Supporting Navigation with a Torso Wearable Tactile Display

by

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THESIS

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To Vasia, my other half, who has been my rock since the first day that I met her. Thank you for your love, support and patience. I couldn't have done it without you.

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VM

CONTRIBUTION OF AUTHORS

Chapter 1 presents some contextual and prerequisite information that is essential to understand the body of the thesis and places the dissertation question in the context of the larger field. Section 1.1 contains parts of a published manuscript (1) for which I was the third author and played a large role in its writing along with John Novak, Jason Archer and Prof. Steve Jones. Chapter 2 contains a literature review that presents previous related research in my field and highlights the significance of my research questions. Chapter 3 describes the design and development of the three SpiderSense prototypes and presents some of the preliminary results. Some of the text in the introductory paragraphs contains parts of the aforementioned published manuscript (1) and section 3.1 contains parts of a published manuscript (2) for which I was the primary author and major driver of the research, along with Brad Haggadone, Prof. Jason Leigh, Brian Kunzer, and Prof. Robert V. Kenyon. Chapter 4 outlines this dissertation's contributions, describes the design of the infrastructure and the various environment-to-vibration pattern and mapping techniques that have been developed. Chapter 5 represents a series of my own unpublished experiments, results and analysis that were used to answer the research questions of this dissertation. Finally, Chapter 6 concludes with the research presented in this dissertation, a discussion section and areas of future research.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

CHAPTER **PAGE**

TABLE OF CONTENTS (Continued)

CHAPTER **PAGE**

LIST OF TABLES

LIST OF TABLES (Continued)

TABLE **PAGE**

LIST OF TABLES (Continued)

LIST OF FIGURES

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LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF ABBREVIATIONS

ETA	Electronic Travel Aid
EVL	Electronic Visualization Laboratory
FOV	Field of View
HMD	Heads Mounted Display
HUD	Heads Up Display
IRB	Institutional Review Board
PCB	Printed Circuit Board
SA	Situation Awareness
SBDC	Small Business Development Center
SD	Spatial Disorientation
TSAS	Tactile Situation Awareness System
TVSS	Tactile Vision Substitution Systems
TCP	Transmission Control Protocol
QS	Quantified Self
UDP	User Datagram Protocol
UI	User Interface
UIC	University of Illinois at Chicago

LIST OF ABBREVIATIONS (Continued)

VR	Virtual Reality

SUMMARY

Umwelt, the German word for environment, is a psychology term referring to the individual's mental image of the surrounding world. This subjective universe is shaped by an organism's unique perception of the environment around them and, therefore, differs from individual to individual. In other words, organisms experience the world through their senses, construct the mental model of their vicinity, and react upon it. Hence, this image never remains static—instead it is constantly refined, as a result of the dynamic nature of the world. *Umwelt* is closely related to the concept of *Situation Awareness*, that is the perception of environmental elements, comprehension of their nature, and projection of their near future status with respect to time and/or space.

Sensory perception (exteroception) of the surrounding environment is, as a matter of fact, restricted to the limitations of biological senses. For example, although we consider humans with five fully developed senses (sight, hearing, touch, smell and taste) as able-bodied individuals, they are essentially blind to a multitude of information that constantly surrounds them. To put things into perspective, both human sight and hearing, can only perceive a fraction of information—part of the electromagnetic spectrum (light waves), and of the sound frequencies accordingly. However, as sensory systems differ among species, other creatures have an entirely different perceptual experience, as they are able to perceive a distinct spectrum of information.

Despite the fact that our limited human senses restrict our *Umwelt* and, therefore, our *Situation Awareness*, *Human Augmentics*, referring to technologies that expand the capabilities and characteristics of humans, allows us to peek into an invisible ”other” world. Thus, some important questions arise: What would the consequences of an expanded perception of the surrounding environment be, and how would that affect an individual’s *Situation Awareness*? Since our *Umwelt* is limited by genetics, how would individuals attune with characteristics and capacities that lie beyond human range? Could *Human Augmentics* possibly expand an individual’s *Umwelt*, leading to improved *Situation Awareness*?

Jakob von Uexküll (1864 - 1944), a German biologist who worked on animal behavior studies, cybernetics of life, and muscular physiology, is attributed for coining the term *Umwelt* (3). Uexküll’s *Umwelt* is the phenomenal world of a living animal, in which it exists and acts, and as a result is shaped according to the stimuli received from its senses. Due to the fact that individuals, even across the same species, sense the world differently, each animal creates its own unique *Umwelt*.

Perception and, as a result, interaction with the world begins with the raw input of data from the environment through the sensory system. Anatomically, the sensory system is part of the nervous system and includes the sensory receptors that act as probes of the environment, parts of the brain that are used for sensory perception, and the neural pathways that connect the brain with the receptors. Notably, humans’ sensory system consists of five traditional senses[1]:

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[1] However, humans’ multitude of sensors allows them to detect other stimuli, as well. Such submodalities include pressure, temperature, pain, itch, joint position, muscle sense, balance and movement, and other internal stimuli like hunger or thirst. The definition, exact number and borders between senses remain debatable in the scientific community and it outside of the scope of this dissertation.

Sight, hearing, taste, smell and touch. The stimulation type and bandwidth of each sensory channel are limited to its characteristics, which in turn constrain the size of the *Umwelt*.

However not all living organisms possess the same qualitative or quantitative senses. Depending on the environment in which they have evolved, their sensory system may be entirely different than ours; some have more while others have less sensitive senses. Others have quite different ones. Bats and dolphins, for instance, have the ability to calculate orientation and position of other animals and objects through reflected beams of sound, an ability known as echolocation. Sharks and rays, on the other hand, can detect changes in the electric field of their vicinity, an ability known as electroreception.

Situation Awareness

It is a well-known fact that humans are capable of sensing only a small fraction of the data that constantly surrounds us. Magnetic fields, infrared light, ultrasound, cosmic rays, radiation are just a few of the things that are completely invisible to us. However, recent technological advances in specialized sensors, enable the detection of some of this information. For instance, geiger counters are used by hazmat personnel to assess radiation levels in nuclear accidents. These technologies provide feedback using one of our existing senses, usually visual or audio, in order to help workers safely perform daily tasks.

Situation Awareness (*SA*) is the perception of environmental elements, comprehension of their nature, and projection of their near future status with respect to time and/or space (4). In other words, it is the awareness of the immediate vicinity, comprehension of the current state of the environment and ability to predict what may happen. Inputs from the sensory system are used by the individual in order to create and update their *Situation Awareness* state, and as a result, decisions depend on the accuracy of the perceived model. *Situation Awareness* is tightly associated with experience; somebody less experienced may miss information that a more experienced user will not. To put things into perspective, the hazmat personnel's (that we discussed above) *Situation Awareness* includes the geiger counter readings, comprehension of their meaning and ability to predict what will happen if they raise above a certain level.

Despite the fact that sensory systems have been honed by millions of years of evolution, they are very limited to a multitude of data. We are blind to a plethora of information that exists around us, and fortunately most of it is harmless. We depend on our sensory system to interpret the world, and we use our *Situation Awareness* to comprehend the environment around us and act upon it. As a result, lack of information for a certain situation may lead to misjudgements and accidents. In fact 76% of aviation errors, happen because the pilot did not perceive one piece of the airplane's crucial information (5). To that end, another important question arises: Given that today's technology can sense some of this invisible information, can we expand the *Umwelt* and improve *Situation Awareness*?

Research Questions

Genetic defects, diseases or accidents can lead to sense disabilities or complete sense lose, which has been observed to both animals and humans. To that end, individuals learn over time to use the remaining of their senses in order to overcome a disability. Recent scientific discoveries have shown that while this new ability results in anatomical changes of the brain, the responsible regions remain the same. In other words, even though the sensory input channel has changed, the brain will still process the information in the same region—a phenomenon known as *Sensory Substitution* (6).

As a result, *Sensory Substitution* devices use one or more of the remaining senses to increase an individual's *Situation Awareness* through a different sensory pathway. More specifically, tactile displays are able to translate external environmental information onto one's skin, through the use of haptics. While these systems are primarily designed for people with disabilities, their concepts can be extended to other sensory deprived individuals, who find themselves in no or limited visibility environments due to external, environmental reasons. For example, firefighters operating within smoky, low visibility hazardous environments or soldiers fighting in pitch black darkness, are more likely to have no *Situation Awareness* of their surrounding environment.

The ever-dynamic nature of the world around us, however, makes navigating with a wearable tactile display, a quite challenging task. From feeling the vibrations onto one's skin, comprehending their meaning and correctly acting upon them, to getting inundated with tactile sensory overload, tactile displays have great potential, when communicating information in an eloquent way.

In this dissertation we will explore different environment-to-vibration mappings while assessing one's *Situation Awareness.* Furthermore, we seek to understand whether one's experience with a tactile display would have an effect on their *Situation Awareness.* Finally, we hypothesize that a one-size-fits-all wearable tactile display would not perform equally well in all environmental scenarios and therefore we are going to explore how different vibration configurations, patterns and environment-to-vibration mappings would affect one's navigation.

All of the above are distilled into the following research questions:

- Could tactile displays be used to increase *Situation Awareness* of visually deprived individuals?
- To what extent would *Situation Awareness* be associated with experience when using a tactile display?

CHAPTER 1

BACKGROUND

Parts of this chapter were previously published as:

Novak, John; Archer, Jason; Mateevitsi, Victor; and Jones, Steve (2016) "Communication, Machines & Human Augmentics," communication +1: Vol. 5, Article 8.

This chapter presents some contextual and prerequisite information that is essential to understand the body of our thesis. In sections 1.1 and 1.2 below, we introduce the concepts of *Human Augmentics* and *Sensory Substitution* that are used throughout this dissertation, while in 1.3 we present contextual information about the sense of touch and the somatosensory system in order to understand how the skin perceives information from tactile displays. Finally, in 1.4 we introduce *Situation Awareness*, methods for measuring it and its importance in dynamic systems.

1.1 Human Augmentics

Humans have long used tools and technology to augment human senses and capabilities. From using a lever to move a large, heavy object to using lenses to correct vision or see at a distance or up close, from using a watch to tell the time, to using writing (and later electricity and electromagnetic waves) to communicate at a distance (and store communication, too), the augmentation of human capabilities has in every instance led to profound changes in knowledge, behavior, communication and culture (7). The miniaturization of technology during the late 20th and early 21st centuries has meant that augmentation has increasingly occurred with technologies that are not only built on a smaller scale but that are also mobile and personal. Mobile media such as phones, GPS trackers, fitness bands, and other devices, have become ubiquitous in most parts of the world and there is at least one mobile connection for every person on the planet (8), and are on or about our bodies almost always. Noting the link between modern technologies and the history of media, Adriana de Souza e Silva and Jordan Frith wrote, "for at least two centuries, individuals have used mobile media, such as books, Walkmans, iPods and mobile phones as technological filters to manage their interactions with otherwise uncontrollable surroundings" (9).

It follows from de Souza e Silva's and Frith's observation that as technology is increasingly miniaturized and networked, at some point electronic tools cease to be "simply" tools or "filters", and become meaningfully part of ourselves, augmenting the self, rather than amplifying our capabilities. They are part of the milieu, the environment that interfaces and mediates between us and the world around us. They become what Mark Weiser and John Seely Brown have termed "calm technologies" (10), ones that, according to Anne Galloway's interpretation of the term are "between the periphery and center of our attention, outside of conscious awareness (but not completely absent) until we actively focus" on them (11). In her essay on the cultural implications of ubiquitous computing she goes on to note that these technologies "would be so embedded, so pervasive, that (they) could be taken for granted" (11). They are less lever and more muscle, it might be said; they cease to be merely "filters to manage... interactions" and become interactive, engaging with users and the world, and mediating users' engagements with the world.

The increasing commodification and commercialization of ubiquitous, pervasive augmentation technologies is leading to "a restructuring and re-bordering of interaction with the world around us... as we increasingly communicate, willingly or unknowingly, with machines" (12). Indeed, the verge on which human-machine communication now finds itself (13) and its intersection with wearable and Internet of Things technologies should cause us to focus on these technological augmentations, which we call *Human Augmentics* (*HA*).

Philosophical discussions concerning exceeding human physical and cognitive limits with technology have been ongoing since at least the publication of Aldous Huxley's Brave New World (14). The term "transhumanism", coined by Julian Huxley (15), as well as the terms "posthuman" and "cyborg" served as umbrellas denoting ideas and efforts in the 1950s and beyond to advance human evolution through the use of technology and medicine. The history and philosophical threads pertaining to transhumanism are well described in The Transhumanist FAQ by Bostrom (16). More recently still, the Quantified Self (QS) movement has emphasized self-tracking through individual data collection using wearable technologies and sensors (17). The persuasive elements of self tracking have drawn on work by B.J. Fogg who coined the term "captology" to denote the connection between computing and persuasion (18). In 2011 Kenyon and Leigh, in "Human Augmentics: Augmenting Human Evolution," describe what is essentially a merging of transhumanism, captology and QS, defining the term *Human Augmentics* as referring to "technologies for expanding the capabilities and characteristics of humans," or as they put it another way, as "the driving force in the non-biological evolution of human" (19). *Human Augmentics* technologies, are meant to compensate for natural cognitive and physiological limitations "so that our abilities can be expanded" (19).

Kenyon and Leigh also proposed three unique characteristics of *Human Augmentics*: First, as non-biological human evolution implies, *Human Augmentics* are strictly mechanical and electrical technologies that do not involve chemicals or other biological modifications to achieve goals. However, it does include interfacing directly with internal and external biological systems. For example, a device interfacing with the brain, which allows an individual to operate a prosthetic arm would be considered *Human Augmentics.* Second, wide distribution of *Human Augmentics* creates ecosystems by bringing devices and users into a network, possibly facilitated by cloud computing and body area networks, that constitute a flexible, ever adapting feedback system. Third, technologies such as wearable devices, virtual reality systems, mobile computing, cloud computing, robots, and other *Human Augmentics* devices will increasingly converge. Smart phones and Google Glass offer examples that are already in use but the foundation of *Human Augmentics* rests on these technologies being made available to all with the potential for inter-technological communication.

1.2 Sensory Substitution

According to Bach-y-Rita, an American neuroscientist, who pioneered the field of neuroplasticity, the concept behind *Sensory Substitution* is that a lost sense is replaced—to some degree—by relying on stimuli targeted to another working sense. As he famously said:

> *"We see with our brain, not with our eyes"* (20).

Due to brain plasticity—the ability of the brain to adapt and change due to external factors—this new sensory channel becomes, after extensive training, usable (6; 21). While unorthodox, this idea was not completely new: Early examples of *Sensory Substitution* include the Braille alphabet and the American sign language; both leverage the properties of a working sensory system to communicate information that would otherwise be invisible. *Sensory Substitution* devices range from tactile shoes that communicate stock information to the wearer (22), to prosthetics that substitute the feeling of pain with pressure in people experiencing physical pain loss (usually leprosy patients) (23). When the replaced sense is vision and the new sensory modality is touch, then the systems are known as *Tactile Vision Substitution Systems* (*TVSS*). *TVSS* stimulate the skin neuroreceptors by the means of either (mechanical or electro) vibration or pressure, with the use of tactile displays, which use a series of electromechanical stimulators to stimulate the skin and provide information to the user.

The first to propose the use of the skin as a communication medium was Geldard in 1957 (24; 25) reasoning that the skin's large body surface is practically unused, and therefore, would become a great input channel due to its discriminative ability to sense fine temporal resolution. He also noted touch's ability and efficiency to capture an individual's attention. Geldard also invented the first vibrotactile language for letter communication, vibratese (24; 25) and conducted experiments, where subjects learned—after 65 hours of training—to perceive sentences with 90% accuracy, at a rate of 38 5-letter words per minute.

However, the first system to project an environmental image onto the skin, was the Tactile Image Projection system by Bach-y-Rita and Collins (6; 21). 400 1mm solenoid stimulators, spaced 12mm apart on a 20x20 array, vibrate providing haptic room information on the user's lower back. The system is controlled by a camera with panning and zooming capabilities and "acts as a mechanical image projector to impress a two-dimensional vibrating facsimile of a visible object onto a large area of skin" (21). Pixels from the video feed are translated onto a tactile image, with each controlling an individual tactile stimulator. Individual actuation is enabled only when light in the corresponding image area is above a threshold. In other words, binary amplitude stimulation is used to control whether the motors are on or off. In their experiments, participants, after approximately 1h of training, have built a tactile vocabulary of approximately 25 objects, including a telephone, a chair, a cup and a toy horse.

Most of the *TVSS* studies are focused on either face, shape or object recognition (6; 21), or on controlled experimental tasks (26; 27; 28; 29) while participants are seated on a *TVSS* chair. For instance, in one experiment, a seated participant managed to use a 20x20 tactile array to identify a rolling ball, guess it's position on the table and successfully bat it (27; 28). In another experiment, a blind worker successfully inspected and corrected errors of an automatic filling machine using a microscope-to-vibration *TVSS* (26). *TVSS* require extensive training with varying success rates (30), however expert, well-trained users perform very well (6; 31).

However using *TVSS* to navigate in three-dimensional environments can be especially challenging due to the dynamic nature of the environment and the lack of depth information. Firstly, the binary nature of the aforementioned pictorial *TVSS* environment-to-vibration mappings is analogous to watching a low-resolution, one shade, black-and-white movie. Secondly, navigating a more complex environment, like a maze, requires coding of all walls and obstacles in such a way that users will not only be able to recognize them but also to extract orientation information in the form of vibration patterns.

Having these limitations in mind, Segond et al. (29) constructed a three dimensional maze and added visual cues to help navigation using a *TVSS*. Users wearing an abdomen 96 microelectrode tactile matrix were seated while guiding a remote robot through the maze. The maze used 2 types of spatial cues to help subjects make choices and find their bearings: The first one, was a line in the middle of the corridors' floors and on the horizontal walls. The second, was arrows on the doors informing the users about which direction they had to follow. Experiments showed that users were successful in navigating from the beginning of the maze to its end, practically only relying on vibration feedback from visual cues (lines and arrows) around them.

While early *TVSS* devices were using the user's back, it soon became clear that other parts of the body, with higher touch sensitivity, could be used as well. For instance, Kajimoto et al. designed a 512 electrodes tactile display for the forehead (32), while Bach-y-Rita (33) and Sampaio (34) designed one for the tongue. In their experiments, participants were able to recognize simple geometric patterns and letters achieving 79.8% and 100% accuracy respectively. Similarly, in another study (35) that used Brainport (36)—a commercially available tongue tactile display that was the outcome of Bach-y-Rita's tongue experiments (33)—30 individuals showed varying accuracy results in successfully recognizing simple geometric shapes.

However, despite the very encouraging results, the following limitations constrain *TVSS* in recognizing only simple geometric shapes:

1. The pictorial-to-vibration mapping method requires a high contrast between objects and background.
2. The actuators are binary communicators (on or off).
3. The systems are operated while the user is seated and therefore do not allow for more complex navigational experiments.
4. Each image is translated as a pictorial vibrating pattern that the user has to learn. While the advantage of this method is letter, face and shape recognition, *TVSS* systems have a steep learning curve, as well as a limited number of shapes that an individual can memorize.

1.3 The Sense of Touch

The skin is considered the largest organ of the human body, covering approximately $2m^2$ of surface and weighing roughly 17% of an individual's total weight. Ninety percent (90%) of that is hairy, while the remainder is glabrous (non-hairy) (37; 38). The skin serves five main functions: As a means to protect from injuries and shield from dangerous microbes, viruses and bacteria; as a regulator of body temperature; as a sensory organ, sensing temperature, pain and touch; as a metabolic organ, contributing to the body's metabolism and oxygen perspiration; and finally, as a storage facility for fat tissues.

1.3.1 The Somatosensory System

The somatosensory system consists of (somatosensory) receptors that perceive touch (mechanoreceptors), temperature (thermoreceptors), pain (nociceptors), smell and taste (chemoreceptors) and an individual's unconscious body part position and movement (39)—an ability known as proprioception or kinesthesis, whose sensation is mediated through specialized receptors, the proprioceptors (muscle spindles, golgi tendon organs and joint receptors) that exist in limbs, muscles, tendons and joints (39). One of the integral parts of the somatosensory system is touch (also found in literature as tactile perception or somatic sense), mediated by five types of mechanoreceptors (39; 40) and summarized in Table I. While each mechanoreceptor type is attuned to a specific sensory function, they also work together in perceiving complex surface properties or haptic sensations (39). The somatosensory system's perceived properties are the following: texture, roughness, hardness/softness, elasticity and viscosity (39).

TABLE I

LIST OF MECHANORECEPTOR TYPES, THEIR SENSORY FUNCTION, IN WHAT SKIN TYPES THEY ARE FOUND AND LOCATION

Mechanoreceptor types	**Sensory Function**	**Skin Type**	**Location in skin**
Free nerve endings	Pain, temperature, tickle	All skin	Superficial
Merkel cells	Static pressure	All skin	Superficial
Meissner corpuscles	Light, dynamic touch	Glabrous	Superficial
Pacinian Corpuscles (PCs)	Pressure, vibration	All skin	Deep
Ruffini corpuscles	Skin stretching	All skin	Deep

1.3.2 Characteristics of Touch

The sense of touch can be characterized by its position on the body, perceived vibration intensity, and temporal pattern (41). Understanding the characteristics and limitations of each is very crucial in tactile display design as the haptics need to convey meaningful information to the user.

- **Touch Position**: While any part of the body can be used as a haptic channel for a tactile display, the haptic sensitivity differs from part to part as it depends on the number of receptors for that particular skin area. For instance, fingertips and the tongue have been found to be the most sensitive body parts (42) having up to 100 receptors per cm^2 (30). In contrast, the back of the hand has fewer than 10 receptors per cm^2 (30). Touch sensitivity declines with age, however, this is not due to changes in the mechanical properties of the skin, but possibly, due to changes in the nervous systems instead (43).
- **Temporal Pattern**: The sense of touch is characterized by its temporal pattern that depends on the amplitude and the frequency of the vibration.
- **Perceived Vibration Intensity**: Perceived vibration intensity is the subjective magnitude of a haptic sensation and it varies based on the location, duration, amplitude and frequency of the vibration (44). More specifically, the perceived magnitude depends on the number of stimulated receptors—rather than to their density (45)—and grows linearly with the number of vibrating stimulators (46).

1.3.3 Importance of Sense of Touch

Touch is the first sense that develops to living organisms as a fetus, when the embryo is less than an inch and younger than eight weeks old (37). The somatosensory system is one of the most sensitive organs of the human body, containing roughly 50 receptors per $100mm^2$, covering $2m^2$ of surface and weighing roughly 17% of an individual's total weight (37). To fully understand its importance, it suffice to examine people with somatosensory disabilities, whose nerves carrying sensory information to the nervous system have been damaged. Only 2 such occurrences have been recorded: G. L. with complete sense of touch loss from the mouth down (including the tongue) and Waterman with complete sense of touch loss below the neck (47; 48; 49) due to an autoimmune disease; he however retained pain and temperature sensations. Proprioception loss consisted him unable to walk or stand, and caused speech impairment and chewing difficulties. He eventually, had to re-learn how to articulate based on audio feedback and how to stand up based on visual feedback, which took him a year and seven months.

1.3.4 Adaptation

One important factor that needs to be taken into consideration when designing and using tactile displays is adaptation (50). Defined as the change in perception of a stimulus after a certain period of time of using a tactile display, adaptation decreases the user's perceived vibration intensity (51). In other words, the more the user (consecutively) uses such a system, the less they feel the vibration—not because its actual intensity alters, but rather because the user adapts to it.

1.4 Situation Awareness

Endsley defines *Situation Awareness* as ”the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future” (52). In other words, it is the awareness of one’s immediate vicinity, comprehension of the current state of the environment and ability to predict what may happen. *Situation Awareness* is tightly associated with experience; somebody less experienced may miss information that a more experienced user will not. Its roots are found in the prehistoric man, who had to be aware of their surroundings in order to successfully hunt while avoiding impending danger. More experienced individuals had a better chance of surviving, due to their increased awareness of environmental signals and cues (5). *Situation Awareness* today is still as important as ever.

Situation Awareness is broken down into three levels:

- **Level 1**: Perception. Perception of environmental cues as early as possible (Level 1) is critical to the outcome of one’s actions. The importance of perception is illustrated in Jones and Endsley, who found that 76% of aviation errors are traced back to this level (53).
- **Level 2**: Comprehension. Comprehension of information acquired in Level 1, including interpretation and combination of all perceived data. Accurate comprehension depends on experience. The importance of comprehension is illustrated in Jones and Endsley, who found that 20% of aviation errors are traced back to this level (53).

- **Level 3**: Projection. Forecasting future events and dynamics, based on Level 1 and 2 *Situation Awareness*. Endsley considers it the highest skill of *Situation Awareness*—"the mark of a skilled expert" (5).

1.4.1 Designing for Situation Awareness and Measurement

One's *Situation Awareness (SA)* depends on the system design itself and therefore careful consideration is needed in order to properly identify key *SA* characteristics. As an example, most aviation errors—that might lead to serious accidents—usually happen in Level 1 or Level 2 *SA*, due to bad system design. Therefore, Endsley (54) identifies the following as the key characteristics that might affect one's *SA*:

- **Elements**. Identifying the elements that the operator needs to perceive and comprehend is system specific and of high importance when designing for *SA* (54).
- **Time**. *SA* is highly temporal by nature. In other words it takes into account various temporal aspects of the environment that are acquirable over time and are used to project its state in the future.
- **Space**. Tasks that require elevated *SA* are usually highly spatial (54). For instance, pilots and air traffic controllers need to be aware of the spatial relationship between aircrafts, which in turn are highly temporal themselves.

In the context of *TVSS* systems—as per Endsley—the key *SA* characteristics depend on the specific task the user is performing. For instance, in the Tactile Image Projection system (6), the operator is the user controlling the camera and the elements are the geometric shapes that are perceived through the use of the tactile display. Additionally, time and space play a crucial role in their elevated *SA* as the operator needs to move the camera around over a period of time until they can properly identify the requested shape. Well-trained individuals have acquired "the mark of an expert" as their performance is substantially elevated due to increased Level 3 *SA*.

Furthermore, a literature review by Mantelow and Jones (55) has shown that one's *Situation Awareness* determines their ability to come up with a successful problem solving strategy. This observation indicates a link between poor performance and incomplete *SA*, when factors limit an individual's ability to perceive, comprehend or project the environment.

Before we can improve a system's *SA*, we have to measure it first. A summary of the most commonly used methodologies with advantages and disadvantages can be found in Table II (52).

TABLE II

SITUATION AWARENESS MEASUREMENT METHODOLOGIES

Methodology	**Description**	**Advantages**	**Disadvantages**
Physiological Techniques	Measurement of physiological changes. Examples: electroencephalographic measures, eye trackers, etc.	Quantitative measurement of perceived elements.	No insight on quality and quantity of perceived elements and/or comprehension. Intrusive to the user.
Performance Measures	Simulation scenarios recording performance data.	Good quality data, objective and non-intrusive.	Limitations in using performance data to infer SA.
Subjective Techniques	Self or observer rating of SA.	Low-cost, easy to use.	Difficulty to evaluate incomplete knowledge.
Questionnaires	Questionnaires assessing element-by-element SA.	Objective assessment and direct measure without self-judgement.	Questionnaire administered after experiment: Difficulty in recalling experiment's specific events. Questionnaire administered during experiment (freeze technique): Halt of the experiment.

