user’s attention if they went off-track.*



Design alerts specific tasks and contexts of use

People interpret alerts based on their context and the task with which it is associated. In this study, the persistent fast rhythm tactile pattern on the left-most finger was interpreted as turn left now because participants were engaged in navigation tasks. However, this might not be the case in the context of other tasks that use everyday technology for such activities as time-keeping or gathering information. Therefore, it is essential to evaluate the interpretability of an alert pattern in each context of use.

Use an appropriate resolution for alerts

The amount of information an alert can convey depends on the sensory modality it is engaging. In the context of navigation, a tactile alert was able to convey an approximate distance to the next waypoint while a visual alert was able to convey the exact distance to the next waypoint. Therefore, it is critical to be mindful of the affordance of the sense that is being engaged and to align information to it appropriately. This approach to multi-sensory communication could help designers effectively communicate information to users without overburdening their attentional and cognitive resources.

When appropriate, enable customization of tactile alerts

Sensory and perceptual capacities can vary greatly among people. Not only is it possible for some people to lack one or more sensory fundamental sensory capacity, but people's sensory capacities can be highly subjective as well. A tactile alert that might successfully work to alert one user, might annoy another. Therefore, as with all alerts, but it is also important to enable users to customize the various aspects of tactile alerts such as the intensity, the duration, and the rhythm of the tactile pattern.

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CONCLUSION AND FUTURE WORK

CONCLUSION

This thesis investigated the benefits of offloading directional instructions to touch. However, I believe the discoveries I made can also aid the design for interactions across multiple senses using everyday technology Strong foundational research exists that supports the benefits of effectively dispersing information across all the senses to reduce the perceptual load of a task. Nonetheless, the lack of prototyping tools and techniques available to design for senses, other than vision, still remains a significant challenge to the widespread adoption of multi-sensory design. Insights from my research on attention and perceptual load (Lavie, 2005) and my discoveries from this thesis study point towards a need to carefully design the distribution of information across senses and that such efforts are easily realizable using current technology. My research indicates the value of dispersing information across the senses such that a relatively large load is placed on those senses that are not critical for users to attend to their environment, particularly while performing tasks that have high attentional demands. This approach can help designers enhance users' experiences by minimizing their overall perceptual load.

NEXT STEPS

The next step for this thesis would be to evaluate the efficacy of the haptic prototype I designed in an outdoor navigation setup because it warrants widespread testing that include a range of settings and tasks. A GPS module and a triple axis compass were integrated with the prototype to enable it to assist users in navigating a simple route outdoors. The prototype is capable of guiding users through preprogrammed waypoints between an origin and a destination point. This study would also enable me to investigate the interpretability of the corrective tactile alerts designed to bring users back on track when they make mistakes and therefore it dynamically adapts to the navigational decisions users make.

Numerous robust tools and libraries have been developed for the purpose of designing interactions for vision. However, there is a significant gap in the tools and resources that exist for haptic design. I strive to further develop the tactile design language I designed and create a system that would enable the continued authoring of tactile patterns that can serve as a tool for those who wish to design for haptics.

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