CHAPTER 2

RELATED WORK

The skin is considered to be the largest organ of the human body (37; 38) being "actually one huge sheet of tactile receptors" (30). The skin protects the body from the environment, regulates the body temperature, senses temperature, pain and touch, contributes to the body's metabolism and serves as a storage facility for fat. Tactile receptors in the skin are responsible for the sense of touch, which is also one of the first senses that a fetus develops (37). The sense of touch, while often underestimated due to the intensity of an able individual's other senses, such as vision, is intertwined with our basic physical and emotional needs, from knowing where our limbs are (47; 48; 49) to conveying distinct emotions—which may vary across different cultures (56).

Due to its discriminative ability to sense fine temporal resolution (24; 25), researchers have used the skin and the sense of touch to convey information—through the use of tactile displays. The first tactile displays were purely finger reading aids for the blind and the visually impaired (57; 58; 59), until Bach-y-Rita et al. and Collins (6; 21) experimented with positioning them on other body parts as well. Their experiments spurred a revolution and a new scientific term was coined: *Sensory Substitution.*

In the following sections we will take an in-depth look at various types of tactile displays, in particular *Tactile Vision Substitution Systems* that are used for pictorial haptic transmission, and haptic navigational aids. These aids, under the umbrella of *Electronic Travel Aids* (*ETA*), are using haptics as a means to improve navigation. Finally, we will look into how tactile displays are used to increase *Situation Awareness* in low visibility or sensory deprivation situations.

2.1 Tactile Vision Substitution Systems

A Tactile Vision Substitution System (*TVSS*), "acts as a mechanical image projector to impress a two-dimensional vibrating facsimile of a visible object onto a large area of skin" (21). Pixels from the video feed are translated onto a tactile image, with each controlling an individual tactile stimulator. Bach-y-Rita et al. and Collins (6; 21) were the first to use tactile displays for image-to-haptics translation. Their prototype consisted of a 20x20 array of tactors built into a dental chair and connected to a camera that subjects were able to pan and zoom. During their experiments, blind subjects learned to recognize lines, shapes, letters, objects and individuals, described shadows and perspective distortion, and were able to discriminate between overlapping objects. After hours of training, expert users reported that the external localization of stimuli comes from the front of the camera, rather than from the tactors on their back.

The aforementioned *TVSS* could be described as two-dimensional, as it maps images into tactile patterns using a binary translation. Each haptic pixel is either on or off, therefore lacking any shading information of the environment. To overcome this problem, Shinohara et al. designed a 64x64 three-dimensional tactile display and added a third dimension with the addition of 100 discrete levels per tactor (60). In their experiments, 6 blind participants were able to recognize Chinese ideograms, locate features on haptic maps—like for instance buildings and roads—, recognize familiar objects and read scientific illustrations with various success rates.

Following Bach-y-Rita's steps, early *TVSS* were using the user's back for conveying tactile stimuli. However, it soon became clear that other more sensitive body parts could be used as well, like for instance, the tongue. The tongue in particular, is very sensitive, has its sensory receptors close to the surface and ensures good electrolytic contact due to the presence of saliva (61). Bach-y-Rita et al. was the first to demonstrate the feasibility of using the tongue as a tactile display's input channel, through a 49-point electrotactile array that yielded a 79.8% shape recognition performance—higher than even the fingertip (33). Furthermore, Sampaio et al (34) used a 12x12 electrotactile display to demonstrate that "visual" acuity of a tongue *TVSS* can be quantified. In their experiments, trained blind and sighted individuals had to recognize the letter Snellen E—in six sizes and four orientations—and reached 75% recognition at the lowest acuity level (20 / 240 Snellen fraction (62)) and 100% at all others.

2.2 Haptic Navigational Aids

Cardin et al. developed a wearable system for mobility improvement that consists of 4 rangefinders and 8 vibration motors (63), where the distance from objects is linearly mapped to vibration. The 4 rangefinders are fixed onto the participant's jacket at shoulder height with 8 vibration motors (2 per sensor) right behind them. In preliminary experiments subjects were able to walk corridors and avoid dynamic objects, like doors and people in front of them. After a couple of minutes of training, a 50% reduction of the time needed to pass through the obstacles was observed. Limitations of the system include the hands occluding the sensors, the reflectance of different environmental materials that alter the reliability of the ultrasonic sensors and the fact that there was only one horizontal level of sensors.

Another system, *CyARM* is a handheld device that uses wire tension to convey distance from object information (64). A handheld "scanner" measures distance to objects using an ultrasonic rangefinder and is tethered through a wire to another device on the user's belt. If an object is near, then the *CyARM* will pull the wire and, as a result, the reach of the arm will be reduced. In other words, the user holds a device that is attached to their belt with a cable and causes the cable to shorten or lengthen according to their distance from an object. (If an object is further away, then *CyARM* will ease the wire and, as a result, the reach of the arm will be increased). In their experiments, users were able to detect obstacle presence with 90% accuracy and correctly guess their distance.

Another handheld device is the Tactile Handle (65) that uses 4 ultrasonic rangefinders for environmental sensing, and a 4x4 tactor array for vibrotactile feedback (4 motors per finger). The tactors were positioned on a handheld device so as to coincide with the finger phalanxes and palm. While the authors do not describe how they coded the distance information onto vibration, in one of their experiments, the blindfolded participants had to find an open door while avoiding 4 randomly positioned obstacles. 73% of the participants successfully found the door on 2.57 minutes on average, with reportedly increased perception accuracy, and improved performance as they became more familiar with the vibrotactile device.

In contrast to the aforementioned systems, the *GuideCane* (66; 67) has taken inspiration from robotics. While not a tactile display, we found it noteworthy because the participants are using haptic sensation to infer the direction they have to follow. *GuideCane* is a cane with a unmotorized wheeled device at the end, that is equipped with 10 ultrasonic sensors. Users select orientation of travel, using a set of buttons, and the cane guides them towards that direction while steering them away from obstacles. The authors describe the perceived sensation as of following somebody—in contrast to being pulled—as the device operates without any motors and therefore, the subjects have to push it. Experimental results showed that the participants were able to safely navigate indoors in both cluttered and uncluttered spaces. The authors however note, that the device cannot detect overhanging obstacles, like tabletops, and is not suitable for outdoor navigation as it lacks the ability to detect features such as curbs.

ActiveBelt is a wearable device that conveys directional information through eight vibrators that are positioned at equal distances along the length of a belt (68). The wearer selects a destination and the belt, like a compass, vibrates in the direction that the user needs to travel to. The distance to the target destination is conveyed through changes in vibration frequency. In the user study, even though subjects failed to recognize changes in pulse intervals when walking, they succeeded in navigating to the target location.

All of the above systems, however, are not considered purely tactile displays. While haptics were used to convey navigational information, in contrast to *TVSS*, the vibration motors are very limited in number and do not necessarily form an array. The merging of *TVSS* systems with navigational travel aids was first recorded by Johnson and Higgins (69) who used a sparse torso tactile display and a pair of stereo cameras to convey depth information to the user.

However, no experiments were performed and there is limited information about the tactile display.

2.3 Situation Awareness Tactile Displays

Tactile displays have been shown to increase *Situation Awareness* in degraded visual environments where operator awareness is critical. One such example is helicopter landings in "brownout" conditions, where visibility is limited due to sand and dust stirred up by the helicopter's rotary wing. *FlyTact* is a tactile display that conveys altitude and groundspeed information to the pilot and has been tested in flight trials with a Cougar helicopter (70). Experiments demonstrated significant landing improvement in degraded visual environments when using the tactile display. More specifically, the pilot performed the landings faster, more controlled and with less mental effort.

Similarly, the *Tactile Situation Awareness System* (*TSAS*) was developed to improve helicopter pilot's *SA* and *Spatial Disorientation* (*SD*) by presenting three-dimensional orientation information (71). The tactile display was designed to communicate the helicopter's velocity vector: The direction was spatially mapped onto the tactile display (i.e. if the helicopter was moving forward, the forward vibration motors were vibrating) and the magnitude was perceived through changes in frequency—the greater the speed the higher the frequency (72). Pilots reported improved *SA*, and experienced improvements in control of forward flight, and hover maneuvers while blindfolded, as well. Additionally, they were able to safely recover from unusual attitude.

In addition, Bach-y-Rita et al. present the difficulties of astronauts to feel objects in space because of their space suit gloves, which are thick and have a pressure difference causing them to balloon (73). These gloves are made out of durable fabric to protect the astronauts, which as a result, eliminates tactility and reduces *SA*—due to sensory deprivation. As a consequence, astronauts cannot feel when an object is slipping from their hands and are forced to grip all objects firmer, leading to increased levels of fatigue. To overcome these problems, the authors propose the use of *Sensory Substitution* systems which could feed tactile information to the skin's mechanoreceptors.

Astronauts experience sensory deprivation of the proprioceptive system due to weightlessness, and therefore use visual cues to orient themselves, like for example the position of the space station or of other astronauts. Unexpected visual cues, like for instance another astronaut oriented upside-down, can be very disturbing. To overcome this problem and increase *SA*, van Erp and van Veen created a tactile display that supports the astronaut's orientation in space by creating an artificial gravity vector, with the location of vibration indicating the "down" direction and being aligned to the space station's modules and equipment (74). Their experiments showed that touch cues can be used to determine orientation in the absence of visual and gravitational cues (75).

Based on the *TVSS* and tactile displays that have been previously developed (see Table III for a summary of the reviewed tactile display systems) we formed our research goal to create a sparse torso tactile display and investigate three-dimensional navigation. The next chapter describes the iterative design process of developing the 3 *SpiderSense* prototypes, their limitations and preliminary results.

TABLE III

A SUMMARY OF THE REVIEWED TACTILE DISPLAY SYSTEMS CATEGORIZED BASED ON THEIR FEATURES. *SPIDERSENSE* IS THE SYSTEM THAT WE PROPOSED AND DEVELOPED AND IS DESCRIBED IN THE NEXT CHAPTER

System	**Wearable**	**Used for navigation**	**Obstacle detection**	**Discrete Height Levels**	**360°**
Tactile Image Projection	No	No	No	No	No
Tongue Tactile Display (61)	No	No	No	No	No
Tongue Tactile Display (34)	No	No	No	No	No
Three-dimensional Tactile Display	No	No	No	No	No
Wearable Mobility Improvement (63)	Yes	Yes	Yes†	No	No
CyARM	Handheld	Yes	Yes†	No	No
GuideCane	No	Yes	Yes†	No	No
Sparse Tactile Display (69)	Yes	Yes	Yes†	No	No
ActiveBelt	Yes	Yes	No	No	Yes*
SpiderSense	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

† No obstacles at head height
* Only one direction vibrates

CHAPTER 3

SPIDERSENSE

Parts of this chapter were previously published as:

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Novak, John; Archer, Jason; Mateevitsi, Victor; and Jones, Steve (2016) ”Communication, Machines & Human Augmentics,” communication +1: Vol. 5, Article 8.

Implicated and embedded in the dynamic practices of design, use and understanding of self and environment, *Human Augmentics* devices ought not be merely conveyors of information about the environment or user, but instead be actively engaged in processing and communicating information about the user and environment. *Human Augmentics* devices operate in the verge between body and machine, wherein sensing of the environment and the body are the fulcrum, and Human-Machine Communication is the lever. By dynamically mapping, in real time, what had hitherto been unmappable (synchronously and/or invisible to the senses) *Human Augmentics* at once recedes as a technology and grows as an interlocutor. As James Carey reminds us, any act of mapping is ”a reduction of information... that bring(s) the same environment alive in different ways" (76). *Human Augmentics* devices do not merely represent reality but act collaboratively with the user in its construction.

One such example is *SpiderSense*, a *Human Augmentics* device we iteratively designed drawing inspiration from Stan Lee's Marvel superhero Spider-Man. In the following sections we will elaborate on the design, development and some preliminary results of each of the *SpiderSense* prototypes: In sections 3.1 and 3.2 we will take an in—depth look in *SpiderSense 1* and *SpiderSense 2* respectively. Finally, in section 3.3 we will discuss the design of *SpiderSense 3*, which we used to test our research hypotheses.

3.1 SpiderSense 1

SpiderSense 1 (2) is a wearable tactile display that maps the environment onto the skin by utilizing the skin's pressure receptors. In contrast to other tactile displays that communicate either pictorial information (*TVSS*) (6; 21), or directional information (Haptic Navigational Aids) (68), *SpiderSense 1* aims to create an actual, real-time "feeling" of the environment.

The goal of this work was to understand if a tactile display can be effectively used by vision deprived individuals for navigation purposes. Similar to the white cane used by blind and visually impaired individuals to inform them of obstacles around them (but not the obstacles' nature), our hypothesis with *SpiderSense 1* was that users would only need to be aware of an obstacle's presence and location in order to successfully navigate.

SpiderSense 1 consists of 13 Sensor Modules that are positioned on the user's body (Figure 2) in order to provide a 360° haptic coverage. The Sensor Modules scan the environment in real time, using ultrasonic rangefinders, and alert the user of any objects closer than 60in.

Figure 1. Blindfolded user wearing *SpiderSense 1*

3.1.1 Design

3.1.1.1 Hardware

The prototype wearable system (Figure 3) consists of:

- Sensor Modules that scan the environment and provide pressure feedback.
- The Controller Box that contains the system's power source, electronics and microcontroller. The Sensor Modules are connected to the Controller Box through 10-pin ribbon cables, however, a wireless option could be used in future versions.

3.1.1.2 Sensor Module

The Sensor Module (Figure 4) scans the room for objects and provides pressure feedback to the wearer. Each Sensor Module box houses an ultrasonic distance sensor, a rotary servomotor and a 10-pin connector port. The distance sensor detects the closest object in its Field of View (FOV); then the servomotor's arm rotates to provide pressure information to the wearer in accordance to distance—the shorter the distance, the stronger the pressure. The rangefinder used was the HC-SR04 sensor with a 15° FOV and 200 inch range. Pressure sensation is created using the T-Pro Mini Servo SG-90 9G that has a stall torque of 16.7oz/in and rotation speed of 0.12sec/60°.

3.1.1.3 Controller Box

The Controller Box (Figure 5) houses an *Arduino Mega* microcontroller, a custom PCB allowing the connection of multiple Sensor Modules and the batteries. The Controller Box

Figure 2. Positioning of Sensor Modules and Controller Box

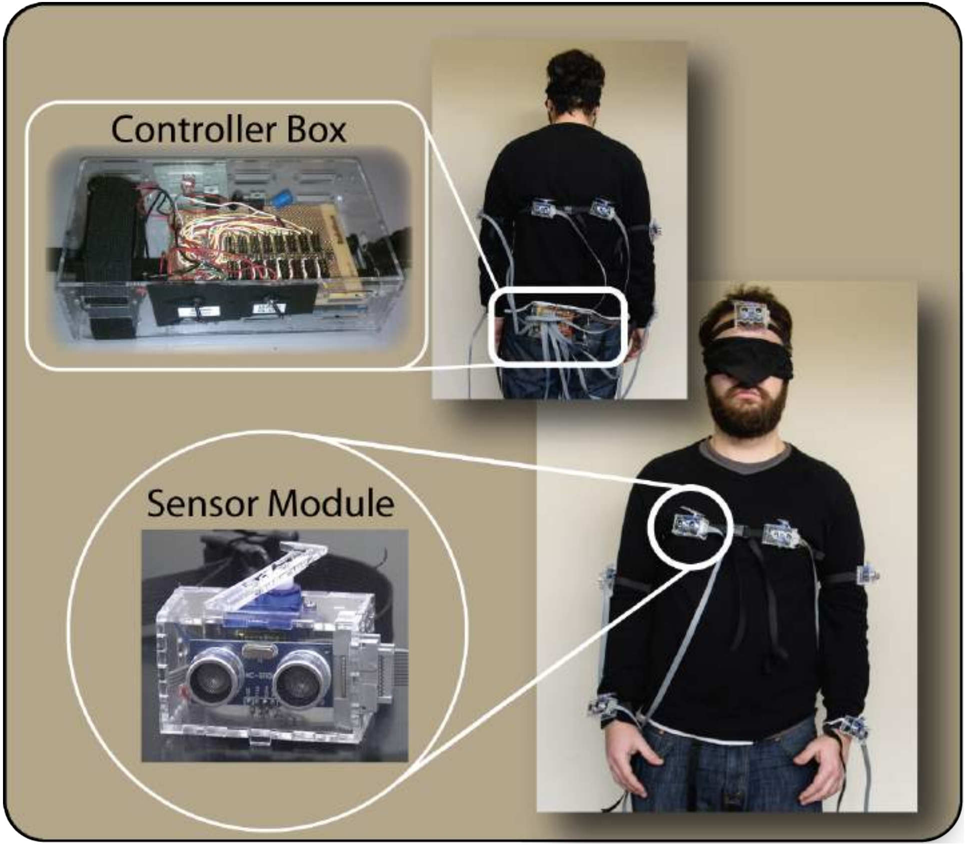
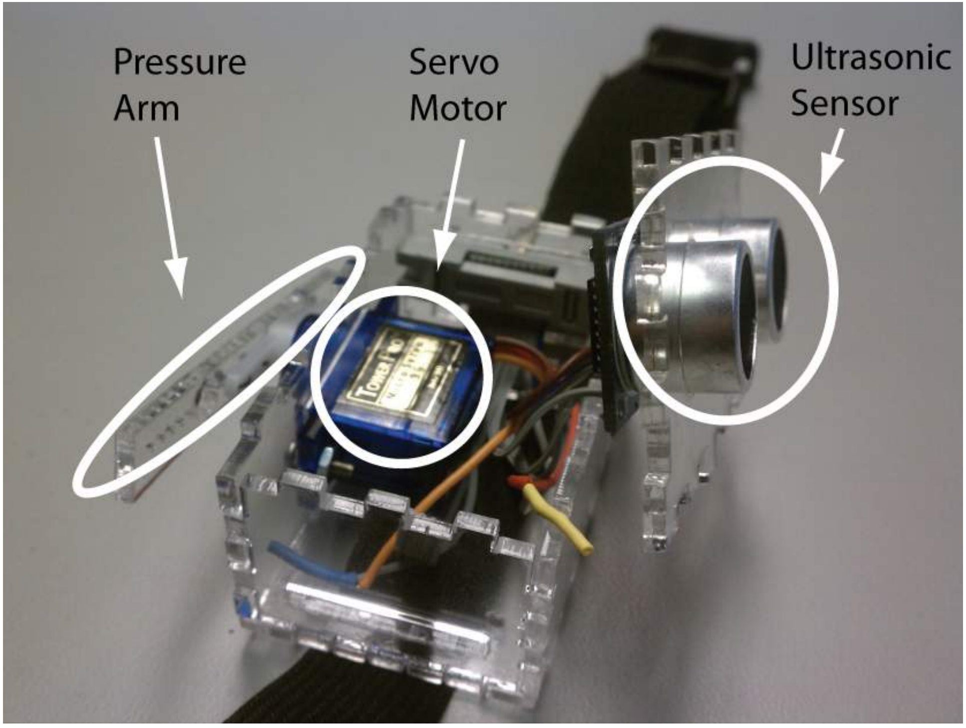
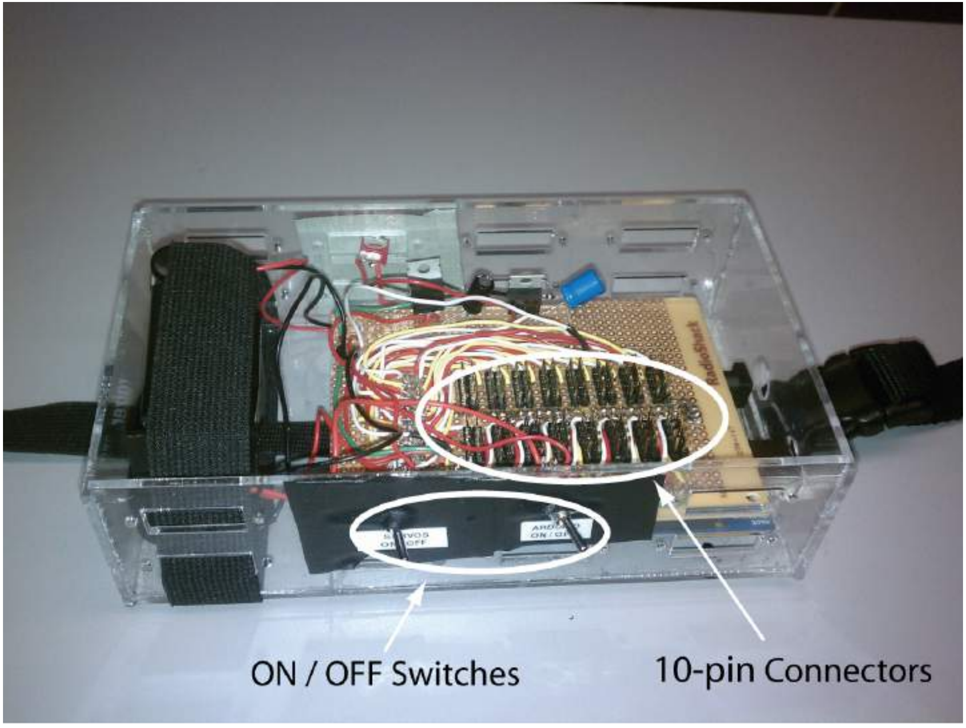


Figure 3. The Sensor Module



controls the rangefinders, calculates the distance to rotation mapping and rotates the servo motors.

Figure 4. The Controller Box



3.1.2 Controller Algorithm

The Sensor Module initially emits an ultrasonic pulse and waits for a reflection. If a reflection is detected by the ultrasonic sensor, the Controller Box will linearly map the distance to arm rotation and rotate the servomotor. Otherwise a timeout occurs and the next Sensor Module is triggered. The scanning procedure of the system is shown in Figure 6.

All HC-SR04 sensors operate on the same frequency and therefore their concurrent use leads to interference. To overcome this limitation, a round-robin algorithm was implemented, where only one Sensor Module would operate at a time. Another observed issue was the fact that the sensors' readings were quite unreliable when the servos were rotating. While in the original *SpiderSense* paper (2) we attributed the interference to the ultrasonic microphone picking up sounds from the servo motors, we now believe that it was due to the fact that we did not use any decoupling capacitors to suppress any high-frequency noise created by the servo rotation.

3.1.3 Preliminary Evaluation

To asses the prototype we performed four preliminary experiments: A hallway navigation trial; an outdoor walkway pedestrian recognition trial; a library navigation trial and a static surrounding threat detection. In all the experiments the subject was blindfolded.

3.1.3.1 Hallway Navigation

The experiment took place inside a building's hallway (80in wide and 50ft long) (Figure 7). The blindfolded subject, who was initially seated on a chair and spun several times to disorient, had to successfully reach the end of the hallway being mindful of surrounding walls. No obstacles were present at this time. Over the course of 8 trials, experiments showed that the subject was successful in identifying the hallway's orientation and navigating to its end. Furthermore, as the subject became more accustomed to the new sensory input we observed that their walking speed increased. This, however, led to more wall bumps.

Figure 5. Scanning Procedure

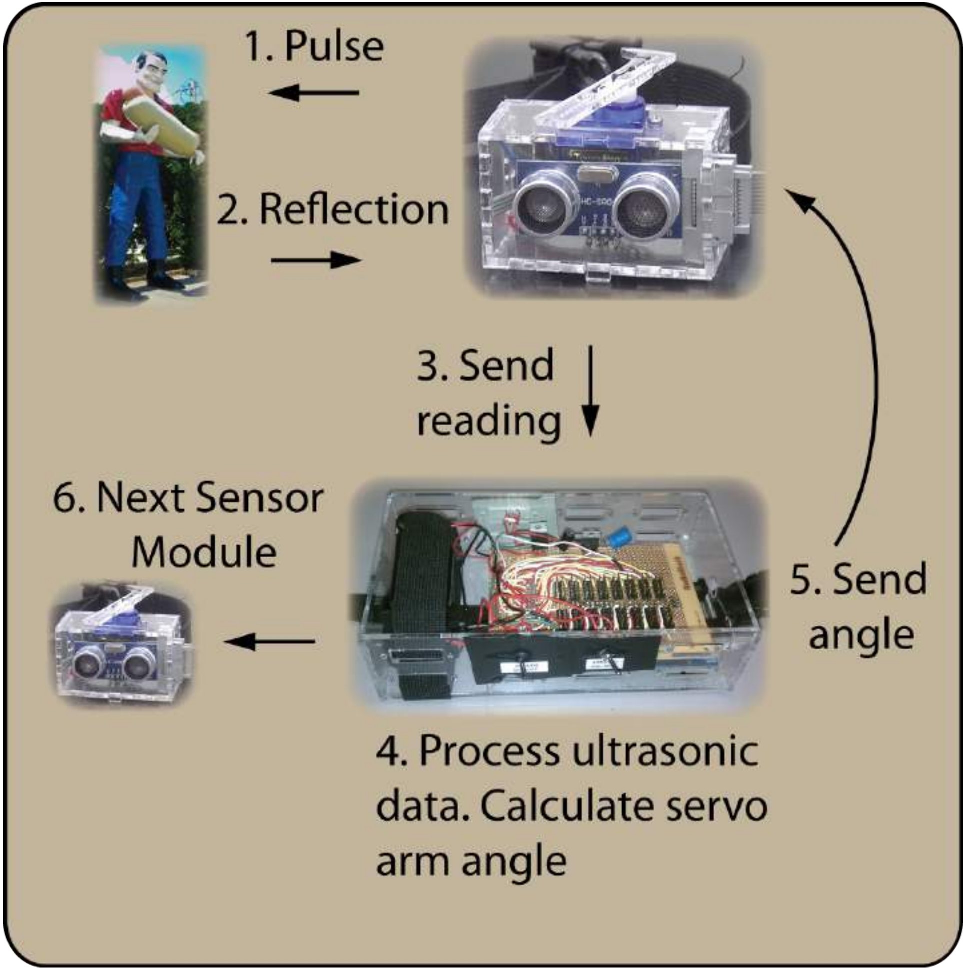


Figure 6. Hallway Navigation Experiment

3.1.3.2 Outdoors Pedestrian Recognition

The second experiment took place on a 26ft wide walkway outdoors (Figure 8). The subject was initially instructed to carefully observe their surroundings. They then had to walk straight and verbally communicate every time they felt a pedestrian walk by. The subject successfully sensed all the pedestrians that walked within the sensor's range (60in) and reported that the haptic feedback was more apparent due to the fact that the space was open.

3.1.3.3 Navigating inside Library

The third experiment's goal was to determine whether navigation in tight spaces was possible. For that purpose we chose to use the University's library (Figure 9). It is important to note that the space between bookshelves was so limited that even a fully sighted individual would have to be mindful during navigation.

Figure 10 shows a top-down view of the space, starting position and example path for one of the trials. The subject was initially given verbal instructions of the route (e.g.: On the third opening go left, then straight down the corridor and on the first opening go right and then straight again). During this experiment 10 trials were performed, none of which was successful due to the subject's difficulty in distinguishing corridors from bookshelves. Post-experimental discussion revealed that the subject was unable to perceive their actual position within the space, due to the lack of pressure changes onto their body (i.e. the bookshelves were so close that the small distance fluctuations were not felt onto the skin). Another observation was that empty, open-back shelves were falsely interpreted as corridors—as the ultrasonic signal could not reflect on any object, no pressure was applied onto the user's skin.

Figure 7. Outdoor Walkway Experiment

Figure 8. Library Experiment

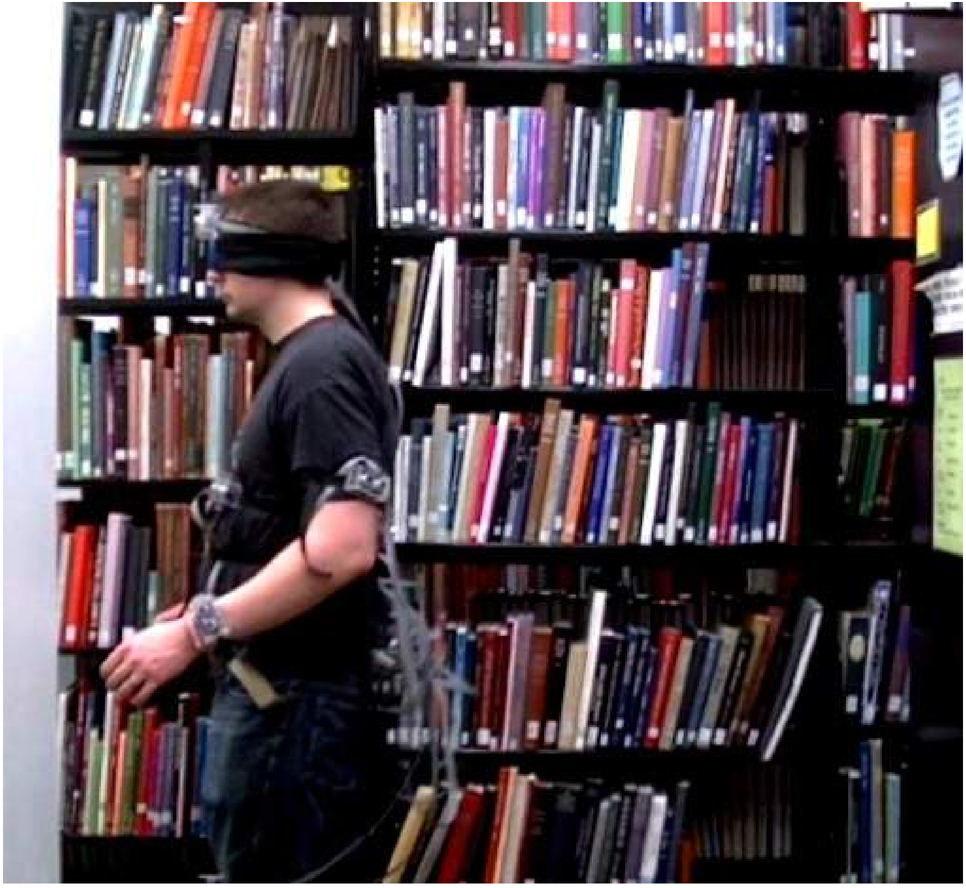
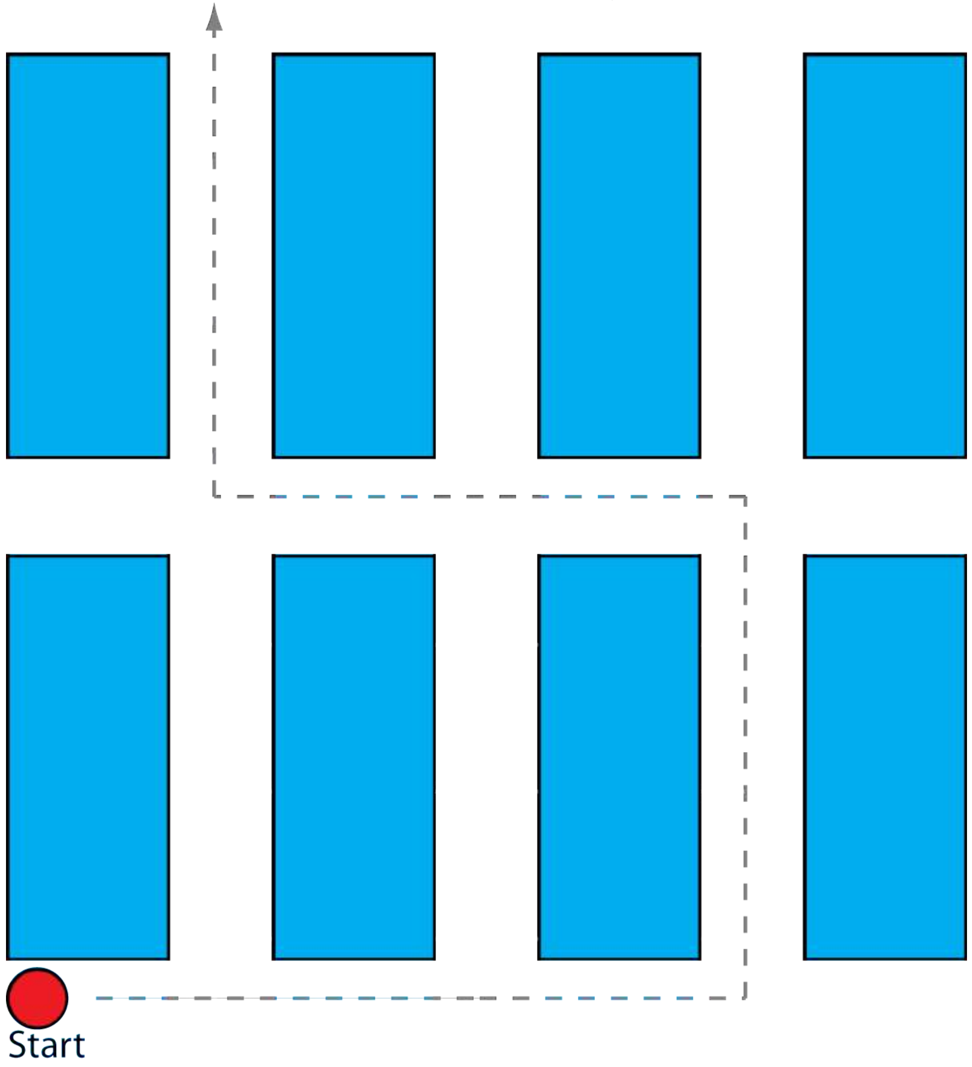


Figure 9. Library Experiment Example Path: Participant's Starting Position (blue rectangles indicate bookshelves)



3.1.3.4 Static Surrounding Thread Detection

Finally, during the last experiment, the blindfolded subject had to stand still in an open space and attempt to hit incoming experimenters with cardboard ninja star cutouts (Figure 11). The participant successfully sensed and localized the movement around them and managed to hit incoming "attackers" by throwing them ninja stars.

3.1.4 Limitations

Preliminary experiments with *SpiderSense 1* showed that navigation using a directional tactile display is possible, however navigation in small spaces is especially challenging. This was probably due to sensory overload as most servo motors were applying pressure onto the skin concurrently. Additionally, the participant reported inability to discern between small pressure changes. Moreover, the FOV orientation of the sensors would depend on the participant's body type/shape. For instance, sensors placed on a participant with a flat stomach would point forward, while sensors placed on a participant without a flat stomach would point upwards and possibly more sideways. In other words, acquiring quantitative data would be much more challenging and/or make results harder to compare, as the vibrating experience would be different for each user. Finally, the participant needed to be especially mindful not to block the sensors' FOV with their arms/hands while in motion, thus avoiding false-positive obstacle detection. Concluding, while more experiments are needed, the design of *SpiderSense 1* was unsuitable for a controlled quantitative study, difficult to wear (someone had to help the user with the fitting) and finally, limiting to the user's movement due to the presence of cables.

Figure 10. Static Surrounding Thread Detection (a participant sensing one of the experimenters approaching them from behind and throwing a cardboard ninja star cutout)

3.1.5 Media Coverage and Outreach

SpiderSense 1 sparked the media's attention and was featured on more than 200 media outlets, including *New Scientist, Forbes, National Geographic Kids* and *Gizmodo.* Furthermore, it was presented on various television shows, including *Discovery Channel's Daily Planet Show, popCultured* and *ABC7 Eyewitness News.* (For a detailed list of *SpiderSense* mentions and appearances see VITA). What fascinated people the most was that merging technology with humans in such a way could give one new abilities and senses, otherwise only found in comic books—in SpiderSense's case, a "sixth sense". Building on that, *SpiderSense 1* has been included in various educational programs, nationally, focused on showcasing the potential of *Human Augmentics* technologies in improving quality of life and extending to people with disabilities for rehabilitation purposes. (For a detailed list of *SpiderSense* invited keynotes, talks, presentations and demonstrations see VITA).

3.2 SpiderSense 2

Going a step further, we seeked to widen our observational study with more blindfolded participants and include feedback from visually impaired people, as well. This requirement led us to design a new wearable device, *SpiderSense 2*, that is smaller and easier to wear. Additionally, that gave us the opportunity to seamlessly weave the technology into regular clothing. Our goal was to make this new version of the device completely invisible, as people with disabilities favor technology aids that attract as less attention as possible, in order to avoid the stigma (77; 78). As Kent and Smith put it "inherent in stigmatization is a perception of normality and, by implication, the risk of being identified as not normal" (77).

3.2.1 Design

3.2.1.1 Hardware

To make the experience of using the device more efficient and pleasurable, as defined by Norman (79), we designed *SpiderSense 2* (Figure 12) in the form of an—easy to wear—jacket that consists of sensors and vibration motors embedded into the fabric. More specifically, there are 12 ultrasonic rangefinder sensors (*Maxbotix Ultrasonic Rangefinder - LV-EZ0*) and vibration motors (*Parallax* 28822 vibration motor), a microcontroller and a battery pack. The electronics consist of an Arduino pico microcontroller, a custom circuit board housing *Sparkfun*'s motor shield and a voltage power regulator. To power the system, 4 AA batteries are used. In our efforts to make the technology completely invisible we paid special attention in miniaturizing all the electronic components, that were hidden inside the jacket's chest pocket.

In contrast with *SpiderSense 1*, in *SpiderSense 2* we decided to use vibration motors as they were significantly smaller and easier to hide inside the jacket. To sew the vibration motors onto the jacket, we first had to create a custom housing around them using moldable plastic (*InstaMorph*) and leaving small holes for the needle to go through. That enabled us to successfully mount the motors onto the fabric (Figure 13). The motors were positioned at chest height (on either side—left and right—of the chest area, on each shoulder, and on the shoulder blades) and at waist height (left and right stomach area, on each wrist and on each side of the lower back) and contained within a custom designed zippable lining (Figure 14). The lining's purpose was twofold: Firstly, to hide all the cabling and motors from the user while protecting

Figure 11. *SpiderSense 2*

them from the electronics, and secondly, to provide a quick and easy access to the electronics if need be. Finally, the rangefinders were positioned directly in front of the motors.

Figure 12. *SpiderSense 2* jacket with electronics

For mapping the environment to vibration, we used the same linear mapping algorithm as in *SpiderSense 1.* The new rangefinders, however, allowed for concurrent operation and therefore the serial limitation and time delay of *SpiderSense 1* was lifted: All rangefinders were able to operate at the same time and a fast serial inspection could read their values without the use of timeouts. Furthermore, decoupling capacitors were used to avoid any sensor interference and, as a result, the feedback loop significantly improved.

Figure 13. *SpiderSense 2* lining

3.2.2 Preliminary Results

Over the course of one year, and several invited public talks, presentations and demonstrations, more than 60 people, half of whom were blind and visually impaired, informally tried *SpiderSense 2* and gave us detailed feedback: In general, the majority of the users liked the concept, the device and its potential. After navigating complex, indoor and outdoor environments they reported that they found it very useful as it could provide a greater understanding of their whereabouts. However, some visually impaired users reported that they probably wouldn't use it without a cane or a guide dog, since curb detection is very important when outdoors. They also found that *SpiderSense 2* has the potential to resolve one of their greatest concerns, head injuries, as the top row of sensors could detect obstacles at head height. Similar to Kent and Smith's, and Ravneberg's (77; 78) findings, the visually impaired users reported that they prefered that the device looks inconspicuous and could go almost unnoticed. Furthermore they overall enjoyed the vibration feedback—a feeling they (surprisingly) described as rather soothing. Finally, all users suggested that adding a feature to control the vibration range (some reportedly prefered more intense vibration feedback than others) would be especially beneficial. The ability to ”invert” the vibration feedback, with vibrations indicating open space rather than obstacles, was also considered. Although those observations were not a result of an formal user study, the provided feedback proved quite valuable as it has guided some of the design decisions of *SpiderSense 3*, and furthermore, has the potential to inform future studies.

3.2.3 Limitations

One of the limitations was that the jacket wasn't able to fit on each user's body (this prototype was built on a size large jacket) in some cases making it difficult for the user to feel the vibration. While we used clamps to overcome this limitation by improving the fit, we still couldn't guarantee that each vibration motor was equally touching the user's skin. Moreover, the FOV orientation of the sensors would depend on the participant's body type/shape. For instance, sensors placed on a participant with a flat stomach would point forward, while sensors placed on a participant without a flat stomach would point upwards and possibly more sideways. In other words, acquiring quantitative data would be much more challenging and/or make results harder to compare, as the vibrating experience would be different for each user. Finally, the participant would be especially mindful not to block the sensors' FOV with their arms/hands while in motion, thus avoiding false-positive obstacle detection.

3.2.4 Media Coverage and Outreach

Similarly to *SpiderSense 1*, *SpiderSense 2*, attracted significant media attention, this time focused on praising the benefits of its technology to the visually impaired community. Additionally, *SpiderSense 2* has been included in various educational programs, nationally, focused on showcasing the potential of *Human Augmentics* technologies in improving quality of life and extending to people with disabilities for rehabilitation purposes. (For a detailed list of *SpiderSense* invited keynotes, talks, presentations and demonstrations, including *Chicago Tribune*, the *Small Business Development Center (SBDC) Client Showcase reception*, as well as *Science Channel*'s television show *All-American Makers*, see VITA).

3.3 SpiderSense 3

Based on our observational studies with *SpiderSense 1* and *SpiderSense 2*, we designed *SpiderSense 3*—a new technology able to operate in a controlled experimental setup that would enable us to collect quantitative data (Figure 15).

3.3.1 Design

SpiderSense 3 was designed as a modular tactile display able to work with any kind of external sensor, similar to a computer monitor that is agnostic of the computer or graphics card being used. To connect sensors with *SpiderSense 3* we designed a communication protocol allowing for remote control and communication. Furthermore, Wifi capabilities were added in order to improve mobility by making the tactile display untethered.

3.3.1.1 Hardware

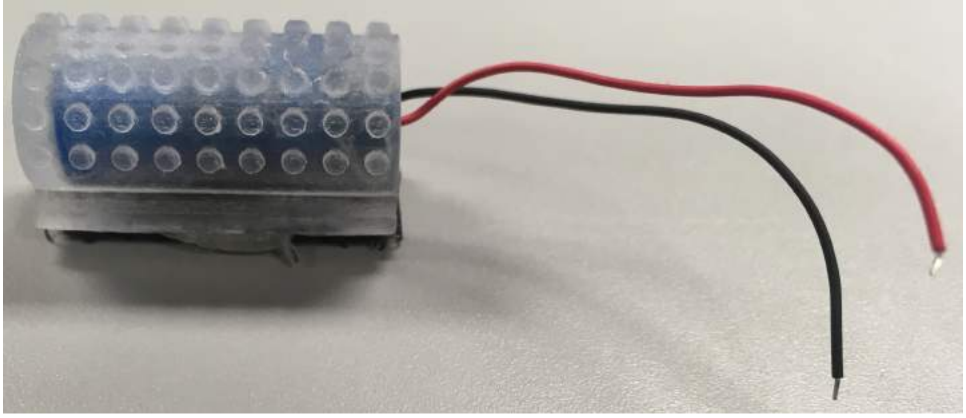
SpiderSense 3 consists of a tactile display torso band and a backpack housing the electronics.

Figure 14. *SpiderSense 3*

Vibration motors

We used the *Parallax* 28822 vibration motors and housed them inside a custom designed 3D printed case—its flat bottom allowed for easier mounting on the torso band. To increase tactility, the housing was designed with 3D bumps, while velcro was added on its flat bottom for easier mounting of the motors (Figure 16). Housing was designed in *Autodesk Inventor* and printed on a *Stratasys uPrint SE*.

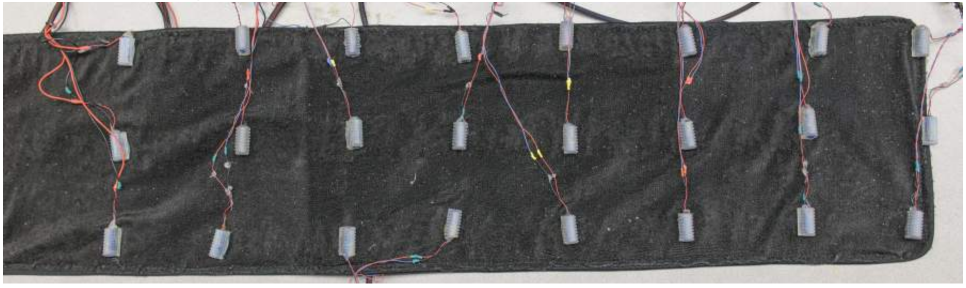
Figure 15. Vibration Motor inside 3D Printed Housing



Torso Band

To accommodate various body types, we used an elastic back band to wrap around the user's body (see section 4.3.1.1.2). Vibration motors were positioned on a 3x8 array on the band and securely fastened with the velcro on their flat side (Figure 17).

Figure 16. The 3x8 *SpiderSense 3* Tactile Display



Backpack

The *SpiderSense 3* electronics were kept in a custom made 3D printed case and securely stored inside the backpack (Figure 18). That includes a *Spark Photon* microcontroller with Wifi capabilities, a 2-layered custom PCB for the electronics, and the batteries. Each PCB was stackable (see Figure 19 and Figure 20) and could support up to 16 vibration motors. In this case, 3 layers were used, meaning that our tactile display could drive up to 48 vibration motors. The PCB was designed using *Eagle* software, etched on a *Othermill Pro* and its trace width was calculated to withstand the current-hungry motors without any overheating. 6x 18650 *Samsung INR18650-25R* 2500mAh 3.6v 20A rechargeable lithium-ion batteries were used to drive the motors and electronics, allowing for over 4 hours of constant operation. Finally to keep the voltage steady as the batteries discharge, 3 step-down-step-up converters (8A/100W 12A Max DC 5-40V to 1.2-36V) were used (one for each PCB layer).

Figure 17. The 3x8 *SpiderSense 3* Backpack

3.3.1.2 Firmware

In order to control the tactile display we created a protocol that accepts 2 types of commands: Global settings commands (like for example to turn all the motors off or to switch vibration modes) and commands that set a specific motor to a specific amplitude or frequency. Additionally, to reduce latency, the following optimization techniques were used:

- **Motor Value Caching**: The firmware caches the current motor's value. If the new value remains unchanged, then no action is taken.
- **Individual Motor Control**: The tactile display accepts setting each motor individually, therefore reducing bandwidth utilization. (Unlike our initial design that included

Figure 18. The Printed Circuit Board (PCB)

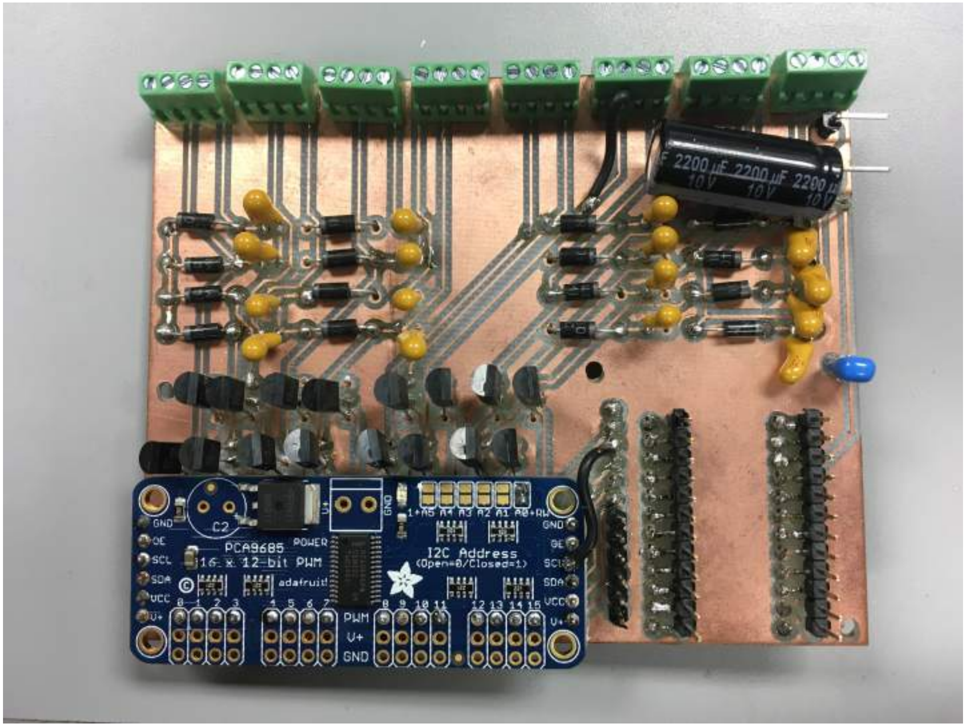
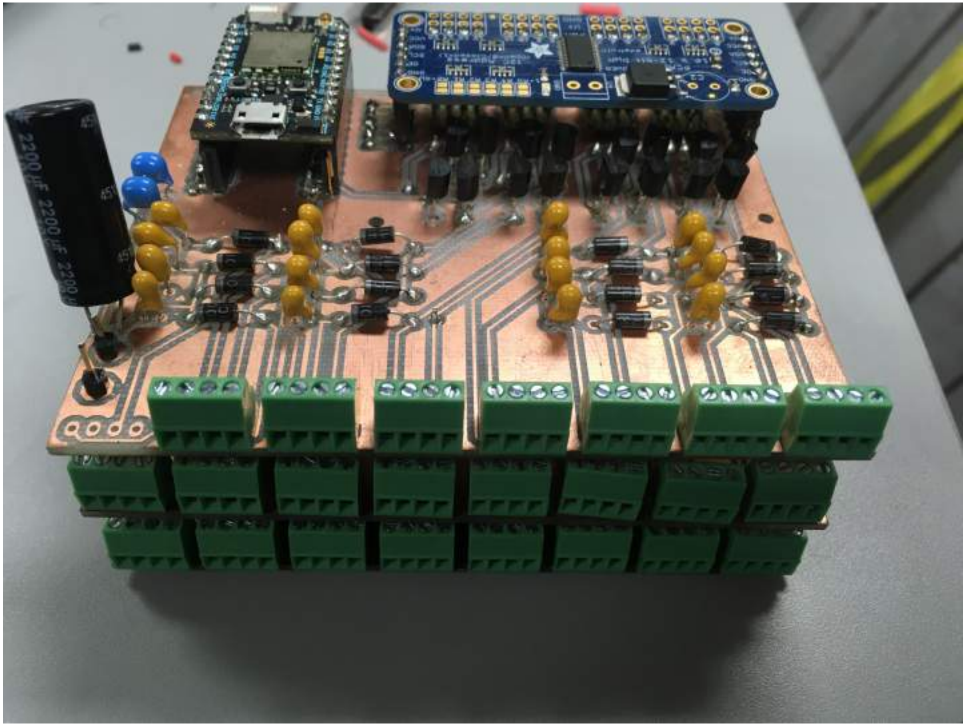


Figure 19. *SpiderSense 3* Electronics (please note the stacked PCB design)



packaging all 32 motor values into a packet and sending it to the tactile display at a rate of 120 frames per second, therefore creating unnecessary network congestion).

Finally, we used Transmission Control Protocol (*TCP*) instead of *User Datagram Protocol* (*UDP*) in order to guarantee the order of packets. During the initial networking experiments we experienced situations, where, due to network delays, a motor would either never receive the shut off command or would receive it out of order, resulting in inconsistencies.

In this chapter we described the *SpiderSense 1*, *SpiderSense 2* and *SpiderSense 3* prototypes. The next chapter details our research goals and hypotheses, and the pilot and user studies that were designed to address them.

CHAPTER 4

WEARABLE TACTILE DISPLAYS FOR SPATIAL ENVIRONMENTAL INFORMATION

Visual impairments can severely impact one's daily life. People are often challenged in performing daily, otherwise simple, tasks such as cooking a meal, walking to the bedroom or enjoying the outdoors. Regardless of the severity of the disability and whether it is permanent or temporary, visual impairments can significantly lower one's quality of life. In addition, they are a major cause of minor to severe injuries.

While a variety of medical and non-medical aids have been helping people overcome this disability over the years, in this dissertation we will solely focus on *Sensory Substitution* tactile displays, which channel the visual sensory system through the use of haptics. For instance, Bach-y-Rita's chair (6) has been used by blind and visually impaired people to overcome vision loss, thus improve their quality of life. Additionally, while these systems are primarily designed for people with disabilities, their concepts can be extended to other sensory deprived individuals, who find themselves in no or limited visibility environments due to external, environmental reasons. For example, firefighters operating within smoky, low visibility hazardous environments, or soldiers fighting in pitch black darkness, are more likely to have no *Situation Awareness* of their surrounding environment.

Navigating, however, using a wearable tactile display is often not as easy as it may sound due to the ever-dynamic nature of the world around us. In other words, our *Umwelt* becomes an ever-changing hostile environment, where any physical object is a potential threat—open cabinets, chairs and coffee tables within one's own home, or stop signs, sidewalk bumps or even distracted passersby when outdoors, continually move and morph.

As research with *SpiderSense 1* and *2* has shown, successful navigation with a wearable tactile display is indeed possible; it has however exposed the following insights:

Firstly, successfully navigating dynamic spaces, while vision deprived, requires a meaningful environment-to-vibration mapping. In other words, considering what kind of environmental information would be transmitted to the user, and what kinds of vibration patterns would translate this information. Essentially, how would the user feel walls or obstacles around them.

Secondly, a one-size-fits-all wearable tactile navigation system would not necessarily perform equally in all environmental scenarios. As an illustration, preliminary experiments with *SpiderSense 1* revealed that navigation in small spaces was especially challenging due to the fact that the entire vest was more likely to vibrate at once, providing overwhelming tactile feedback and making it impossible to properly identify and understand the surrounding space.

Our main dissertation contribution is twofold:

- Evaluating different environment-to-vibration patterns and their effect on navigational tasks.
- Introducing and evaluating new ways of environment-to-vibration mapping to improve navigational tasks.

4.1 Design of Infrastructure

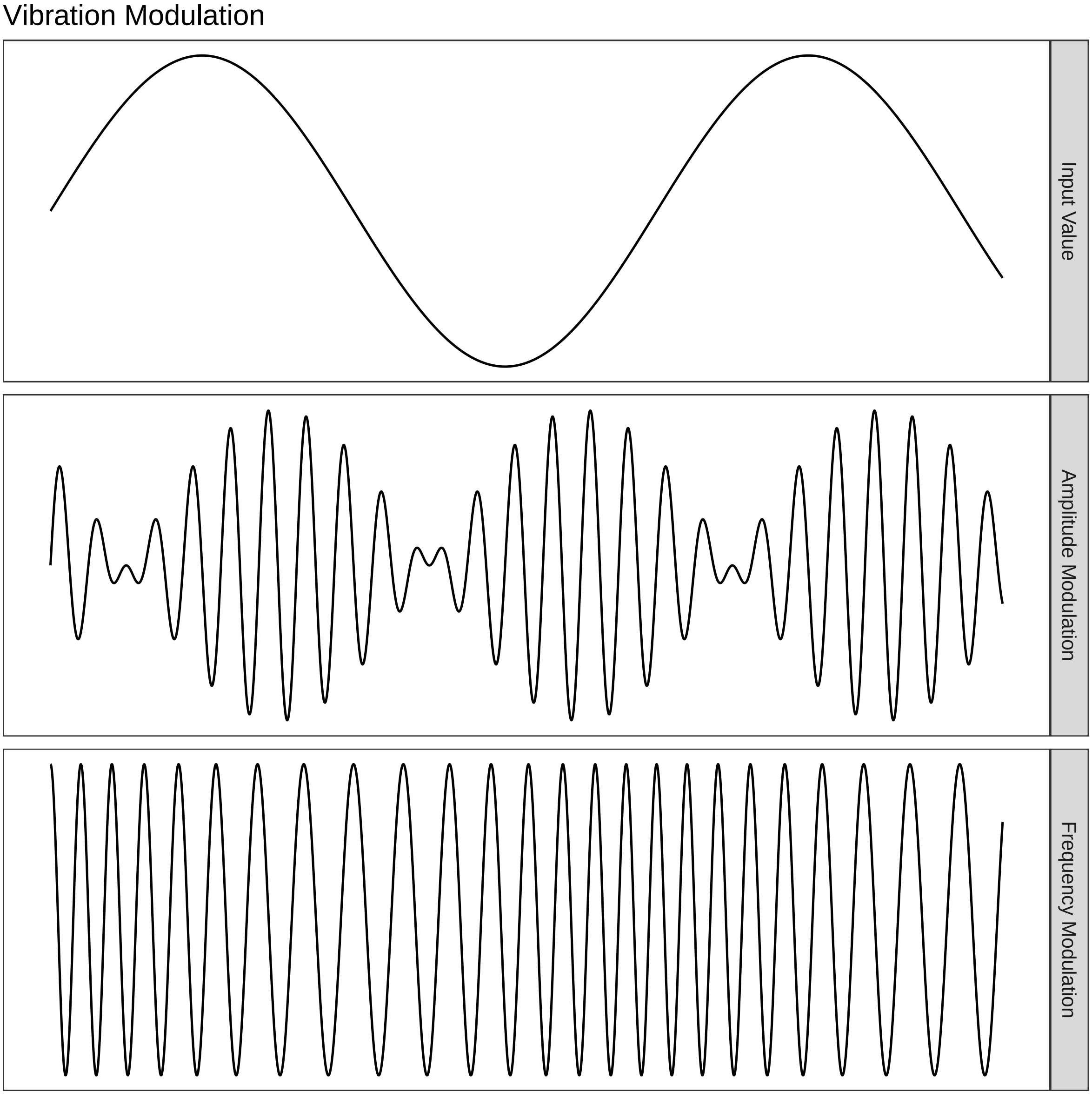
The preliminary work previously done on *SpiderSense 1* and *2*, made it possible for blindfolded and visually impaired users to successfully navigate mazes by using feedback translated onto their skin through vibration. However, while both devices linearly mapped distance from object to tactile feedback, we questioned whether there might be other, more efficient methods of mapping objects to vibrations. To put it another way, we sought to investigate whether different methods of mapping could possibly lead to better navigation results.

Furthermore, the observed difficulty in navigating small spaces, revealed that specific vibration techniques might not quite work in all environmental scenarios. Therefore, we developed a set of vibration patterns and mappings to provide additional aid to the user. We planned to improve vision deprived navigation using a tactile display by evaluating the different environment-to-vibration pattern and mapping techniques, as described in sections 4.1.1 and 4.1.2 respectively.

4.1.1 Environment-to-Vibration Mapping Techniques

For the purposes of this study, there are 2 main factors characterizing vibration perception: vibration amplitude and frequency. While there are other variables that could potentially manipulate the vibration sensation, such as vibration pattern and roughness, we chose to keep those static, and only manipulate one dimension at a time. Simply put, distance changes from objects are either amplitude or frequency modulated.

Figure 20. Modulation Types Based on Input Value. Top: Input Value. Middle: *Amplitude Modulation*. Bottom: *Frequency Modulation*



4.1.1.1 Vibration Modulation

Amplitude Modulation

The amplitude of the vibration modulates based on the distance from an object (Figure 21). This mode feels like a smooth vibration increase or decrease (depending on whether the object gets closer or further away).

Frequency Modulation

The frequency of the vibration modulates based on the distance from an object (Figure 21). This mode feels like a pulsating vibration that accelerates or decelerates as the participant moves into space.

4.1.1.2 Distance Mapping

Furthermore, we also needed a way to map (object) distance to vibration. For the purposes of this study, we chose to test Linear, Exponential and Power Mapping (Figure 22).

Linear

Distance from an object is linearly mapped to a value that controls the vibration modulation (Figure 22).

Technically, the amplitude of the vibration motor can take 4,096 discrete values. However, the human skin lacks resolution to distinguish between all those individual vibration values. Therefore, we further divided Linear Mapping into three additional subcategories (Figure 23):

- **Smooth Vibration Mapping**: Distance from objects is mapped onto 4,096 distinct levels.
- **5-Level Vibration Mapping**: Distance from objects is mapped onto five distinct levels.

Figure 21. The 3 Mapping Functions. Left: Linear Mapping. Middle: Exponential Mapping. Right: Power Mapping

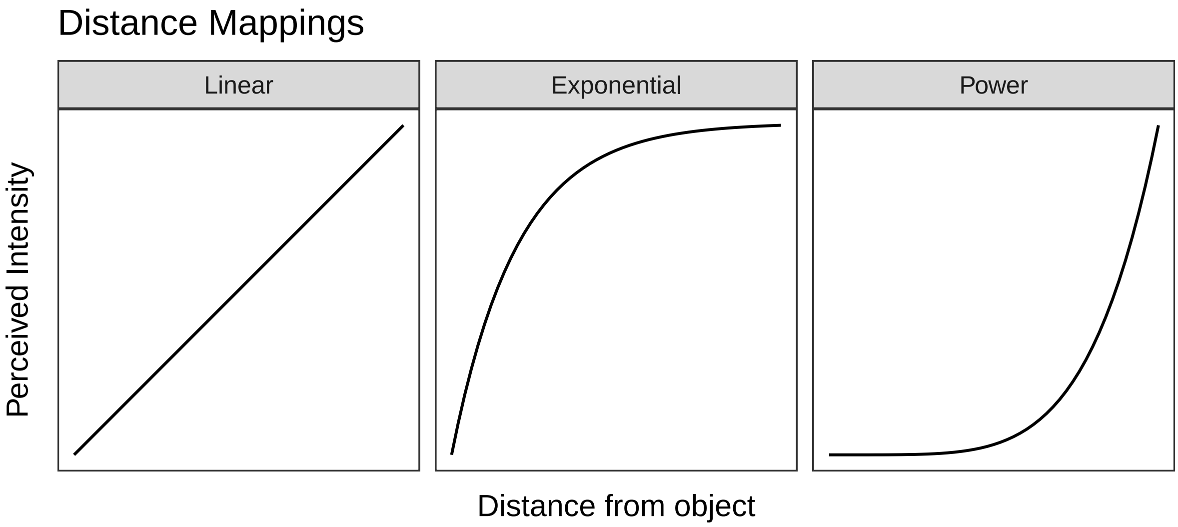
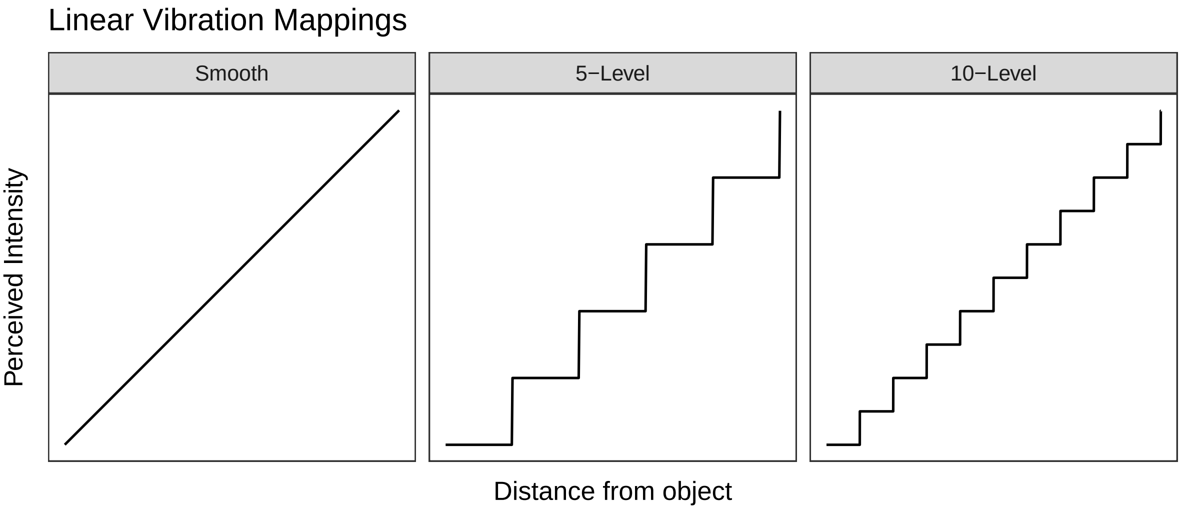


Figure 22. The Linear Distance Mappings. Left: Smooth Mapping. Middle: 5-Level Mapping. Right: 10-Level Mapping



  - **10-Level Vibration Mapping**: Distance from objects is mapped onto ten distinct levels.

Power Mapping

A power function maps distance from objects onto a value that controls *Vibration Modulation* (Figure 22).

Exponential Mapping

An exponential function maps distance from objects onto a value that controls *Vibration Modulation* (Figure 22).

4.1.1.3 Distance-to-Vibration Mapping

Finally, *Distance-to-Vibration Mapping* controls the perception of objects onto the skin.

Beware Vibration Mode

Vibration indicates obstacles. This mode essentially warns against objects to be avoided (Figure 24).

Follow Vibration Mode

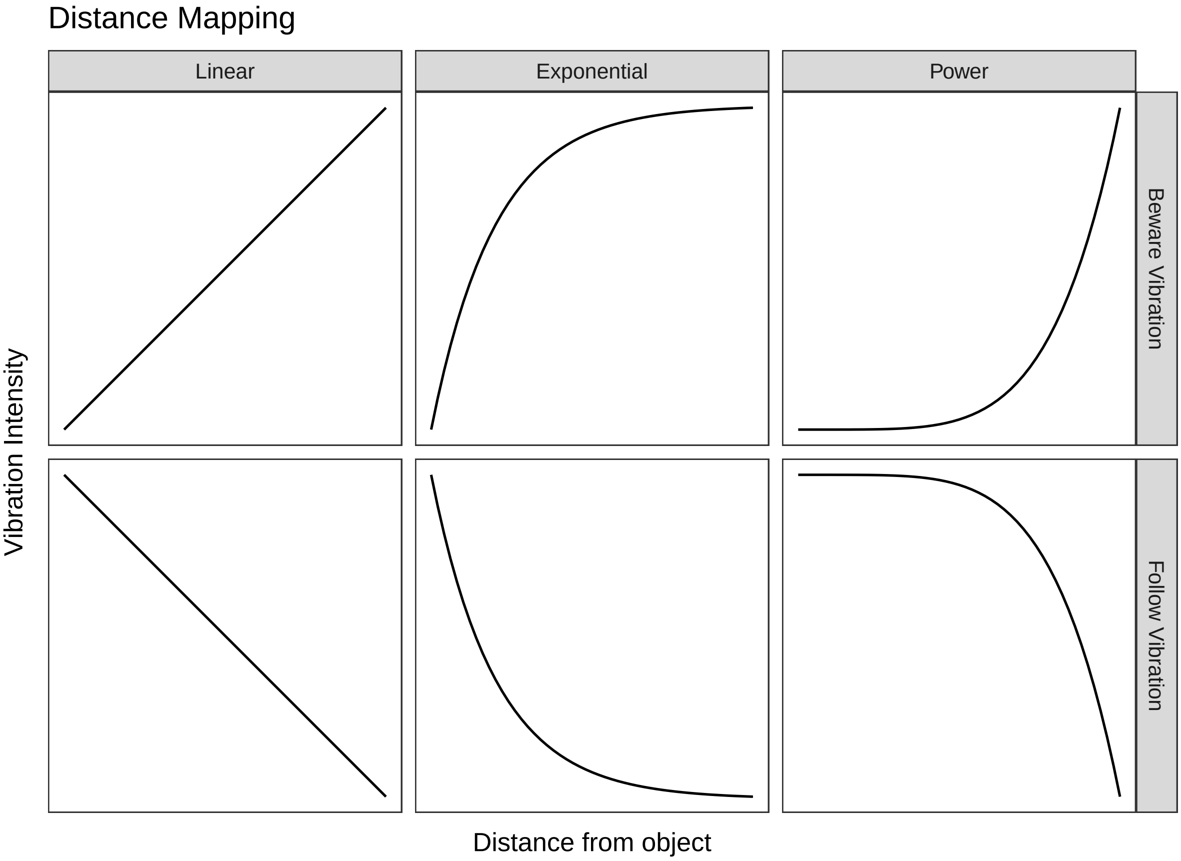
Vibration indicates open space (no objects). This mode essentially indicates a clear path, safe to be followed (Figure 24).

4.1.2 Environment-to-Vibration Mapping

Environment-to-Vibration Mapping consists of three different mappings that aid the user in navigation. Each one differs in terms of environmental scanning method, and therefore enables different vibration experiences.

Virtual sensors, with a horizontal and vertical Field Of View (FOV) of 30°, control the vibration of each motor. Sensor positioning depends on each mapping, as described below:

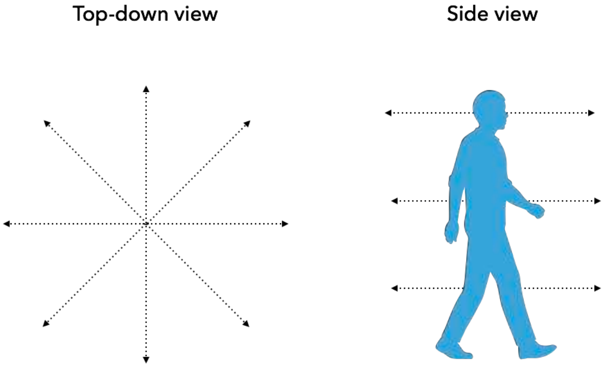
Figure 23. *Beware* and *Follow Vibration Mode* Mappings



360° **Mapping**

A 360° view of the environment is mapped onto the user's body. Three rows of virtual sensors are vertically spread at head, torso and knee levels, and horizontally at 45° increments, similar to the motors (Figure 25). For instance, if the user faces an obstacle at head height, only the top row motors would vibrate. Similarly, if there are multiple obstacles—at different heights—surrounding the user, the corresponding areas of the torso band will vibrate accordingly.

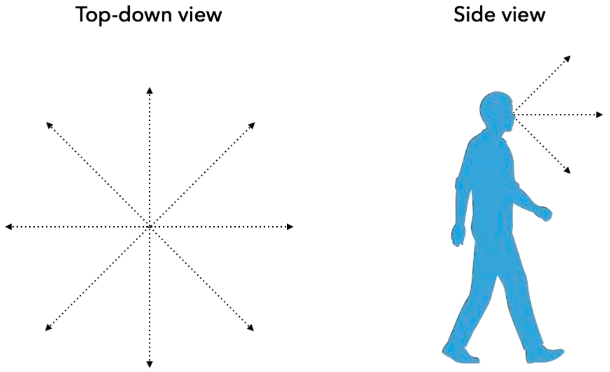
Figure 24. 360° *Mapping*



Head Gaze Mapping

Inspired by biological vision, the user "feels" the environment according to the direction they are looking towards. A 3x3 virtual sensor array, (virtually) attached to the participant's Head Mounted Display (HMD), is controlled by head movement (Figure 26). The sensors control a

Figure 25. *Head Gaze Mapping*

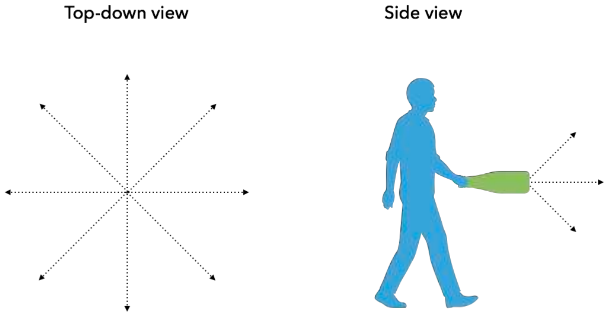


3x3 vibration subarray in the forward direction of head gaze, while head tilt and yaw are also taken into consideration. The total horizontal and vertical FOV is 120°.

Flashlight Mapping

Similar to a flashlight's operation, the user ”feels” the environment by pointing to a specific

Figure 26. *Flashlight Mapping*



area using a controller. A 3x3 virtual sensor array is attached to a controller, which can be used to actively scan the environment (Figure 27). The sensors control a 3x3 vibration subarray in the forward direction of the flashlight, while the controller's tilt and yaw are also taken into consideration. The total horizontal and vertical FOV is 120°.

Table IV summarizes *Environment-to-Vibration Mappings*, anchor points and effective FOVs. Please note that sensors do not get triggered by the floor or the ceiling.

TABLE IV

ENVIRONMENT-TO-VIBRATION MAPPINGS, THEIR ANCHOR POINTS AND EFFECTIVE FOVS

Environment-to-Vibration Mappings	**Anchor Point**	**Horizontal FOV**	**Vertical FOV**
360°	Torso	360°	30° (per row)
Head Gaze	Head	120°	120°
Flashlight	Controller	120°	120°

4.2 Hypothesis

Due to the previous research on *Sensory Substitution* tactile displays, we formed two hypotheses surrounding our main research questions regarding the Environment-to-Vibration Patterns and Mappings we had developed.

- Minimally trained blindfolded individuals can efficiently use tactile displays for completion of navigational tasks. For the purposes of this user study, ”minimally trained” defines users who do not have any prior experience using a tactile display and are minimally trained for this specific user study. Efficiency and precision (defined in sections 5.1.1 and 5.2.1) can be assessed in different ways, but for this experiment we chose to concentrate on task time-to-completion and number of valid walks respectively.
- The participants' efficiency and precision (defined in sections 5.1.1 and 5.2.1) is related to their experience with the tactile display and would significantly improve over time.

4.3 Evaluation

The requirements of this study are the following:

1. Having an easily reconfigurable, flexible environment that allows testing different spaces and scenarios.
2. Testing different vibration mappings, patterns and mechanisms.
3. Selecting participants who would undergo necessary training to get comfortable with vision deprivation, as well as learn how to use a variety of vibration mappings, patterns and mechanisms.
4. Designing tasks in such a way that users can complete them within the allocated time frame (for the purposes of this study we determined this time frame to be 60 seconds) after minimal training.

For this evaluation, we considered 2 different approaches. The first was to build the *SpiderSense 3* hardware with external environmental sensors (similar to those used in *SpiderSense 1* and *2*) and construct an obstacle course within a physical space, for the users to navigate through. However, this approach has certain limitations resulting in increased difficulty in acquiring consistent quantitative data. The above-mentioned challenges/limitations are described below:

1. Increased physical danger for the participants to fall/trip/harm themselves, especially when doing trials that include obstacles at head height.
2. The extremely challenging task of building a highly sophisticated maze that would have the flexibility of dynamically reshaping itself. In other words, we hypothesized that since the maze would remain the same between walks, it would eventually become easier for the subjects to memorize. Additionally, taking into consideration the physical constraints, some obstacles (like for instance, an obstacle at head height) would be difficult to construct. Finally, even if we managed to build said maze by using movable walls and obstacles—and therefore allowing quick re-configuration—it would be impossible to perform the number of experiments that we planned to.
3. Physical limitations/restrictions of the participants: As described in sections 3.1.4 and 3.2.3, one of the limitations of using real environmental sensors (like sonar range-finders), is that the direction in which they point depends on the body type/shape of the participant.

The above challenges and limitations bring us back to our initial questions: Could tactile displays be used successfully for navigation? What kinds of vibration mappings could make this task easier?

The second approach includes testing vision deprived navigation with the help of different vibration mappings and examines their use in a controlled user study environment. To overcome the limitations described above, while adhering to the requirements, we chose to use a Virtual Reality (VR) environment that would allow us more flexibility:

1. No physical danger for the participant, as virtual objects would be used in a physical space cleared of potential hazards.
2. The use of a virtual environment would allow us immediate reconfiguration with infinite combinations and without any physical constraints.
3. There are no physical limitations or restrictions, as we are using virtual sensors (section 4.1.2).

To measure *Situation Awareness* we will be using the performance measure methodology (see Table II or for a more thorough review see (52)). Our performance metrics are defined in sections 5.1.1 and 5.2.1.

Given the desire to collect quantitative data on the effectiveness of the tactile display, we concluded that the controlled experiment (option two) would be a better choice. Hence, fulfilling the above requirements, the following sections will detail the design, methods, and task of the controlled quantitative experiment.

4.3.1 Pilot Study

The purpose of this pilot study was to evaluate and compare the Environment-to-Vibration Patterns we defined above in regards to vision deprived navigation using a tactile display.

4.3.1.1 Materials

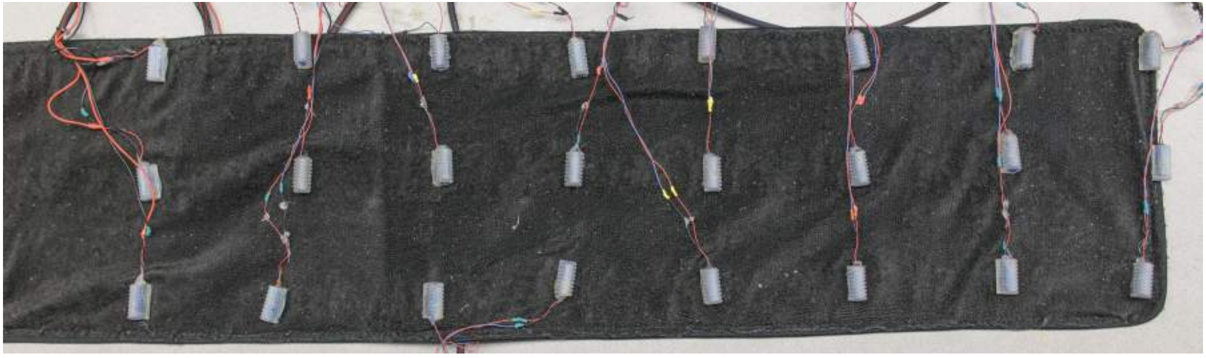
This pilot study was based on a set of navigational tasks conducted by subjects that were artificially deprived of vision. Six participants (2 female and 4 male) completed 486 walking trials. The following section describes the general system setup.

4.3.1.1.1 Setup

The study was carried out in a room cleared of all objects or obstacles that could potentially create a hazardous environment for the user. The participants were fitted with *SpiderSense 3*, the *HTC VIVE VR* Head-Mounted Display (HMD) and a pair of noise-canceling headphones. In order to eliminate any background noises and to mask the vibration motor noise (which could hint at which motors are vibrating) and create a sensory deprivation environment, the headphones were playing rainy environmental sounds in the background. However, for safety reasons, we decided to use audio chat software (*Discord app*), so we could instruct and/or warn the participants throughout the experiment. Communication was limited to directions for starting/stopping a trial and for stopping walking immediately in the case of wandering outside the experimental area. The HTC VIVE was tethered to a local desktop computer (*Intel Core i7-6700 3.40GHz, 32GM RAM, NVIDIA GeForce GTX 1070*). Prior to the start of the study, users were also asked to fill a demographic survey (to review the material used in this study refer to Appendix A). Finally, a camera mounted on the ceiling recorded a top-down view of the experiment, and a second tripod-mounted camera with a wide field of view lens was used to record the session itself.

4.3.1.1.2 Tactile Display

Figure 27. The 3x8 *SpiderSense 3* Tactile Display



Users were fitted with *SpiderSense 3* (Figure 28), which, as described in section 3.3.1, contains 24 vibration motors—more specifically 3 rows of 8 vibration motors. During the fitting, the experimenter measures the circumference of the participant's torso and adjusts the motors on the torso band to be equidistant to their body (one motor every 45°).

Set of variations

The vibration sensation of each actuator depends on the combination of *Vibration Mode*, *Vibration Modulation* and *Distance-to-Vibration Mapping*. These 3 variables provide 14 combinations in total, which can be found in Table V below. Please note that due to the vibration motors' technical limitations we could only test *5-Level* and *10-Level* Mappings while in *Frequency Modulation*. More specifically, the vibration motors' frequency range was quite limited and did not allow for *Linear*, *Power* and *Exponential Mappings*.

TABLE V

THE 14 POSSIBLE COMBINATIONS

Distance-to-Vibration Mapping	**Vibration Modulation**	**Distance Mapping**
Beware Vibration Mode	Amplitude	Smooth
Beware Vibration Mode	Amplitude	Power
Beware Vibration Mode	Amplitude	Exponential
Beware Vibration Mode	Amplitude	5-Level
Beware Vibration Mode	Amplitude	10-Level
Beware Vibration Mode	Frequency	5-Level
Beware Vibration Mode	Frequency	10-Level
Follow Vibration Mode	Amplitude	Smooth
Follow Vibration Mode	Amplitude	Power
Follow Vibration Mode	Amplitude	Exponential
Follow Vibration Mode	Amplitude	5-Level
Follow Vibration Mode	Amplitude	10-Level
Follow Vibration Mode	Frequency	5-Level
Follow Vibration Mode	Frequency	10-Level

4.3.1.1.3 Alarm Mode

Since this study was conducted in experimental circumstances rather than in a real-world environment, we observed some challenges/limitations that prompted troubleshooting: Due to the immaterial nature of the virtual space, in which this user study was conducted, there was no physical feedback to indicate when a subject would touch or go through a wall. To alleviate this problem, we designed *Alarm Mode*, a unique vibration pattern with the sole purpose of informing the user when in contact with a virtual object. For the purposes of this study, we have decided to use a distinct high-frequency (50 Hz), high amplitude vibration pattern.

Furthermore, the purpose of *Alarm Mode* is twofold:

1. Helps keep the subjects inside the virtual space, while at the same time uses reinforced learning to teach them how to avoid making the same ”mistake” again.
2. Helps examine whether the subjects can distinguish different alarm patterns and whether this will alter their navigational course. While in this case (virtual environment), *Alarm Mode* signifies that a wall has simply been touched, in a real-life scenario it would be the last resort effort to prevent the user from falling/bumping/crashing into walls and/or objects and unavoidably getting hurt.

We further hypothesized that the users' mistakes (touching or going through walls/objects and hence triggering *Alarm Mode*) would decrease over time.

4.3.1.1.4 Experimental Sets

To begin with, 6 participants were asked to perform three sets of at least 14 and at most 42 walking trials, with 5-minute resting breaks in between, while vision-deprived. The subjects, had 60 seconds to get to the end of a straight-line virtual corridor simply using the vibration feedback translated onto their body. Each experimental set starts either in *Beware* or in *Follow Vibration Mode*, with the remaining variables (*Vibration Modulation* and *Distance-to-Vibration Mapping*) being randomly selected using a pseudo-random selector (see section 4.3.1.1.7). If the subjects do not successfully complete a walk, said walk is marked as invalid. The same applies, in the event of the user walking through a wall; however in this case, another attempt is given, with three attempts at most. Table VI below summarizes these actions.

TABLE VI

POSSIBLE OUTCOMES OF A TRIAL

Trial Outcome based on user action	**Action**
Reached end	Combination removed from set
Timed out	Combination removed from set
Touched Wall	Alarm mode, trial continues
Went through wall	Trial ends, combination added back to set unless it was the third attempt, in which case it is removed from set

4.3.1.1.5 Virtual Corridor

The experiment consists of a straight-line virtual corridor walking trial, within a 2x3m space, that the participants have to navigate wearing a VR Head Mounted Display (HMD). The virtual corridors are 1m wide, 2m high, and 2.7m long; their starting and ending points, as well as their direction, are randomized for each trial. The randomization method randomly selects the edges of an equilateral triangle (each side is 2.7m), as well as a walking direction at the beginning of each trial, to avoid path memorization by the user. The starting point is marked by a 3D cylinder (see section 4.3.1.1.6) which disappears once the trial begins. As a result, the starting direction that the user is facing towards depends on the random direction of the corridor, on the user's incoming direction, as well as their positioning. Thus it changes from trial to trial, further ensuring randomness.

4.3.1.1.6 3D Cylinder

The trial begins once the participant is "inside" a red 3D cylinder that indicates the starting position, at which point it disappears, in which case only the *Heads Up Display* (*HUD*) is visible (see section 4.3.1.1.8).

4.3.1.1.7 Pseudo-Random Selector

For the purposes of this study, a pseudo-random selector is used to randomly select a *Vibration Modulation* and *Distance-to-Vibration Mapping* from the possible list of combinations (see Table V). This single, random combination will be removed from the selection list if the trial is valid, if it times out or if it's been the third time the participant walks outside the virtual corridor. Thus it contributes to eliminating bias towards a specific pattern combination and further ensuring randomness.

4.3.1.1.8 Heads Up Display (HUD)

A simple text User Interface (UI) on the participant's HMD informs them of the current mode—*Beware* or *Follow*—and of the remaining time to complete each trial. For the purposes of this study, the participants are not provided with any information regarding the current *Vibration Modulation* or *Distance-to-Vibration Mapping.*

4.3.1.1.9 Safety Assistant

A Safety Assistant is responsible for the participants' safety during the study. Specifically, he/she monitors the subjects to ensure they remain within the tracked area and are responsible for holding the HMD's tethered cable out of their way. The Safety Assistant is equipped with a microphone and can talk to the participant in case they deem that the participant's safety might be in danger. We are extremely proud to report that no injuries (tripping or otherwise) were incurred during this study.

4.3.1.2 Methods

The study consists of three main phases: Control, Training and Evaluation. Participants initially read, agree and sign the Institutional Review Board (IRB) documents (that include study and media consent forms—see Appendix A). They, then, get fitted with *SpiderSense 3.*

4.3.1.2.1 Pilot Study Phases

1. **Control Phase**: A Control Phase during which the participants walk a straight-line virtual corridor (see section 4.3.1.1.5) utilizing their visual system (the HMD renders the corridors). The subjects starting position and corridor direction is randomized as described in section 4.3.1.1.7. The baseline walking pace is measured by having participants walk the corridor, without touching any walls/objects. The participants repeat the task 7 times. Please note that during this phase the vibration is turned off and the VR HMD displays the straight-line virtual corridors. As a result the participants rely solely on visual cues for navigation. The goal of this phase is twofold: To calculate the participants' walking pace, and to make them comfortable walking within a VR environment, since some of the participants had never used any type of VR HMD before and might not be as comfortable as others.

2. **Training Phase**: A Training Phase during which the participants walk a similar type corridor, with the VR HMD and vibrations enabled. The goal of this phase is to get them accustomed to the tactile display itself, and to the vibration feeling on their body. This will also help them identify the differences between the 2 modes (*Beware* and *Follow*) as well as the emergency *Alarm Mode*, which they are encouraged to trigger for training purposes. At this point, the participants have not been briefed about the *Vibration Modulation* nor the *Distance-to-Vibration Mappings*—they are only informed that for each walk, a different randomly selected vibration pattern will occur. Finally, once a different vibration configuration is selected—as described in section 4.3.1.1.4—each individual trial starts

within a 90-second time frame. At the end of the training phase, a scheduled 5-minute resting break occurs.

3. **Evaluation Phase**: An Evaluation Phase during which the VR HMD is blank displaying only the *HUD* (section 4.3.1.1.8). From this point forward there are no visual cues, so the participants are effectively blindfolded, having to rely solely on vibration feedback. Trials start at the starting position marked by the 3D cylinder (section 4.3.1.1.6) and have to be completed in 60 seconds or less. This phase is repeated 3 times, with scheduled, 5-minute resting breaks in-between.To get more information about the virtual corridors or the vibration settings selection, revisit section 4.3.1.1.5 and section 4.3.1.1.1 respectively.

4.3.1.2.2 Order of Trials

The first three participants began trials in *Beware Vibration Mode* and concluded in *Follow Vibration Mode*. The remaining three had the order reversed in order to eliminate bias towards specific vibration mode and further ensure randomness.

4.3.1.2.3 Pilot Study Structure

1. The Participant gets briefed about the experiment and completes the initial consent and media release form, as well as the demographic survey.

2. The Experimenter, measures the participant's torso circumference using a tape, then fits *SpiderSense 3* to their body. More specifically, the Experimenter places—in the horizontal plane—the vibration motors at 45°intervals.

3. The Participant is briefed in detail about the Control and Training Phases of the experiment.
4. The Participant wears *SpiderSense 3*, the backpack, and the headphones. The Experimenter and the Safety Assistant ask the Participant to confirm that the audio link is working.
5. For calibration purposes, the Participant is asked to stand straight, and look forward, until the application loads.
6. The Control Phase of the experiment starts. The Participant walks a straight-line virtual corridor (7 trials).
7. The Training Phase of the experiment starts. The Participant walks a straight-line virtual corridor (14 trials).
8. The Participant takes a scheduled 5-minute resting break, in which time, they are still wearing the torso band (with the motors turned off) and the backpack, but the HMD and headphones have been taken off.
9. The Evaluation Phase begins. First set of experiments start. The Participant walks a straight-line virtual corridor (14 to 48 trials).
10. The Participant takes a scheduled 5-minute resting break, in which time, they are still wearing the torso band (with the motors turned off) and the backpack, but the HMD and headphones have been taken off.

11. The second set of experiments start. The Participant walks a straight-line virtual corridor (14 to 48 trials).
12. The Participant takes a scheduled 5-minute resting break, in which time, they are still wearing the torso band (with the motors turned off) and the backpack, but the HMD and headphones have been taken off.
13. The third (and last) set of experiments is performed. The Participant walks a straight-line virtual corridor (14 to 48 trials).
14. After completion, the Participant removes *SpiderSense 3*, headphones and backpack and the Experimenter performs an unscripted interview.

4.3.1.3 Participants

We recruited participants by posting announcements to the University of Illinois at Chicago (UIC) graduate student mailing list. Potential participants were recruited using email (recruitment letter is attached in Appendix A). The study took place at the Electronic Visualization Laboratory (EVL), at the University of Illinois at Chicago (UIC).

4.3.1.4 Data Collection

Demographic information was collected at the beginning of the pilot study through a paper user survey (see Appendix A). The full duration of the pilot study, excluding briefing, was audio and video recorded. The application automatically collected user tracking data (head position and rotation, torso position and rotation, controller position and rotation, controller input and sensor data) at a frame rate of approximately 60 frames per second. User tracking data was saved in 2 separate files, one for the sensor data and one for the tracking data for each experiment. Files were named based on user's coded ID number and experiment's unique ID number. Additionally, information about each trial (*Vibration Mode*, *Vibration Modulation*, *Distance-to-Vibration Mapping*, virtual corridor starting and ending position, elapsed time and walk status) was also saved into a separate file.

4.3.2 User Study

4.3.2.1 Materials

This user study was divided into various experimental sets, each consisting of 24 navigational trials. First, 5 vision deprived participants (1 female, 4 male) completed 2 sets of 24 trials (48 in total). Then, 11 vision deprived participants (2 female, 9 male) completed 3 sets of 24 trials (72 in total). At the end of the sets, an additional more complex navigational task was performed (as described in section 4.3.2.1.4). The next section will describe the general system setup.

4.3.2.1.1 Setup

The setup for this study was identical to the setup for the pilot study. For more information, please refer to section 4.3.1.1.1.

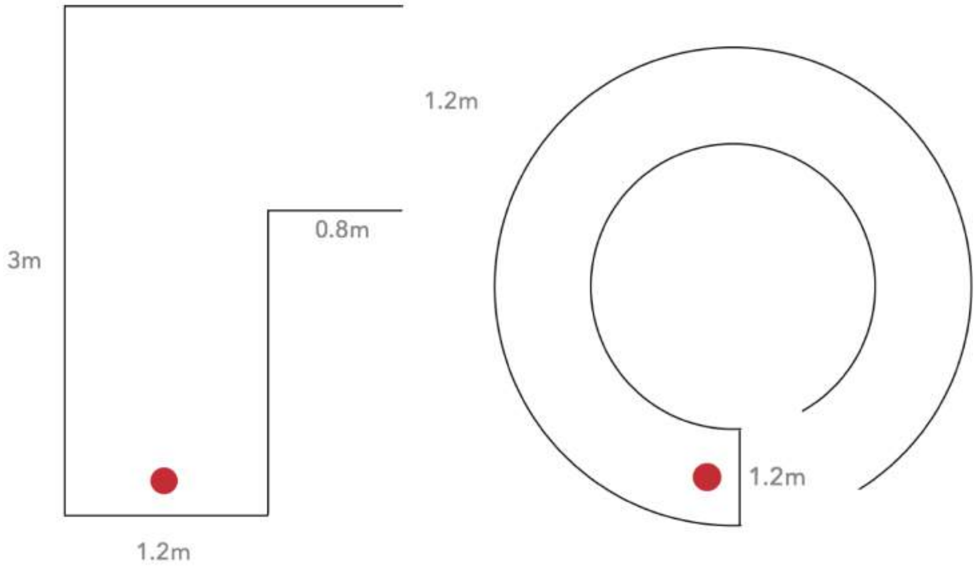
4.3.2.1.2 The Tactile Display

The setup for this study was identical to the setup for the pilot study. For more information, please refer to section 4.3.1.1.2. Additionally, based on the results from the pilot study (section 5.1), we chose *Beware Vibration Mode*, *Amplitude Modulation* and Linear Mapping as the Environment-to-Vibration Pattern.

4.3.2.1.3 Virtual Paths

All paths are 1.3m wide and 3m high with a random starting position and direction. For the purposes of this study, 2 types of *Virtual Paths* were used: A right angle, and a 350° circular one (Figure Figure 29). Additionally, each path might or might not have an obstacle blocking the participant's way (see section 4.3.2.1.5). In order to eliminate bias and further ensure randomness, each path's direction is also random (left or right).

Figure 28. Right angle and circular *Virtual Path*. Red dot denotes starting position

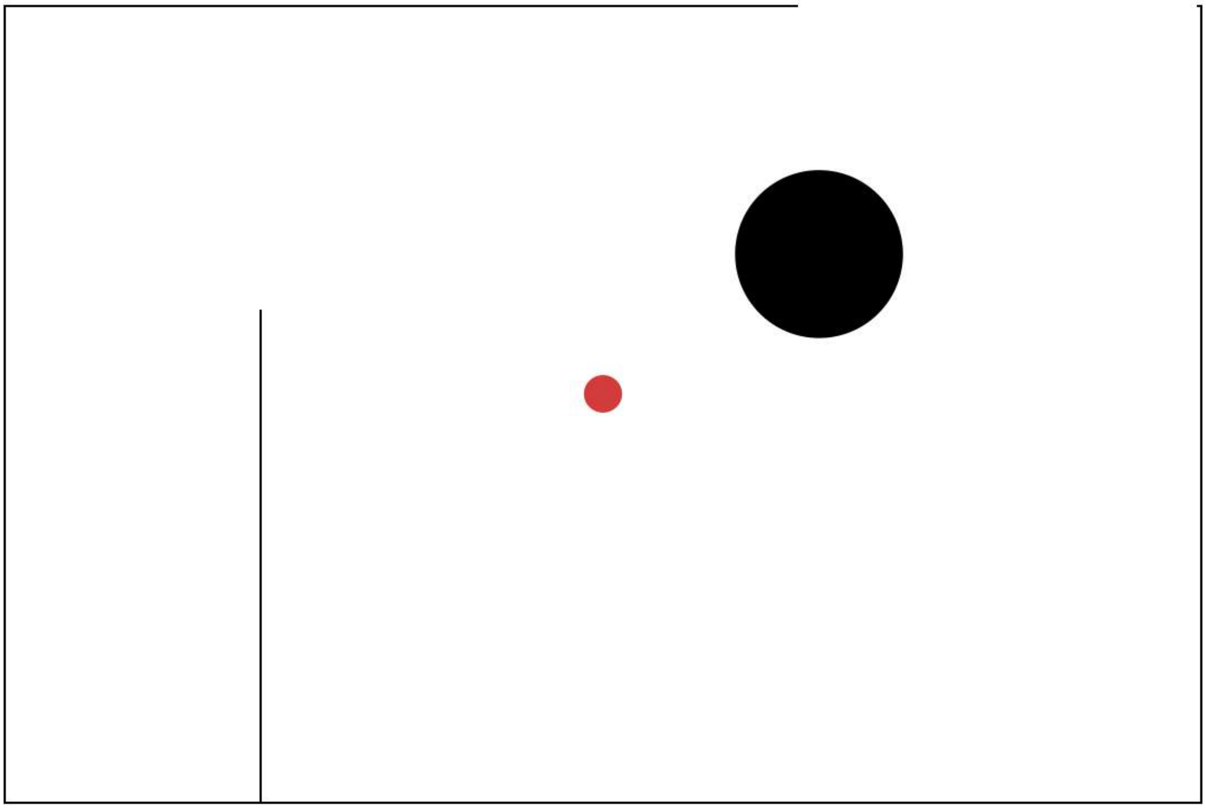


4.3.2.1.4 The Virtual Room

The final experiment of this study is a more complex navigational task, where the participants find themselves in a *Virtual Room* (Figure Figure 30) and have to find their way out through an open door. Unlike the *Virtual Paths* experiment, which was more directional (simple point A to point B navigation), there are now more than one ways to move in the virtual space. Participants begin in the middle of the Virtual Room and are now able to move in any direction in order to get to the open door. Some paths might lead them to the exit, while others might not. Please note that the participants were not trained in this new task, thus giving the Experimenter the opportunity to observe how well the acquired knowledge translates into more complex tasks.

To simulate a closer to reality scenario, the participants are told that they are firefighters trapped in a flaming building with zero visibility due to heavy smoke. The participants then have 10 minutes and 5 attempts to find the open door without touching any walls around them—the walls are considered to be on fire and therefore a hazard! The room is 2x3m and includes 2 obstacles: An obstacle at head height, and a 3m high, cylindrical virtual pillar. To ensure randomness, the room configuration randomly changes in order to mitigate any learning effects. In order to make the experiment more realistic and compelling, participants are able to see smoke and fire during the trials, however, the architecture (shape) of the room still remains invisible. Similar to the *Virtual Paths* experiments, the *HUD* indicates the current *Environment-to-Vibration Mapping* and the remaining time. Unlike the *Virtual Paths* experiments, the participants now have the opportunity to choose among *Environment-to-Vibration Mappings*, using the controller, as they see fit.

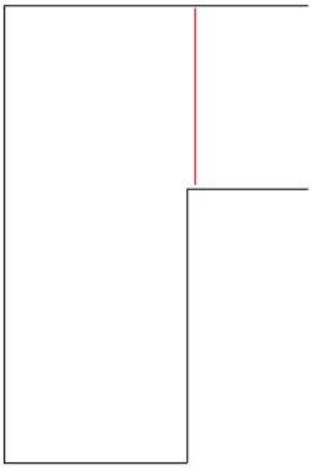
Figure 29. The *Virtual Room.* Red dot denotes starting position. Please note the two obstacles



4.3.2.1.5 Virtual Obstacles

Real-life physical spaces are significantly more complex than simple point A to point B navigation, as appears in the pilot study. Hence, building on our initial idea we have decided to add an additional level of complexity to the user study, in the form of *Virtual Obstacles.* This new task would allow us to test if users would be able to successfully navigate while identifying and avoiding *Virtual Obstacles* as they go.

Figure 30. A right angle *Virtual Path* with an obstacle



Obstacle location is random for each trial and is at least 60cm from the participant's starting position. For experimental consistency reasons, obstacle height is 20cm below the participant's head. Obstacle types come in 2 forms: During the *Virtual Path* experiments, obstacles are always blocking the participant's way (the participants would essentially need to duck or squat in order to finish the trial). During the Virtual Room experiments (section 4.3.2.1.4), however, the participants have the opportunity to walk around the obstacle (but they are not aware of it beforehand).

4.3.2.1.6 3D Cylinder

The trial begins once the participant is "inside" a red 3D cylinder that indicates the starting position, at which point it disappears, in which case only the *HUD* is visible.

4.3.2.1.7 Pseudo-Random Selector

The pseudo-random selector randomly selects a *Virtual Path* and an *Environment-to-Vibration Mapping* from the possible list of combinations (see Table Table VII). This single, random combination gets removed from the selection list if the trial is valid, if it times out or if the participant touches a wall or an object.

Each experimental set consists of trials uniquely combining all variables (*Environment-to-Vibration Mapping*, path type, path direction and obstacle presence) at most once. Simply put, each experimental set consists of 6 left-turn virtual corridors, 6 right-turn virtual corridors, 6 left-turn circular virtual corridors, and 6 right-turn circular virtual corridors. Half of the above trials randomly contain obstacles (section 4.3.2.1.5). Table VII, below, summarizes the *Environment-to-Vibration Mapping*, path type and path direction combinations per experimental set.

TABLE VII

MODES AND PATHS PER EXPERIMENTAL SET

Environment-to-Vibration Mapping	**Path Direction**	**Path Type**
Full Body	Left Turn	right angle corridor
Headgaze	Left Turn	right angle corridor
Flashlight	Left Turn	right angle corridor
Full Body	Right Turn	right angle corridor
Headgaze	Right Turn	right angle corridor
Flashlight	Right Turn	right angle corridor
Full Body	Left Turn	circular corridor
Headgaze	Left Turn	circular corridor
Flashlight	Left Turn	circular corridor
Full Body	Right Turn	circular corridor
Headgaze	Right Turn	circular corridor
Flashlight	Right Turn	circular corridor

4.3.2.1.8 Heads Up Display (HUD)

A simple text User Interface (UI) on the participant's HMD that informs them of the current *Environment-to-Vibration Mapping* and of the remaining time to complete each trial.

4.3.2.1.9 Safety Assistant

For the purposes of this study, we followed the same safety protocol as in the pilot study. For more information, please refer to section 4.3.1.1.9.

4.3.2.2 Methods

The study consists of three main phases: Control, Training and Evaluation. Participants initially read, agree and sign the Institutional Review Board (IRB) documents (that include study and media consent forms—see Appendix A). They, then, get fitted with *SpiderSense 3*.

4.3.2.2.1 User Study Phases

1. **Control Phase**: For the purposes of this study we followed the same process as in the pilot study. For more information, please refer to section 4.3.1.2.3.
2. **Training Phase**: A Training Phase during which the participants will experience 2 types of virtual spaces with the vibration turned on: A straight-line *Virtual Path* and a single Virtual Wall. During this phase they are instructed to take their time in order to learn how to use the different *Environment-to-Vibration Mappings* in regards to the visuals. In other words, they are prompted to explore what happens when they get closer to or move further away from a Virtual Wall or *Virtual Obstacle.* The participants are thoroughly briefed about the three different *Environment-to-Vibration Mappings*, their respective FOVs as well as the nature of the *Virtual Obstacles.* Additionally, they are encouraged to explore the virtual space during this phase and try to figure out a navigational "strategy" beforehand in order to be able to distinguish a Virtual Wall from a *Virtual Obstacle*—a

significantly challenging task. Finally, once a different vibration configuration is selected—as described in section 4.3.2.1.7—each individual trial starts within a 60-second time frame. At the end of the Training Phase, a scheduled 5-minute resting break occurs.

3. **Evaluation Phase**: An Evaluation Phase during which the VR HMD is blank displaying only the *HUD* (section 4.3.2.1.8). From this point forward there are no visual cues, so the participants are effectively blindfolded, having to rely solely on vibration feedback. This phase is divided in 2 stages: The *Virtual Paths* experiments, and the Virtual Room experiments. The *Virtual Paths* stage is further divided into various experimental sets, each consisting of 24 navigational trials. First, 5 vision deprived participants completed 2 sets of 24 trials (48 in total). Then, 11 vision deprived participants completed 3 sets of 24 trials (72 in total). The Virtual Room stage, consists of 5 trials of 10 minutes each. Trials start at the starting position marked by the 3D cylinder (section 4.3.2.1.6). Between stages and experimental sets scheduled, 5-minute resting breaks occur.

4.3.2.2.2 User Study Structure

1. The Participant gets briefed about the experiment and completes the initial consent and media release form, as well as the demographic survey (see Appendix A).
2. The Experimenter, measures the participant's torso circumference using a tape, then fits *SpiderSense 3* to their body. More specifically, the Experimenter places—in the horizontal plane—the vibration motors at 45°intervals.

3. The Participant is briefed in detail about the Control and Training Phases of the experiment. The Experimenter explains all three different *Environment-to-Vibration Mappings* (360°, *Head Gaze* and *Flashlight*) as well as the *Virtual Obstacles* that might appear. Emphasis is given to the fact that the Participant will encounter the obstacle only three times throughout the Training Phase and that they will have to train themselves to distinguish the differences between walls and obstacles beforehand.
4. The Participant wears *SpiderSense 3*, the backpack, and the headphones. The Experimenter and the Safety Assistant ask the Participant to confirm that the audio link is working.
5. For calibration purposes, the Participant is asked to stand straight, and look forward, until the application loads.
6. The Control Phase of the experiment starts. The Participant walks a straight-line virtual corridor (7 trials).
7. The Training Phase of the experiment starts. The Participant walks a straight-line virtual corridor (12 trials, 3 of which will have a *Virtual Obstacle*) or explores a Virtual Wall (12 trials).
8. The Participant takes a scheduled 5-minute resting break, in which time, they are still wearing the torso band (with the motors turned off) and the backpack, but the HMD and headphones have been taken off.

9. The Evaluation Phase begins. First set of experiments start. The Participant walks a right angle or 350° circular *Virtual Path* (24 trials).
10. The Participant takes a scheduled 5-minute resting break, in which time, they are still wearing the torso band (with the motors turned off) and the backpack, but the HMD and headphones have been taken off.
11. The second set of experiments start. The Participant walks another right angle or 350° circular *Virtual Path* (24 trials).
12. The Participant takes a scheduled 5-minute resting break, in which time, they are still wearing the torso band (with the motors turned off) and the backpack, but the HMD and headphones have been taken off.
13. For subjects 6-16, a third (and last) set of experiments is performed: The Participant walks a right angle or 350° circular *Virtual Path* (24 trials).
14. The Participant takes a scheduled 5-minute resting break, in which time, they are still wearing the torso band (with the motors turned off) and the backpack, but the HMD and headphones have been taken off.
15. The Participant performs the Virtual Room experiments (5 trials).
16. After completion, the Participant removes *SpiderSense 3*, headphones and backpack and the Experimenter performs an unscripted interview.

4.3.2.3 Participants

We recruited participants by posting announcements to the UIC graduate student mailing list. Potential participants were recruited using email (recruitment letter is attached in Appendix A). The study took place at the Electronic Visualization Laboratory (EVL), at the University of Illinois at Chicago (UIC).

4.3.2.4 Data Collection

Demographic information was collected at the beginning of the user study through a paper user survey (see Appendix A). The full duration of the user study, excluding briefing, was audio and video recorded. The application automatically collected user tracking data (head position and rotation, torso position and rotation, controller position and rotation, controller input and sensor data) at a frame rate of approximately 60 frames per second. User tracking data was saved in 2 separate files, one for the sensor data and one for the tracking data for each experiment. Files were named based on user's coded ID number and experiment's unique ID number. Additionally, information about each trial (*Vibration Mode*, *Vibration Modulation*, *Distance-to-Vibration Mapping*, virtual corridor starting and ending position, elapsed time and walk status) was also saved into a separate file.

CHAPTER 5

RESULTS

5.1 Pilot Study

This pilot study took place between September and October 2017. We recruited 6 participants (2 female and 4 male), who were new to tactile displays and had never worn or used a similar device, other than smartwatches, smartphones or vibration feedback game controllers. The pilot study followed the structure as described in section 4.3.2.2.2 and took approximately 2 hours to complete. No user expressed any discomfort or fatigue during the experiment.

The 6 participants completed 526 trials in total, 42 of which were in Control Phase, 85 in Training Phase and 399 in Evaluation Phase. The participants walked 3.4h and 2,750m in total, 2.7 hours and 2,125m of which, were in Evaluation Phase. On average, the participants walked 34min and 459m each. Table VIII, Table IX, Table X, Table XI, Table XII, Table XIII, Table XIV and Table XV show the number of successful trials, the mean trial duration and distance, the mean number of wall touches per participant and vibration combination.

5.1.1 Metrics

In the following three sections, we will analyze the *Vibration Mode*, *Vibration Modulation*, and *Distance-to-Vibration Mapping* of the trials during the Evaluation Phase, and present our findings. We will compare trials by referring to their performance, which we will then break down into the following metrics:

TABLE VIII

NUMBER OF SUCCESSFUL TRIALS PER PARTICIPANT IN *BEWARE VIBRATION MODE* DURING THE EVALUATION PHASE

	Beware Vibration Mode						
	Amplitude Modulation					**Frequency Modulation**	
Subject	**Smooth**	**Power**	**Exponential**	**5-Level**	**10-Level**	**5-Level**	**10-Level**
1	3	3	3	3	3	3	3
2	3	2	3	3	2	3	3
3	3	3	3	3	3	3	3
4	2	2	3	2	2	1	1
5	3	2	2	2	2	2	3
6	2	2	2	2	2	2	2

TABLE IX

NUMBER OF SUCCESSFUL TRIALS PER PARTICIPANT IN *FOLLOW VIBRATION MODE* DURING THE EVALUATION PHASE

	Follow Vibration Mode						
	Amplitude Modulation					**Frequency Modulation**	
Subject	**Smooth**	**Power**	**Exponential**	**5-Level**	**10-Level**	**5-Level**	**10-Level**
1	3	3	3	3	2	3	3
2	0	2	1	1	2	1	3
3	0	2	1	1	2	2	1
4	1	2	0	0	0	1	0
5	2	3	1	2	2	0	2
6	3	3	1	3	2	2	1

TABLE X

MEAN TRIAL DURATION IN SECONDS PER PARTICIPANT IN *BEWARE VIBRATION MODE* DURING THE EVALUATION PHASE

	Beware Vibration Mode						
	Amplitude Modulation					**Frequency Modulation**	
Subject	**Smooth**	**Power**	**Exponential**	**5-Level**	**10-Level**	**5-Level**	**10-Level**
1	14	12	23	14	17	13	26
2	22	17	15	22	15	23	28
3	11	12	14	12	15	11	15
4	21	15	24	14	20	36	36
5	9	9	15	11	19	14	16
6	11	25	12	26	13	21	15

TABLE XI

MEAN TRIAL DURATION IN SECONDS PER PARTICIPANT IN *FOLLOW VIBRATION MODE* DURING THE EVALUATION PHASE

	Follow Vibration Mode						
	Amplitude Modulation					**Frequency Modulation**	
Subject	**Smooth**	**Power**	**Exponential**	**5-Level**	**10-Level**	**5-Level**	**10-Level**
1	50	23	45	28	37	40	28
2	24	25	26	20	26	28	32
3	18	18	16	24	15	19	12
4	58	58	46	90	65	52	35
5	15	17	15	13	16	14	14
6	28	24	40	32	33	25	35

TABLE XII

MEAN TRIAL DISTANCE IN METERS PER PARTICIPANT IN *BEWARE VIBRATION MODE* DURING THE EVALUATION PHASE

	Beware Vibration Mode						
	Amplitude Modulation					**Frequency Modulation**	
Subject	**Smooth**	**Power**	**Exponential**	**5-Level**	**10-Level**	**5-Level**	**10-Level**
1	3	3	5	3	4	3	5
2	4	3	3	4	3	4	5
3	3	3	4	3	4	3	4
4	6	5	6	3	5	7	7
5	2	2	3	2	4	3	3
6	3	5	3	6	3	5	3

TABLE XIII

MEAN TRIAL DISTANCE IN METERS PER PARTICIPANT IN *FOLLOW VIBRATION MODE* DURING THE EVALUATION PHASE

	Follow Vibration Mode						
	Amplitude Modulation					**Frequency Modulation**	
Subject	**Smooth**	**Power**	**Exponential**	**5-Level**	**10-Level**	**5-Level**	**10-Level**
1	11	5	11	7	8	9	6
2	4	5	5	3	5	5	6
3	4	4	3	5	3	4	2
4	15	15	12	21	14	14	6
5	3	3	3	3	3	3	2
6	7	6	8	7	7	5	7

TABLE XIV

MEAN NUMBER OF WALL TOUCHES PER PARTICIPANT IN *BEWARE VIBRATION MODE* DURING THE EVALUATION PHASE

	Beware Vibration Mode						
	Amplitude Modulation					**Frequency Modulation**	
Subject	**Smooth**	**Power**	**Exponential**	**5-Level**	**10-Level**	**5-Level**	**10-Level**
1	1	0	2	0	0	0	3
2	2	1	0	1	1	2	3
3	0	0	1	0	1	0	3
4	3	2	2	0	1	3	3
5	0	0	2	1	3	2	4
6	0	3	1	1	1	4	1

TABLE XV

MEAN NUMBER OF WALL TOUCHES PER PARTICIPANT IN *FOLLOW VIBRATION MODE* DURING THE EVALUATION PHASE

	Follow Vibration Mode						
	Amplitude Modulation					**Frequency Modulation**	
Subject	**Smooth**	**Power**	**Exponential**	**5-Level**	**10-Level**	**5-Level**	**10-Level**
1	13	4	11	6	8	6	5
2	5	4	5	3	4	6	6
3	4	3	3	5	3	3	2
4	16	13	15	20	13	10	7
5	3	4	4	2	4	2	1
6	4	4	9	6	6	4	4

- **Number of valid trials**: A higher number indicates that the participant was able to finish a specific vibration combination easier than others.
- **Time to completion per trial**: Shorter duration indicates that the participant was able to finish faster.
- **Walking distance per trial**: Shorter distance indicates that the participant walked less.
- **Number of Virtual Wall touches**: A lower number indicates that the participant was keeping a straighter path. A higher number might indicate that the participant was using *Alarm Mode* as a navigation strategy (*Alarm Mode* is triggered every time the participant touches a Virtual Wall, as described above. Hence, one might rely on its vibration feedback in order to make it to the end of the trial).

5.1.2 Vibration Mode Results

Our analysis starts with the *Vibration Mode* results. Results from all 6 participants are summarized in Table XVI.

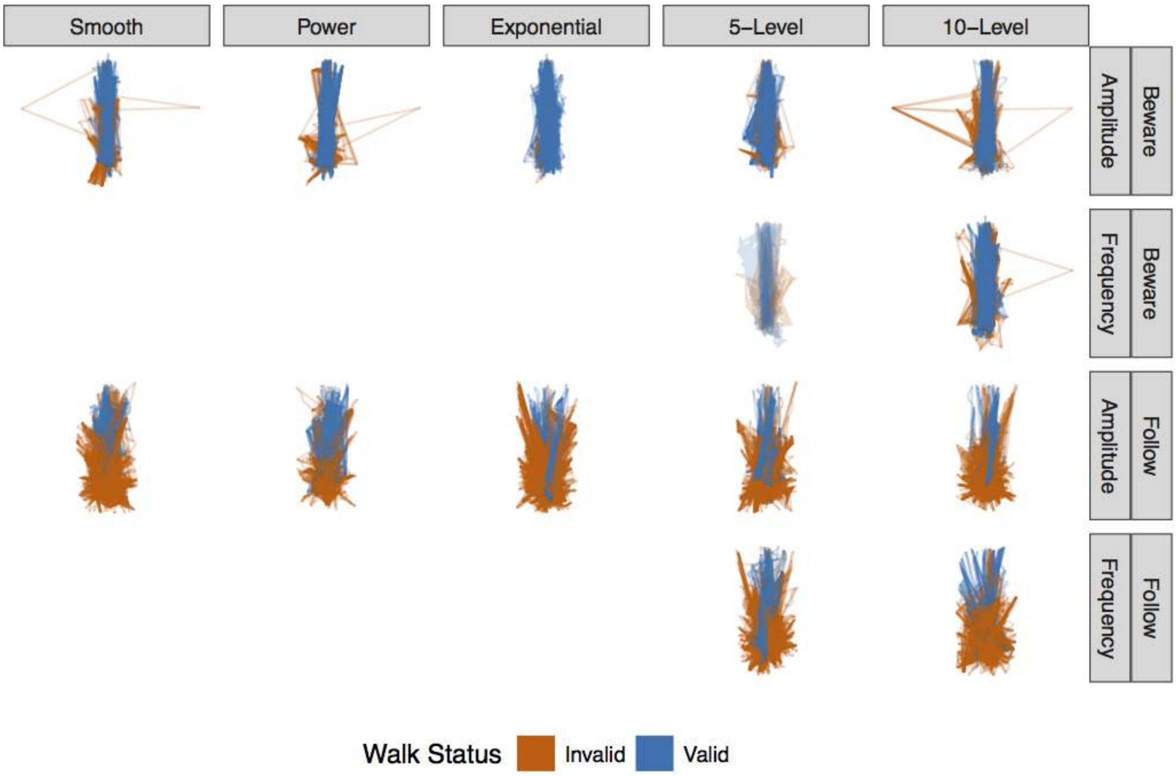
Additionally, Figure 32 plots the participants' walking paths over all vibration combinations, color-coded by validity. Blue indicates the valid trials, while orange indicates the invalid ones. By looking at the figure, we can immediately deduce the following:

- There are a lot more valid walks in *Beware Vibration Mode.*
- The paths in *Beware Vibration Mode* are more directional than the paths in *Follow Vibration Mode*, which seem rather randomly oriented.

TABLE XVI

OVERALL RESULTS OF THE *VIBRATION MODE*, EVALUATION PHASE TRIALS FOR THE PILOT STUDY. THERE WAS A TOTAL OF 6 PARTICIPANTS

Vibration Mode	**Trial Status**	**Mean Duration (in seconds)**	**Mean Distance (in meters)**	**Mean Number of Touches**
Beware Mode	Valid	19.49 ± 12.32	4.54 ± 2.52	1.27 ± 2.43
	Invalid	13.38 ± 20.18	2.43 ± 3.76	1.83 ± 2.46
Follow Mode	Valid	30.40 ± 17.14	6.97 ± 4.38	5.20 ± 4.70
	Invalid	27.84 ± 24.72	5.81 ± 5.95	5.92 ± 6.23

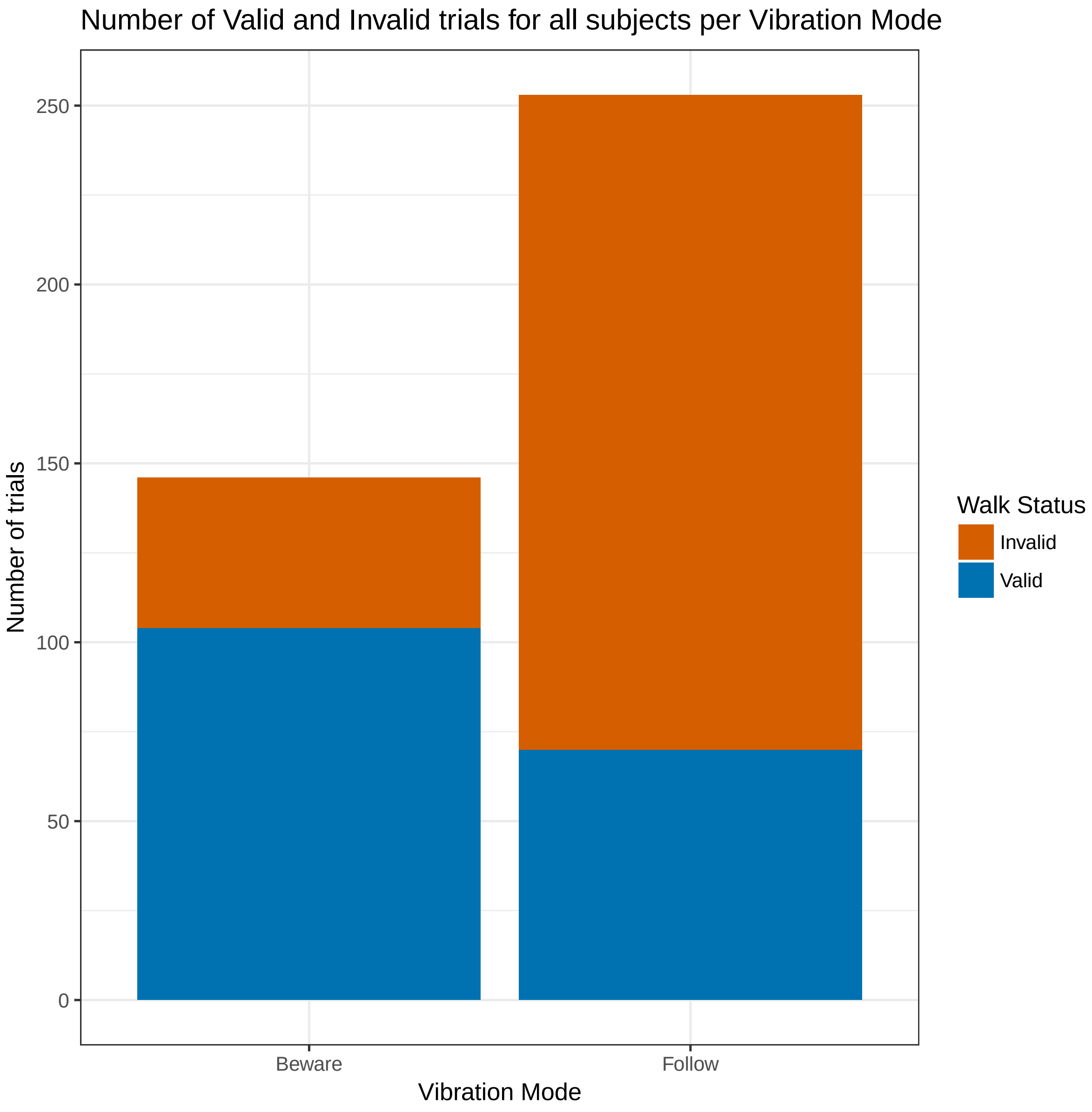


These 2 observations are aligned with the participants' responses as recorded in the exit interview at the end of the study. All the participants reported that the *Follow Vibration Mode* was too intense and confusing. Furthermore, they reported difficulty in finding the motors vibrating the least, as their main challenge: Due to the fact that they weren't able to properly orient themselves and find the right path, they were randomly walking in various directions until they found a spot where vibration was less intense. As Table XVI shows, the average number of touches in *Follow Vibration Mode* (5.20 for valid walks and 5.92 for invalid walks) is at least 3 times the number of touches in *Beware Vibration Mode* (1.27 for valid walks and 1.83 for invalid walks), meaning that the participants were indeed rather disoriented and hence touching the walls more often.

Indeed, looking at the bar plot of valid and invalid walks per *Vibration Mode* (Figure 33), we can see that *Follow Vibration Mode* had 3.35 times more invalid walks than *Beware Vibration Mode*. Therefore, the participants were less successful in finishing a trial in *Follow Vibration Mode*.

Finally, a binomial logistic regression was run to understand the effects of the *Vibration Mode* on the success of finishing a walk. *Vibration Mode* statistically significantly predicted the walk's success ($\beta = -1.87$, $p < .001$). *Follow Vibration Mode* had log-odds -1.87, meaning that it had 1.87 times less log-odds to produce a successful walk, when compared to *Beware Vibration Mode*. To interpret the coefficient as odds-ratio, we exponentiated it, resulting in odd-ratio of 0.15. In other words, a trial in *Follow Vibration Mode*, versus a trial in *Beware Vibration Mode*, decreases the odds of the walk being valid by 15.4%. The 97.5% confidence

Figure 32. Number of Valid and Invalid Trials per *Vibration Mode*



interval for the odds-ratio of a walk being successful in *Follow Vibration Mode*, compared to *Beware Vibration Mode* was [-2.33, -1.42]. Thus there is a strong association between *Vibration Mode* and the walk's chances of being successful.

The goal of this pilot study was to explore different Environment-to-Vibration patterns and identify the best performing Vibration Combination—for this specific task—that will be used in the user study. Based on the above observations, we conclude that *Beware Vibration Mode* was more directional, had less average touches and increased the odds of the walk being valid. It was therefore a better choice for navigational tasks in similar-type environments. Hence, for all the forthcoming results, only Vibration Combinations that include *Beware Vibration Mode* will be analyzed.

5.1.3 Vibration Modulation Results

Our analysis continues with the *Vibration Modulation* results. Results from all 6 participants are summarized in Table XVII. Please note that due to the vibration motors' technical limitations, we could only test *5-Level* and *10-Level* Mappings while in *Frequency Modulation* (section 4.3.1.1.2). Therefore results are limited to *5-Level* and *10-Level* Mappings.

Figure 34 illustrates the paths color-coded by walk status (valid/invalid). Our first qualitative observation is that *Frequency Modulation* appears to have more invalid walks, with the participants' paths being less directional than *Amplitude Modulation.*

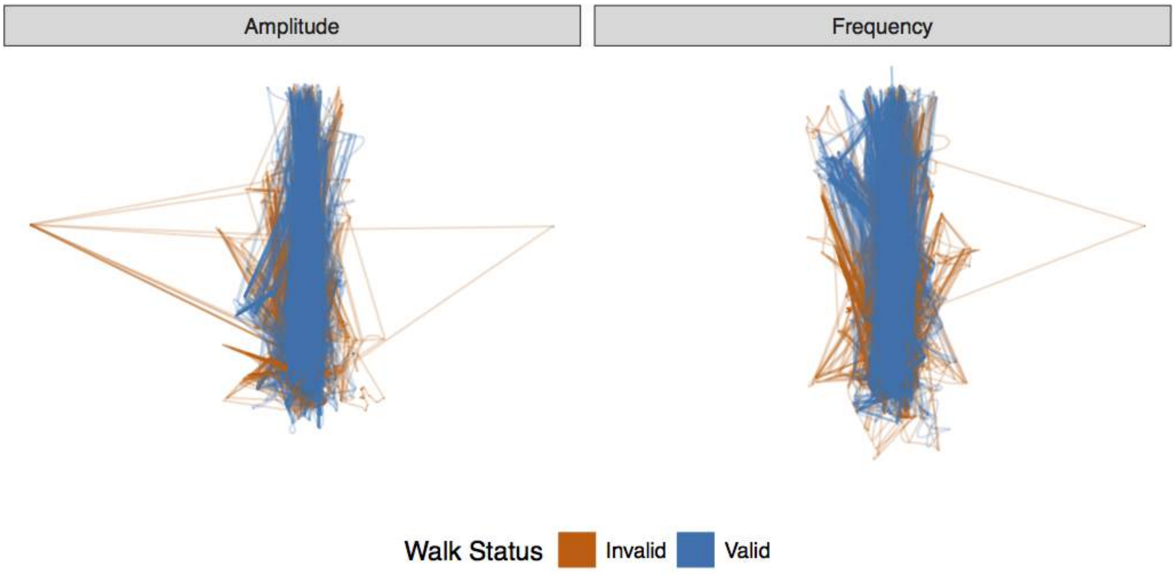
As we continued by comparing the number of valid and invalid trials, we found that they are almost identical for both mappings (Figure 35). However, the boxplot of the trial's duration (Figure 36) shows that the valid trials' *Frequency Modulation*'s spread is almost double than

TABLE XVII

OVERALL RESULTS OF THE *VIBRATION MODULATION*, EVALUATION PHASE TRIALS FOR THE PILOT STUDY. THERE WAS A TOTAL OF 6 PARTICIPANTS. ONLY *BEWARE VIBRATION MODE*, *5-LEVEL* AND *10-LEVEL* RESULTS ARE CONSIDERED

Vibration Modulation	**Trial Status**	**Mean Duration (in seconds)**	**Mean Distance (in meters)**	**Mean Number of Touches**
Amplitude	Valid	18.81 ± 11.18	4.51 ± 2.49	1.00 ± 1.70
	Invalid	9.62 ± 11.81	1.62 ± 2.18	1.30 ± 1.88
Frequency	Valid	21.25 ± 14.96	4.63 ± 2.63	1.97 ± 3.67
	Invalid	20.13 ± 29.30	3.89 ± 5.38	2.80 ± 3.10

Figure 33. Paths of Valid and Invalid Walks for all *Vibration Modulations* (*Beware Vibration Mode*, *5-Level* and 10-Level Mappings only)



the *Amplitude Modulation*'s, while the distance (Figure 37) does not provide any noteworthy insights.

Finally, Figure 38 plots the number of touches for each Vibration Modulation. *Frequency Modulation* had 138% more (number of) touches for valid walks, compared to *Amplitude Modulation*. A lower number of touches indicates that the participant was keeping a straighter path. A higher number might indicate that the participant was using *Alarm Mode* as a navigation strategy. Hence, one might rely on its vibration feedback in order to make it to the end.

A one-way repeated measures ANOVA was conducted to determine whether there were statistically significant differences in the number of touches between the 2 *Vibration Modulations*.

Figure 34. Number of Valid and Invalid Trials for all Subjects and *Vibration Modulations* (*Beware Vibration Mode*, *5-Level* and *10-Level* Mappings)

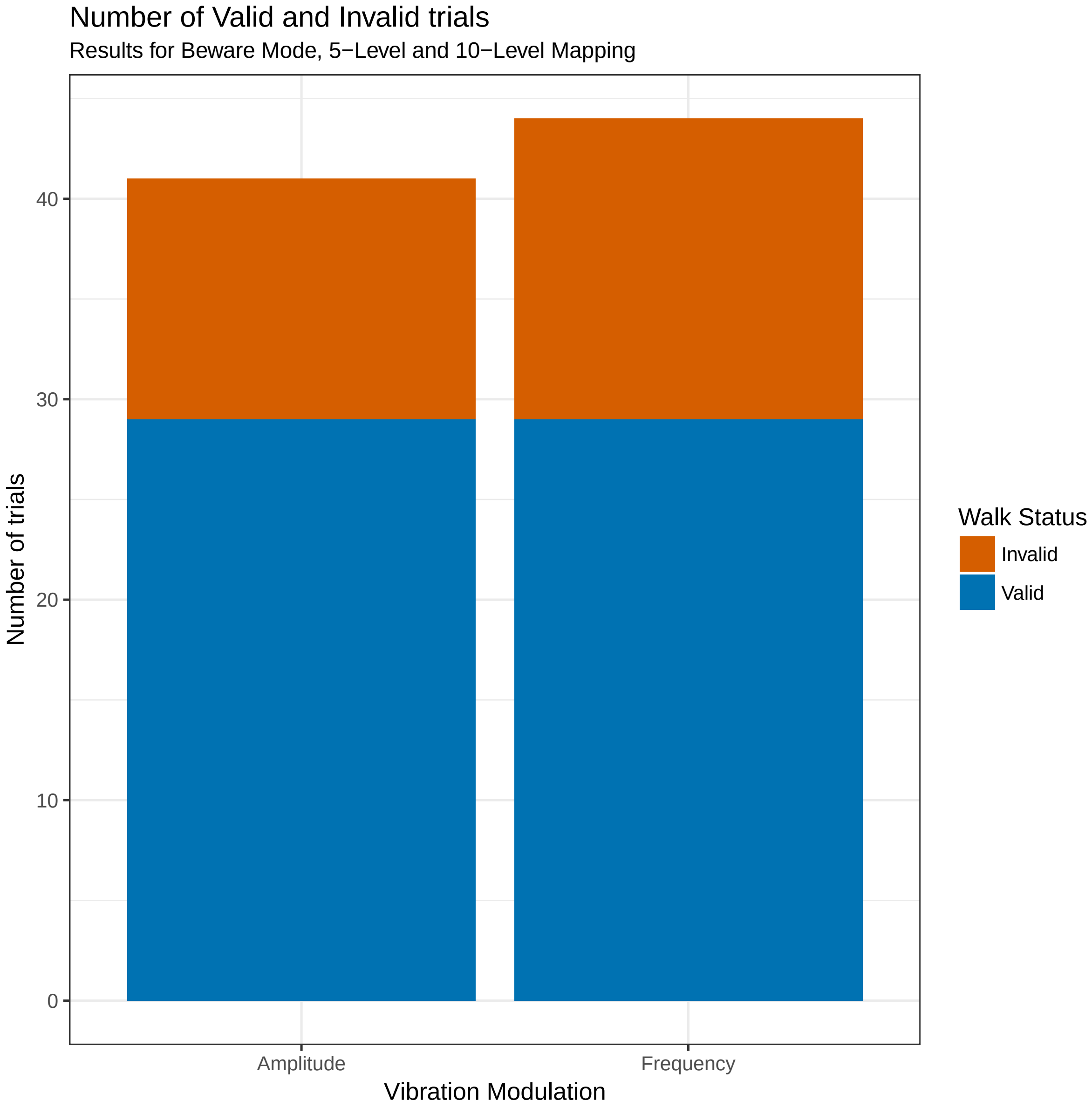


Figure 35. Boxplot for Walk Duration (*Beware Vibration Mode*, *5-Level* and *10-Level* Mappings only)

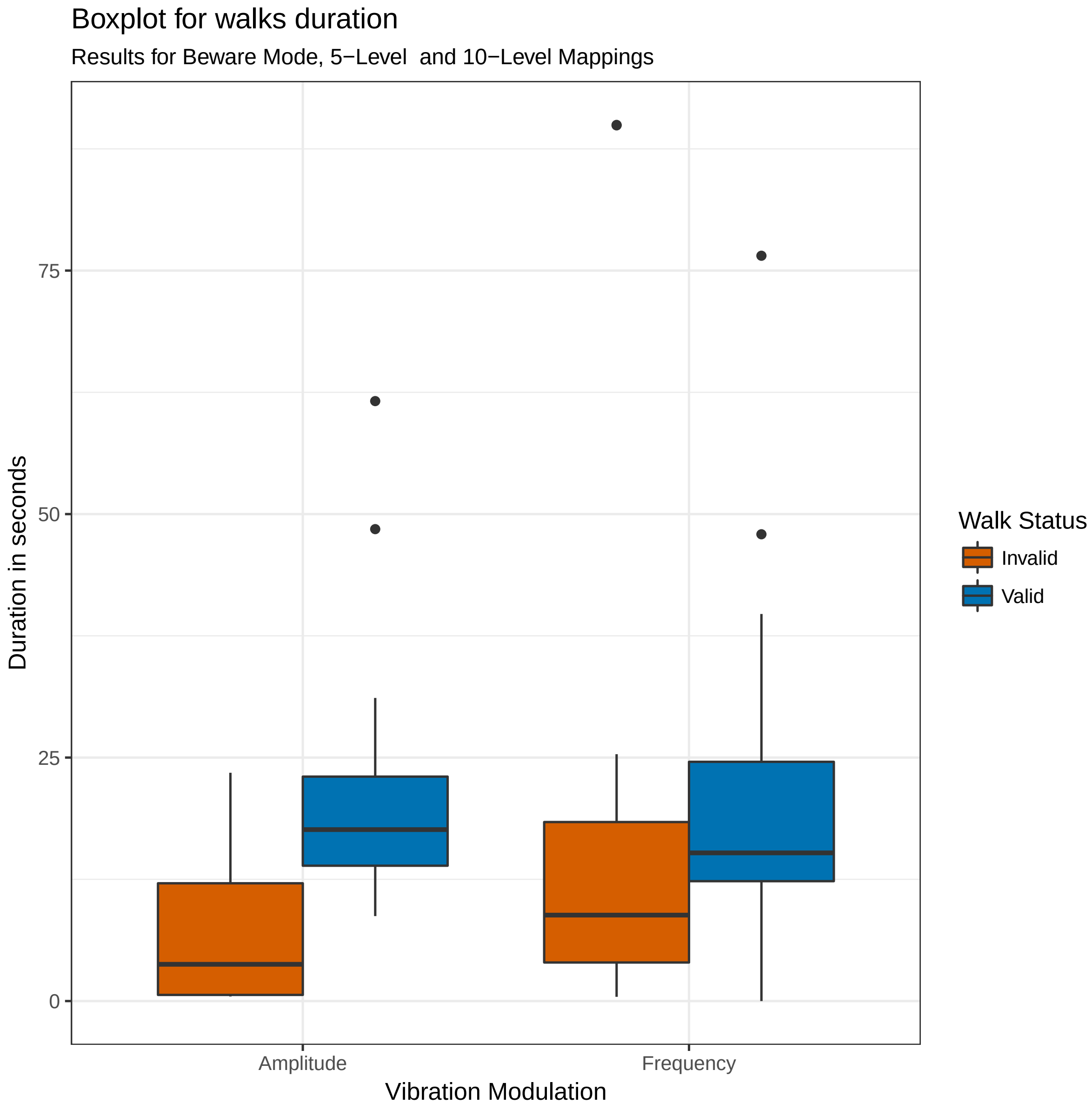


Figure 36. Boxplot for Walk Distance (*Beware Vibration Mode*, *5-Level* and *10-Level* Mappings only)

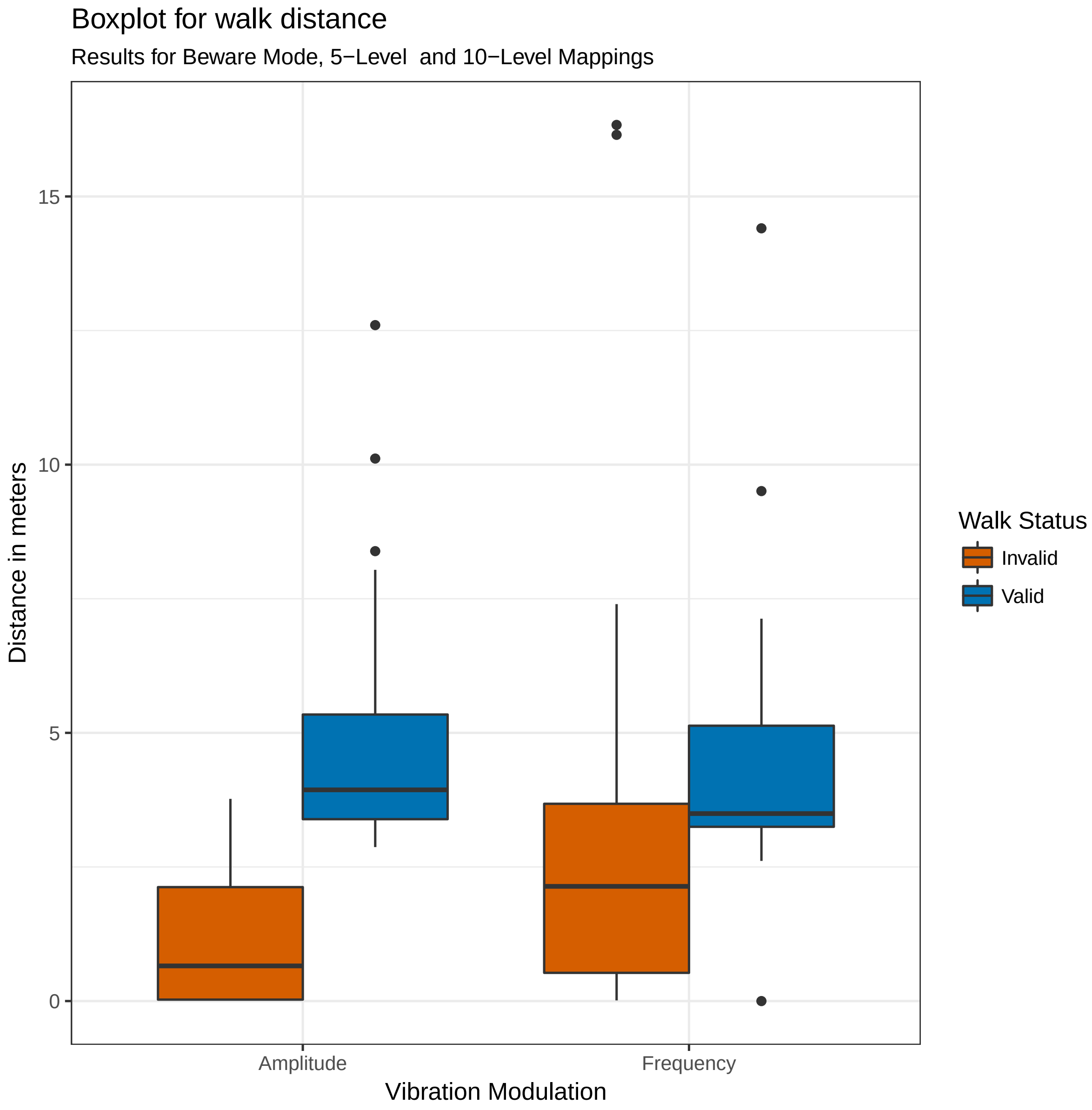
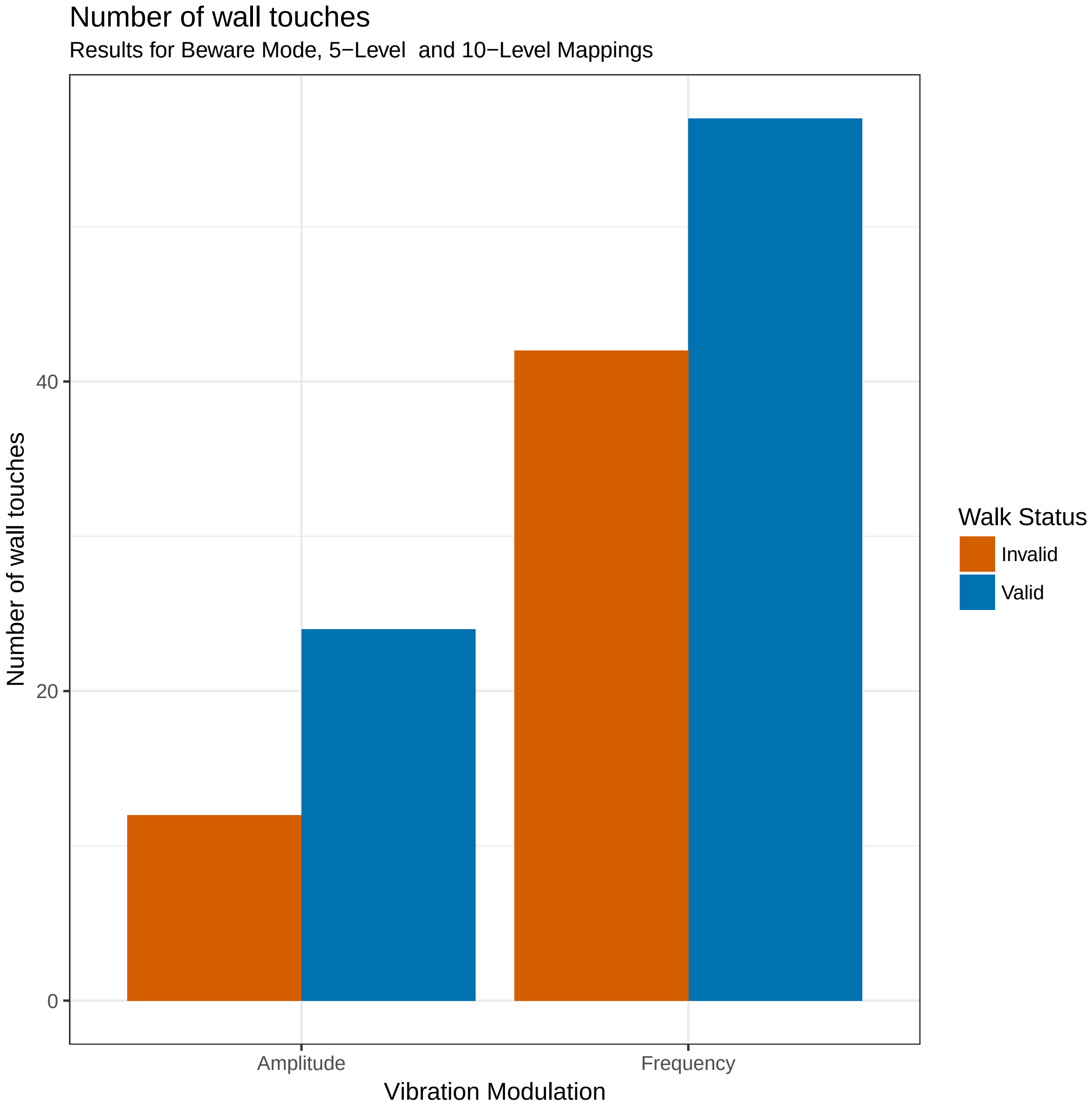


Figure 37. Comparing the Number of Wall Touches per Vibration Modulation (*Beware Vibration Mode*, *5-Level* and *10-Level* Mappings only)



Number of touches was statistically significantly different at the different *Vibration Modulations* during the Evaluation Phase, on the *5-Level* Mapping, *10-Level* Mapping, and *Beware Vibration Mode* $F(1, 78) = 5.63$, $p < .05$. Post hoc analysis with a Bonferroni adjustment revealed that number of touches was statistically significantly increased from *Frequency Modulation* to *Amplitude Modulation* ($M = 1.37$ touches, 95% CI [0.22, 2.52], $p < .05$).

Based on the above observations, we conclude that *Amplitude Modulation* trials took on average less time to complete, were shorter in average distance and had on average less touches than *Frequency Modulation.* Additionally, *Amplitude Modulation* had statistically significantly 1.38 less touches than *Frequency Modulation* and was therefore a better choice for navigational tasks in similar-type environments. Hence, for all the forthcoming results, only the Vibration Combinations that include *Beware Vibration Mode* and *Amplitude Modulation* will be analyzed.

5.1.4 Distance-to-Vibration Mapping Results

Results from all 6 participants are summarized in Table XVIII. Similar to the Vibration Modulation comparison, the three Vibration Mappings had overall the same amount of valid and invalid trials (Figure 39). The boxplots for walk duration (Figure 40) and distance (Figure 41) revealed similar results as well, other than the Exponential Mapping, which shows at least three times the duration spread and twice the distance spread when compared to the other mappings. Bar plot of number of touches (Figure 42) also reveals that Exponential Mapping had roughly twice as many touches as the other mappings.

Based on the above observations, we conclude that Exponential Mapping trials took on average more time to complete, were longer in average distance and had on average more

TABLE XVIII

OVERALL RESULTS OF THE *DISTANCE-TO-VIBRATION MAPPING*, EVALUATION PHASE TRIALS FOR THE PILOT STUDY. THERE WAS A TOTAL OF 6 PARTICIPANTS. ONLY *BEWARE VIBRATION MODE*, *AMPLITUDE MODULATION*, EXPONENTIAL, SMOOTH AND POWER MAPPING RESULTS ARE CONSIDERED

Mapping	**Trial Status**	**Mean Duration (in seconds)**	**Mean Distance (in meters)**	**Mean Number of Touches**
Smooth	Valid	15.89 ± 7.83	3.91 ± 2.23	0.81 ± 1.56
	Invalid	16.94 ± 19.31	2.85 ± 3.69	2.00 ± 2.45
Power	Valid	17.52 ± 13.06	4.47 ± 2.87	1.07 ± 2.40
	Invalid	9.74 ± 10.19	1.59 ± 1.92	1.00 ± 1.26
Exponential	Valid	19.32 ± 12.20	4.56 ± 2.74	1.44 ± 2.00
	Invalid	4.95 ± 7.29	1.04 ± 1.75	1.67 ± 2.89

Figure 38. Number of Valid and Invalid Trials for all Subjects and *Distance-to-Vibration Mappings* (*Beware Vibration Mode*, *Amplitude Modulation*, Exponential, Smooth and Power Mapping only)

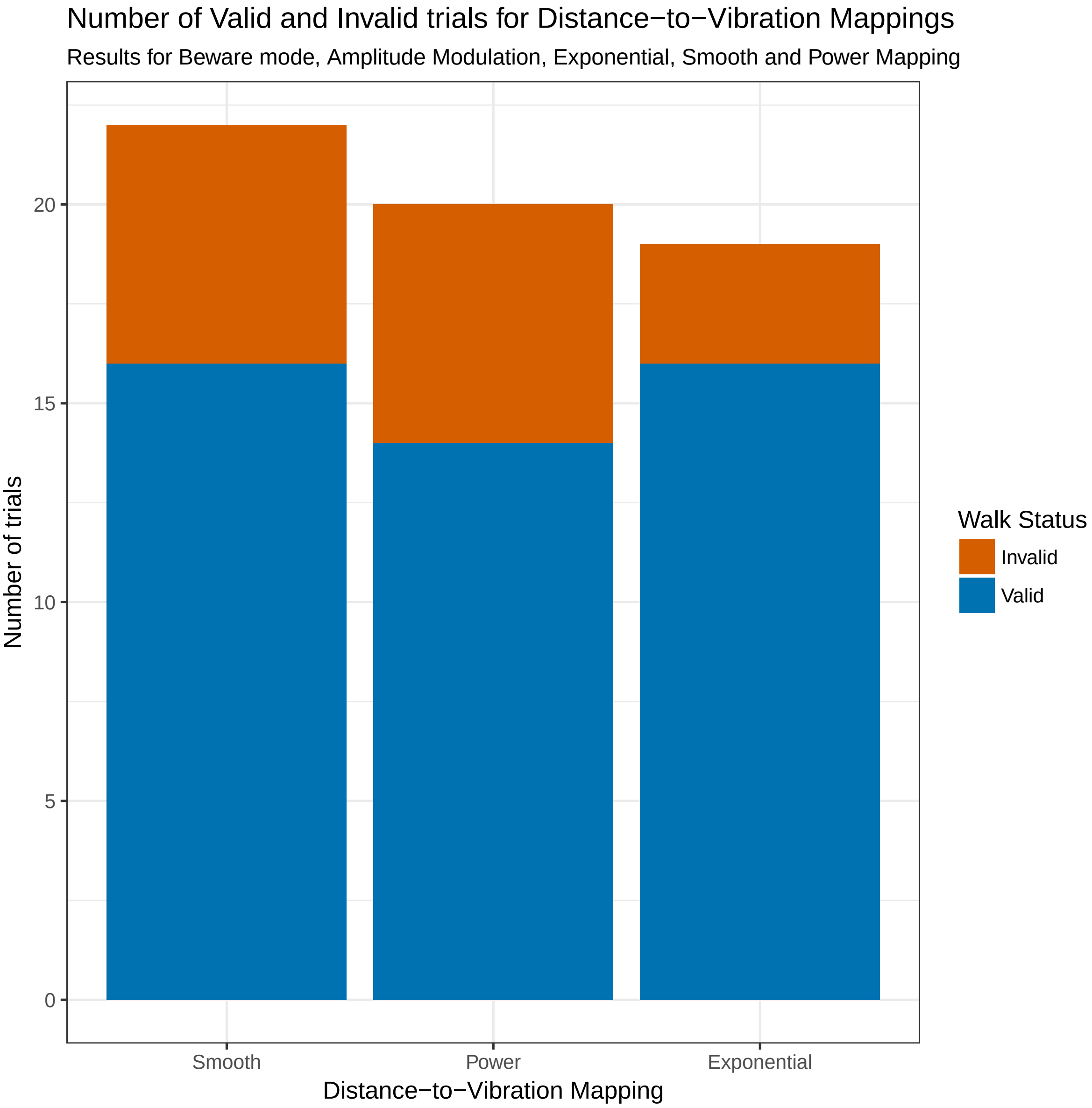


Figure 39. Boxplot for Walk Duration (*Beware Vibration Mode*, *Amplitude Modulation*, Exponential, Smooth and Power Mapping only)

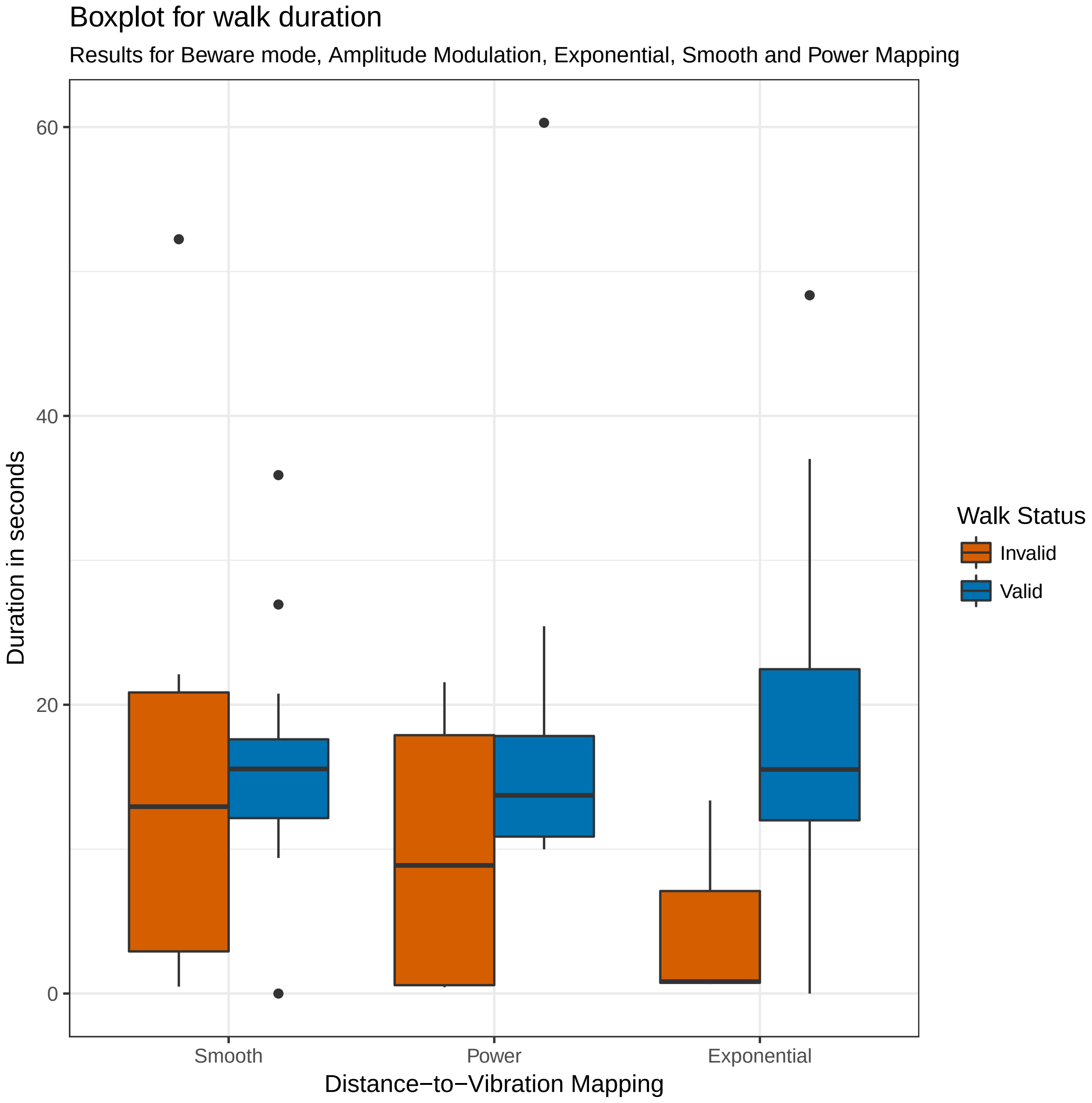


Figure 40. Boxplot for Walk Distance (*Beware Vibration Mode*, *Amplitude Modulation*, Exponential, Smooth and Power Mapping only)

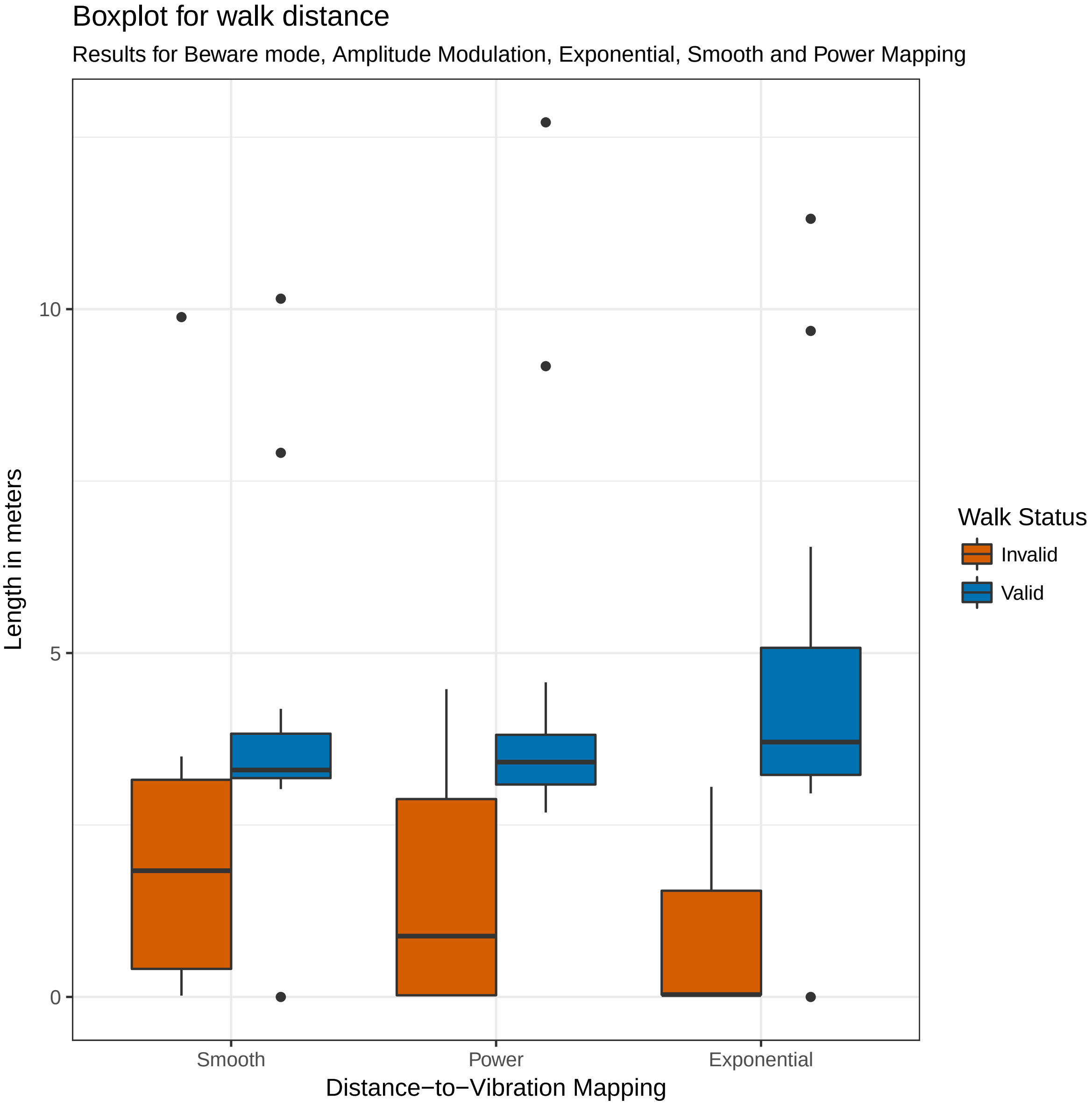
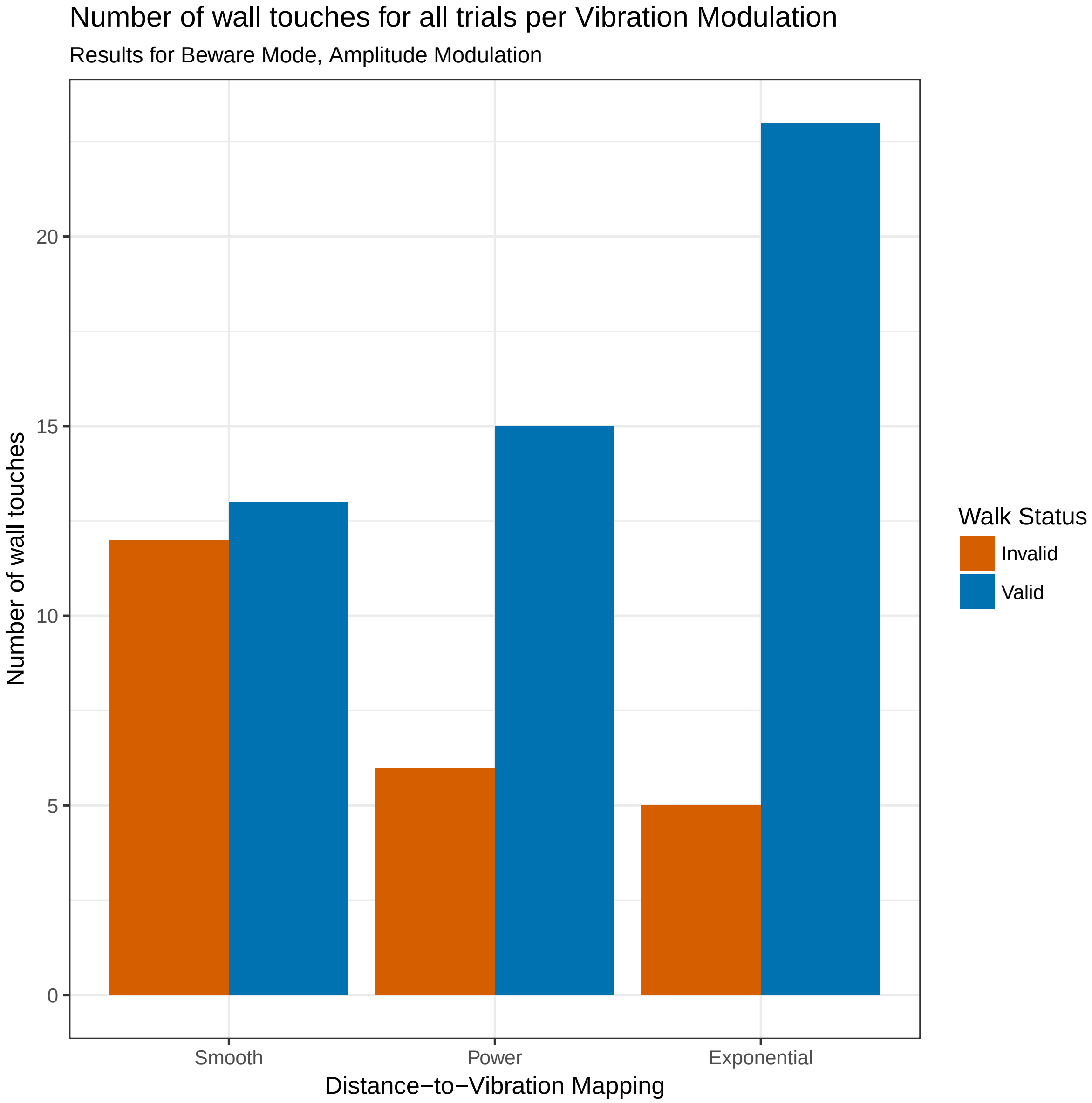


Figure 41. Comparing the Number of Wall Touches per Mapping Type (*Beware Vibration Mode*, *Amplitude Modulation*, Exponential, Smooth and Power Mapping only)



touches than the other 2 mappings. Comparison of the means of duration, distance and number of touches did not reveal any statistical significance. Therefore a more thorough future study leaves a challenge we hope will be taken up by other scholars in the future. For the purposes of this study, we decided to choose Linear Mapping as the *Distance-to-Vibration Mapping* to be used in the user study. As a result the final Environment-to-Vibration Pattern used in the user study is *Beware Vibration Mode-Amplitude Modulation*-Linear Mapping.

5.2 User Study

This user study took place between October and November 2017. We recruited 16 participants (3 female and 15 male), 8 of whom had participated in the pilot study. The remaining 8 participants were new to tactile displays and had never worn or used a similar device, other than smartwatches, smartphones or vibration feedback game controllers. The user study followed the structure described in section 4.3.2.2.2 and took approximately 2 hours to complete. All participants completed three experimental sets, except of the first 5 who completed 2 (see section 5.2.3). Two users expressed discomfort during the study; however, both chose to continue and finish it. The first one expressed an unrelated to the tactile display discomfort with the VR headset, due to bad HMD fitting. The second user expressed fatigue but attributed it to lack of sleep. Interestingly, the latter's performance was the most successful (most valid trials and fastest mean duration per walk) among all participants of the user study.

In total, 16 participants completed 1,417 trials, out of which 111 were in Control Phase, 192 were in Training Phase, and 1,114 were in Evaluation Phase. The participants walked 13.7h and 7,328m in total, 11.4h and 5,787m of which were in Evaluation Phase. On average, the participants walked 51.46min and 458m each. Table XIX, Table XX, Table XXI, Table XXII, Table XXIII, Table XXIV show the number of successful trials, the mean trial duration and distance (with and without *Virtual Obstacles*) per participant and *Environment-to-Vibration Mapping*.

TABLE XIX

NUMBER OF VALID TRIALS PER PARTICIPANT, *VIRTUAL PATH* WITHOUT *VIRTUAL OBSTACLES*, AND *ENVIRONMENT-TO-VIBRATION MAPPING* DURING THE EVALUATION PHASE

	Without Virtual Obstacles					
	360°		**Head Gaze**		**Flashlight**	
Subject	**Angle**	**Circular**	**Angle**	**Circular**	**Angle**	**Circular**
1	2	1	3	1	1	1
2	2	1	3	1	2	1
3	1	1	4	0	3	0
4	1	3	2	3	3	2
5	0	1	1	0	2	2
6	4	6	5	6	6	6
7	1	3	3	3	5	5
8	6	6	4	6	6	6
9	6	4	6	5	3	2
10	4	4	3	5	4	2
11	5	3	3	3	6	1
12	6	3	5	4	5	5
13	5	6	6	5	6	5
14	5	6	4	1	6	3
15	2	3	5	5	4	3
16	5	6	5	6	6	6

TABLE XX

NUMBER OF VALID TRIALS PER PARTICIPANT, *VIRTUAL PATH* WITH *VIRTUAL OBSTACLES*, AND *ENVIRONMENT-TO-VIBRATION MAPPING* DURING THE EVALUATION PHASE

	With Virtual Obstacles					
	360°		**Head Gaze**		**Flashlight**	
Subject	**Angle**	**Circular**	**Angle**	**Circular**	**Angle**	**Circular**
1	0	0	1	0	0	0
2	0	1	2	0	1	0
3	0	0	0	0	0	1
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	2	1	1	0	2	0
7	0	0	0	0	0	0
8	2	2	4	3	4	3
9	1	0	1	2	1	0
10	0	0	1	0	1	0
11	0	0	0	0	1	0
12	0	0	0	0	0	0
13	0	0	2	1	1	2
14	2	0	0	0	0	0
15	0	0	3	0	2	3
16	4	4	3	3	2	3

5.2.1 Metrics

In the following sections we will analyze the *Environment-to-Vibration Mapping*, its completion time results and learning effects, as well as the effects of a *Virtual Obstacle* presence.

TABLE XXI

MEAN TRIAL DURATION IN SECONDS OF VALID WALKS PER PARTICIPANT, *VIRTUAL PATH* WITHOUT *VIRTUAL OBSTACLES*, AND *ENVIRONMENT-TO-VIBRATION MAPPING* DURING THE EVALUATION PHASE

	Without Virtual Obstacles					
	360°		**Head Gaze**		**Flashlight**	
Subject	**Angle**	**Circular**	**Angle**	**Circular**	**Angle**	**Circular**
1	36	34	44	26	32	36
2	31	29	27	28	24	33
3	44	29	45	60	46	43
4	55	43	49	38	45	30
5	31	25	40	47	34	37
6	27	28	23	32	24	31
7	40	42	43	43	35	42
8	33	32	48	42	29	36
9	22	28	23	30	14	39
10	36	25	40	43	33	19
11	44	40	41	49	33	12
12	29	29	24	24	24	27
13	38	35	31	28	29	33
14	30	41	38	41	35	43
15	48	36	39	42	23	29
16	25	22	29	23	25	20

TABLE XXII

MEAN TRIAL DURATION IN SECONDS OF VALID WALKS PER PARTICIPANT, *VIRTUAL PATH* WITH *VIRTUAL OBSTACLES*, AND *ENVIRONMENT-TO-VIBRATION MAPPING* DURING THE EVALUATION PHASE

	With Virtual Obstacles					
	360°		**Head Gaze**		**Flashlight**	
Subject	**Angle**	**Circular**	**Angle**	**Circular**	**Angle**	**Circular**
1	33	29	44	19	35	28
2	15	22	35	16	35	20
3	38	30	37	37	26	34
4	36	47	41	43	60	44
5	22	19	29	24	20	31
6	29	35	46	40	27	35
7	31	42	56	29	35	29
8	45	51	52	46	47	53
9	35	25	36	34	34	19
10	20	17	36	35	32	22
11	44	44	34	34	19	28
12	27	17	27	34	28	44
13	39	37	38	51	21	48
14	37	32	56	47	32	38
15	34	34	47	45	24	19
16	30	43	40	50	19	25

TABLE XXIII

MEAN TRIAL DISTANCE IN METERS PER PARTICIPANT, *VIRTUAL PATH* WITHOUT *VIRTUAL OBSTACLES*, AND *ENVIRONMENT-TO-VIBRATION MAPPING* DURING THE EVALUATION PHASE (VALID + INVALID WALKS)

	Without Virtual Obstacles					
	360°		**Head Gaze**		**Flashlight**	
Subject	**Angle**	**Circular**	**Angle**	**Circular**	**Angle**	**Circular**
1	9	8	8	5	6	6
2	7	6	6	6	5	5
3	9	6	10	12	8	7
4	9	8	8	5	6	5
5	6	5	7	7	5	5
6	6	6	6	6	5	5
7	7	8	6	6	5	5
8	6	6	8	7	5	6
9	6	7	5	6	3	7
10	8	6	8	8	6	4
11	6	7	5	7	5	2
12	5	6	5	5	5	4
13	7	7	6	5	5	6
14	6	8	5	6	5	6
15	11	8	6	6	3	4
16	5	5	7	5	4	5

TABLE XXIV

MEAN TRIAL DISTANCE IN METERS PER PARTICIPANT, *VIRTUAL PATH* WITH *VIRTUAL OBSTACLES*, AND *ENVIRONMENT-TO-VIBRATION MAPPING* DURING THE EVALUATION PHASE (VALID + INVALID WALKS)

	With Virtual Obstacles					
	360°		**Head Gaze**		**Flashlight**	
Subject	**Angle**	**Circular**	**Angle**	**Circular**	**Angle**	**Circular**
1	7	8	9	4	6	5
2	4	5	6	3	6	4
3	10	6	8	6	4	7
4	6	7	5	5	7	7
5	5	3	4	4	3	3
6	6	7	8	6	5	5
7	5	7	7	4	5	4
8	9	9	9	6	7	9
9	8	5	9	7	7	4
10	5	4	6	7	5	4
11	7	6	6	5	3	3
12	6	4	4	5	5	7
13	7	7	6	7	4	7
14	7	6	8	7	4	4
15	8	8	10	7	4	3
16	7	10	8	9	4	6

We will then present our findings. We will compare trials by referring to their performance, which we will then break down into the following metrics:

1. Number of valid trials: A higher number indicates that the participant was able to finish a specific vibration combination easier than others.
2. Time to completion per trial: Shorter duration indicates that the participant was able to finish faster.
3. Walking distance per trial: Shorter distance indicates that the participant walked less.

5.2.2 Environment-to-Vibration Mapping Results

Our analysis starts with the *Environment-to-Vibration Mapping* results. Results from all 16 participants are summarized in Table XXV and Table XXVI.

An initial high-level comparison does not reveal any significant insights, as all *Environment-to-Vibration Mappings* had overall an equal number of valid and invalid trials regardless of whether there was a *Virtual Obstacle* or not (Figure 43). Similarly, the boxplots of the trials duration (Figure 44) and distance (Figure 45) were almost identical.

The third experimental set yielded the highest number of valid walks (Figure 28) over the course of the study, due to the fact that participants were more experienced in performing the tasks. Being the epitome of the *Virtual Paths* Evaluation Phase, we explored whether there were any differences between *Environment-to-Vibration Mappings* in our second group of participants (participants 6-16) during the third experimental set. We initially looked for differences in walked distance, by conducting a one-way repeated measures ANOVA, focusing only

TABLE XXV

OVERALL RESULTS OF THE *ENVIRONMENT-TO-VIBRATION MAPPING* WITHOUT *VIRTUAL OBSTACLE*, EVALUATION PHASE TRIALS FOR THE USER STUDY. THERE WAS A TOTAL OF 16 PARTICIPANTS.

Environment-to-Vibration Mapping	**Trial Status**	**Mean Duration (in seconds)**	**Mean Distance (in meters)**
360°	Valid	32.16 ± 11.14	5.52 ± 1.49
	Invalid	36.57 ± 20.32	6.24 ± 3.62
Head Gaze	Valid	35.35 ± 11.86	5.33 ± 1.64
	Invalid	39.10 ± 18.94	5.48 ± 3.53
Flashlight	Valid	31.90 ± 10.03	4.42 ± 1.07
	Invalid	27.70 ± 22.34	3.29 ± 2.87

TABLE XXVI

OVERALL RESULTS OF THE *ENVIRONMENT-TO-VIBRATION MAPPING* WITH *VIRTUAL OBSTACLE*, EVALUATION PHASE TRIALS FOR THE USER STUDY. THERE WAS A TOTAL OF 16 PARTICIPANTS.

Environment-to-Vibration Mapping	**Trial Status**	**Mean Duration (in seconds)**	**Mean Distance (in meters)**
360°	Valid	40.43 ± 9.93	7.77 ± 1.68
	Invalid	31.90 ± 19.51	5.33 ± 3.75
Head Gaze	Valid	41.35 ± 8.88	7.11 ± 1.32
	Invalid	39.10 ± 18.64	5.12 ± 2.99
Flashlight	Valid	40.56 ± 10.03	6.57 ± 1.28
	Invalid	29.69 ± 18.57	3.41 ± 2.60

Figure 42. Number of Valid and Invalid trials per *Environment-to-Vibration Mapping*

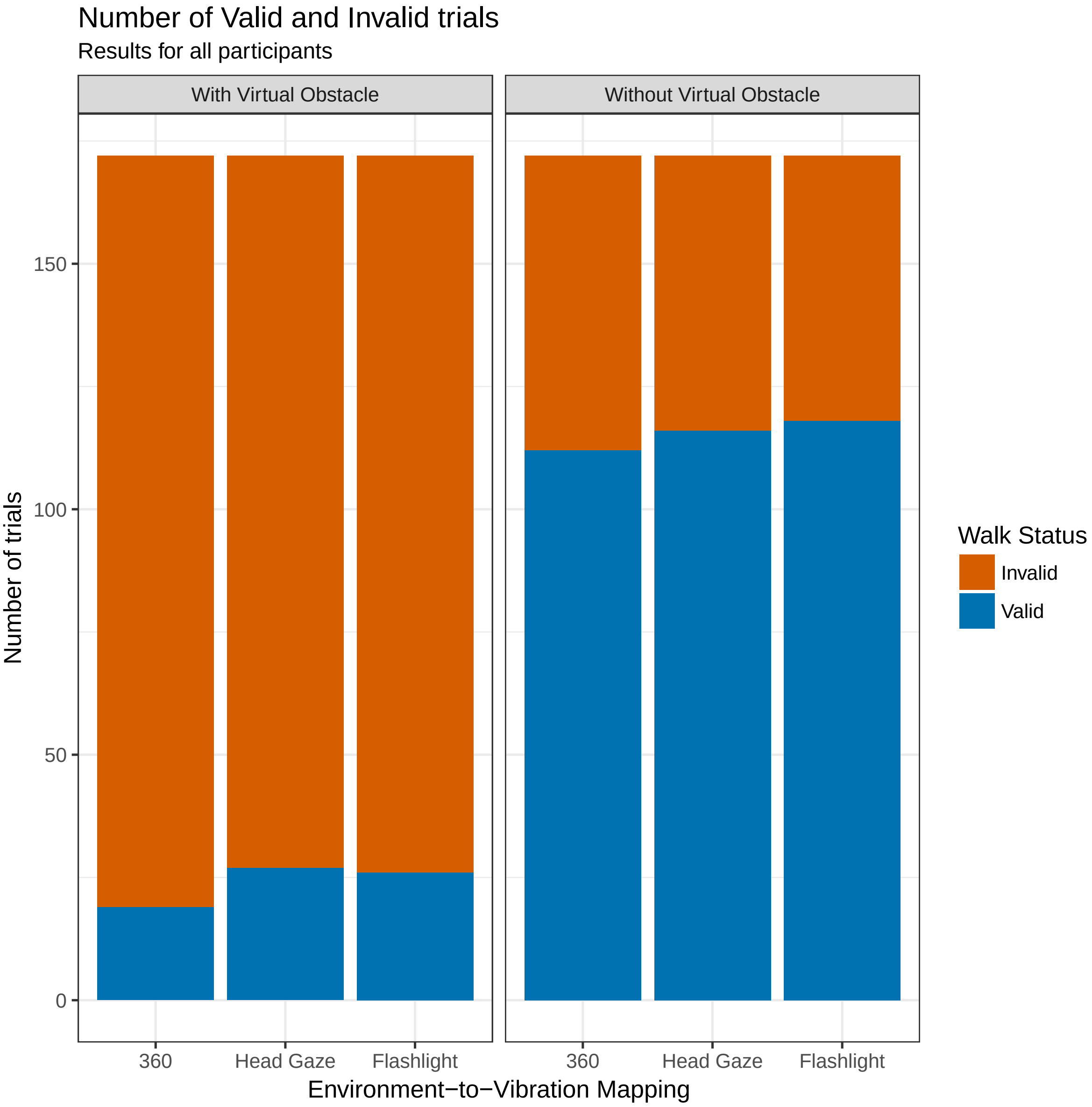


Figure 43. Boxplot of Walk Duration

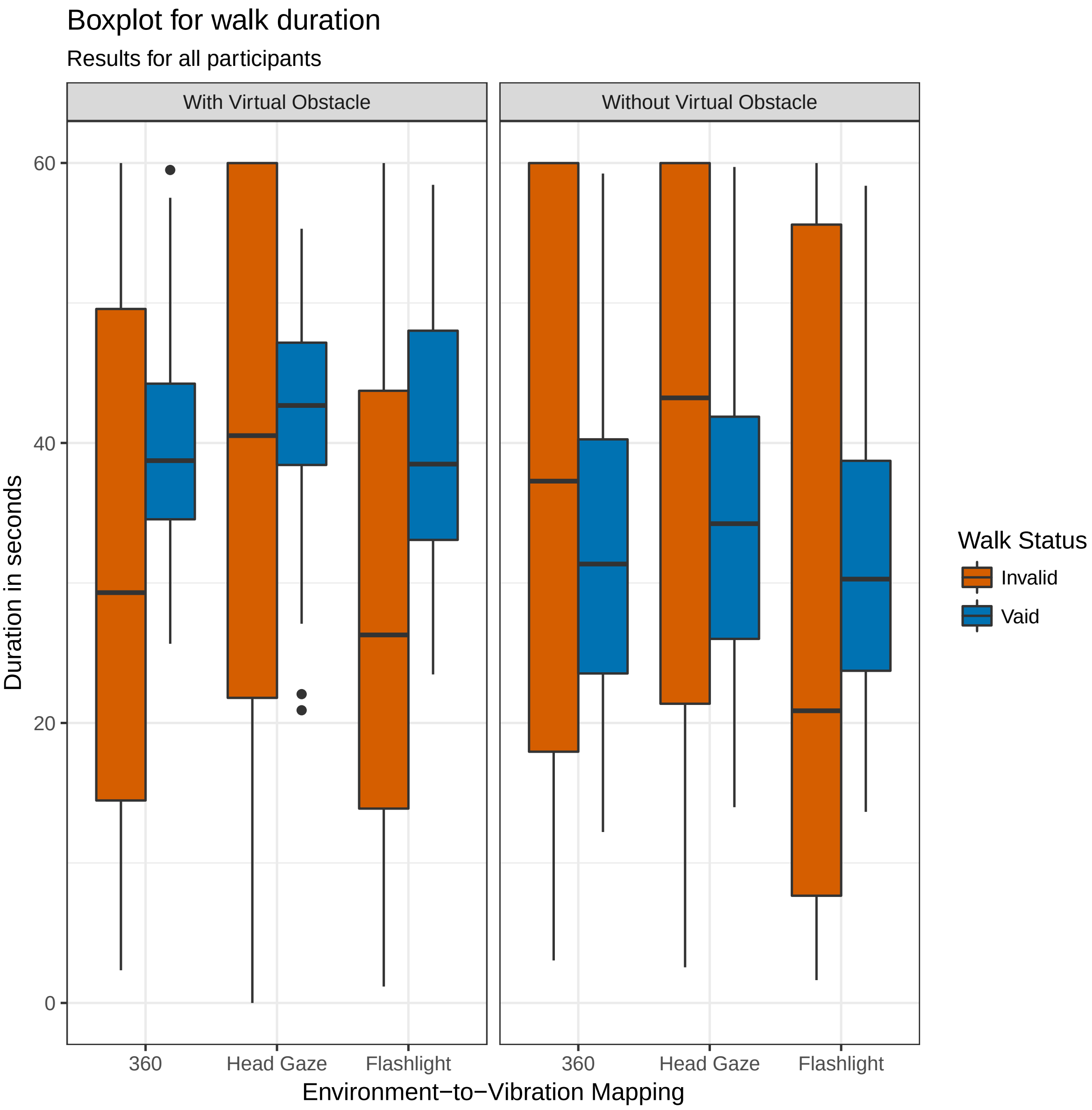
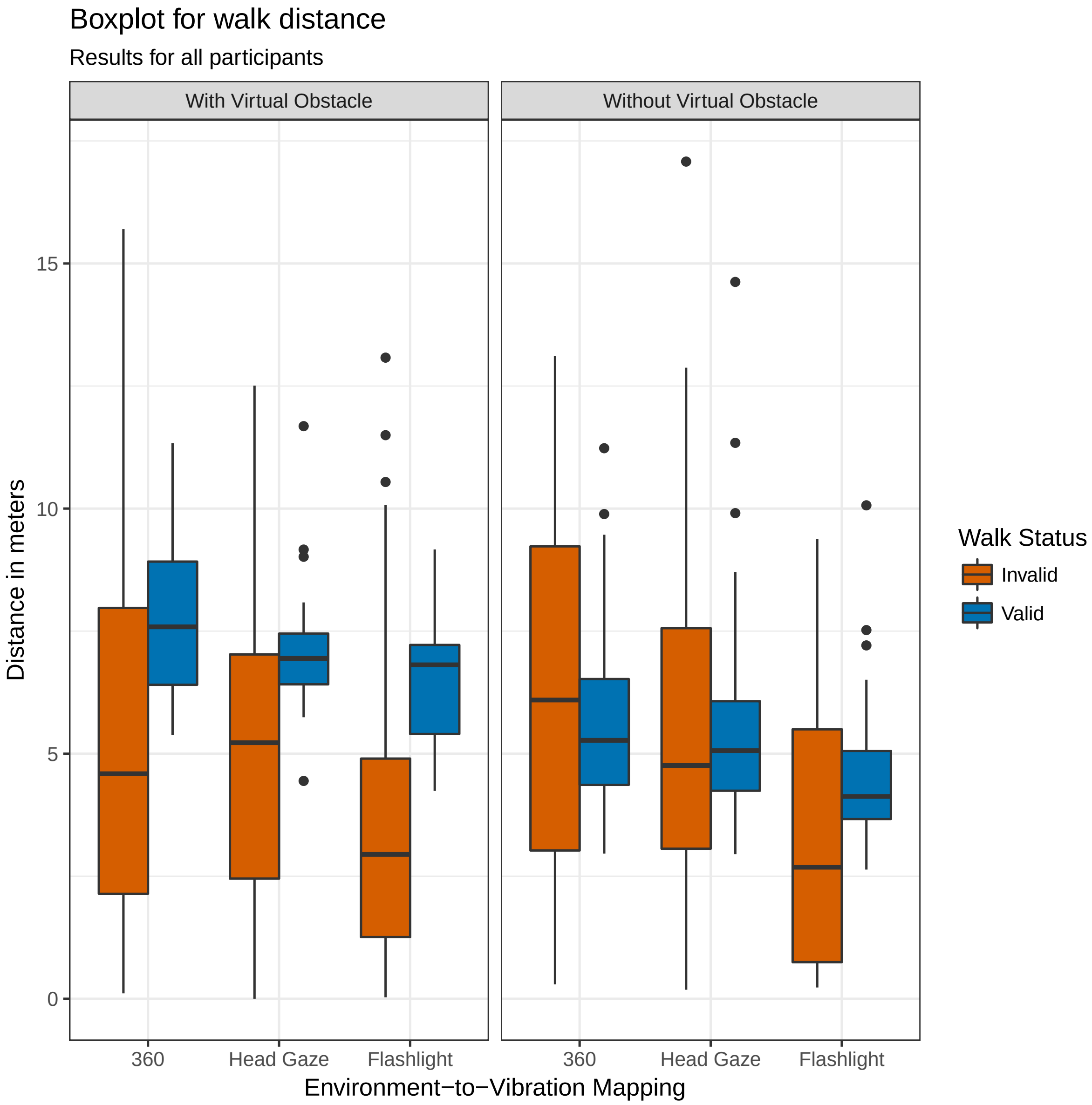


Figure 44. Boxplot of Walk Distance



on valid walks without *Virtual Obstacles.* Walked distance between *Environment-to-Vibration Mappings* was statistically significantly different $F(2, 41) = 5.28$, $p < .05$. Post hoc analysis with a Bonferroni adjustment revealed that walked distance statistically significantly increased from 360° *Mapping* to *Flashlight Mapping* (M = 0.28 m, 95% CI [0.13, 1.14], $p < .05$). Post hoc analysis with a Bonferroni adjustment did not reveal any statistical significant differences between 360° and *Head Gaze Mapping*, or *Head Gaze* and *Flashlight Mapping.*

Comparing the mean duration of the *Environment-to-Vibration Mappings* (using a one-way repeated measures ANOVA) did not yield any statistical significance. However by calculating the pace of each valid walk (duration in meters / distance in seconds) we found statistical significance in the difference of the means. The comparison occurred using a one-way repeated measures ANOVA, focusing only on valid walks without *Virtual Obstacles.* Pace between *Environment-to-Vibration Mappings* during the Evaluation Phase was statistically significantly different $F(2, 41) = 3.29$, $p < .001$. Post hoc analysis with a Bonferroni adjustment revealed that pace statistically significantly increased from 360° *Mapping* to *Flashlight Mapping* (M = 0.025 m/s, 95% CI [0.02, 0.03], $p < .01$) and that it also increased from 360° *Mapping* to *Head Gaze* (M = 0.02 m/s, 95% CI [0.02, 0.03], $p < .05$). Post hoc analysis with a Bonferroni adjustment did not reveal any statistical significant differences between *Head Gaze* and *Flashlight.*

Our analysis focused on the third attempt of the second group of participants, in order to compare the trials conducted by the most experienced users. Our results show a high number of valid walks and a fast completion time for all *Environment-to-Vibration Mappings*, supporting our first Hypothesis—that minimally trained vision deprived individuals can efficiently use tactile displays for completion of navigational tasks. Furthermore, while 360° *Mapping* trials had slightly fewer valid walks, participants had on average the fastest pace, shorter walk duration, and the longest walk distance. In addition, participants using 360° *Mapping* had walked statistically significantly more than when using *Flashlight Mapping* and had statistically significantly a faster pace than when using *Flashlight* or *Head Gaze.* The higher amount of walked distance for the 360° *Mapping* reveals that *Flashlight Mapping* was more efficient for navigation in similar environments, as participants were able to get to the end of the trial without wandering around too much. Additionally, the increased pace reveals that the participants' *Situation Awareness* during 360° *Mapping* was heightened when compared to the other mappings, as mapping the entire environment onto the body allowed them to walk faster due to the fact that they were more aware of their surroundings. These findings further complement our first Hypothesis—that minimally trained vision deprived individuals can efficiently use tactile displays for completion of navigational tasks—by uncovering that performance depends on how the environment is haptically mapped onto one's body.

5.2.3 Completion Time Results and Learning Effects

During the initial experiments, we observed that the first 5 participants, showed significant improvement in the completion of walks during the course of the 2 experimental sets. As seen in Figure 46 and Figure 47, other than *Flashlight Mapping* trials without *Virtual Obstacles*, all other mappings show a significant increase in the number of the participants' valid walks over the course of the 2 experimental sets. These preliminary results suggest that spending more time with the tactile display might lead to more successful task completion. We therefore decided to add another experimental set to more specifically study it further.

As a result, the remaining participants (11 in total) completed 3 experimental sets—instead of the initial 2. As hypothesized, after the addition of the third experimental set (Figure 48), the number of successful trials indeed increased. In fact, for all vibration modes there was an at least 3% increase of the number of valid walks from one set to the next, excluding the 360° *Mapping* which remained the same (Figure 49). Please note that there was no decrease in any of the *Environment-to-Vibration Mappings.*

Furthermore, a multiple regression was run to predict the number of successful trials from experimental set, and *Virtual Obstacle.* The multiple regression model statistically significantly predicted the number of successful trials, $F(2, 15) = 514.2$, $p < .001$. R^2 for the overall model was 98.6% with an adjusted R2 of 98.4%, a large size effect according to Cohen (1988). There was no evidence of multicollinearity, as assessed by tolerance values greater than 0.1. There were no studentized deleted residuals greater than ±3 standard deviations, no leverage values greater than 0.2, and values for Cook's distance above 1. The assumption of normality was met, as assessed by a $Q - Q$ Plot. All 2 variables added statistically significantly to the prediction, $p < .001$. Regression coefficients and standard errors can be found in Table XXVII.

To sum up, we initially observed participant improvement over the course of all experimental sets. We therefore decided to add another experimental set to more specifically study it further. Visual comparison of valid and invalid trials per experimental set barplots, illustrated significant improvement in the number of valid walks over time. Finally to confirm our find-

Figure 45. Number of Valid and Invalid Trials per *Environment-to-Vibration Mapping* for Participants 1-5

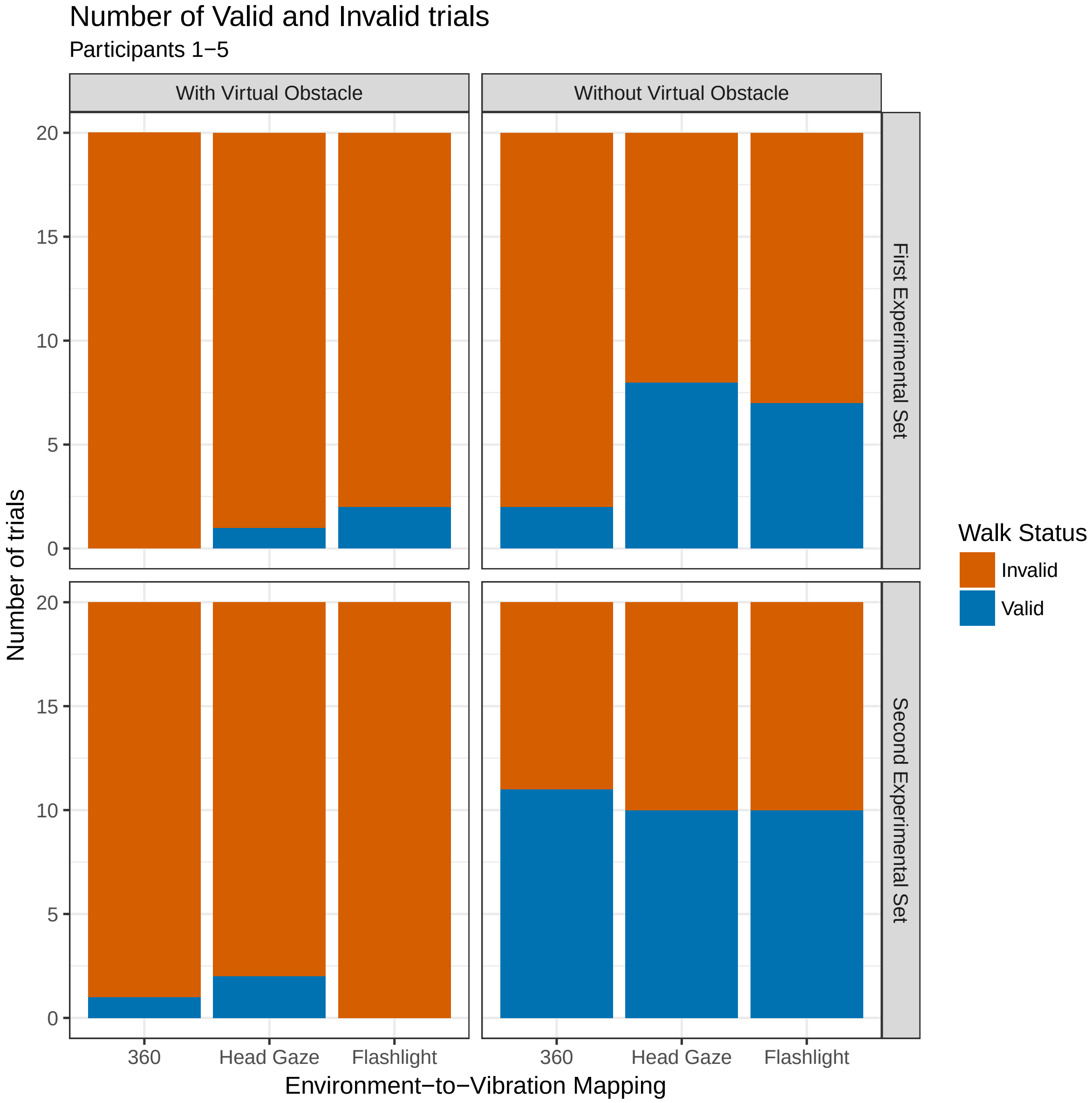


Figure 46. Successful Trials Percentage Change from Set 1 to Set 2 (NOTE: With *Virtual Obstacle*, 360° Mapping jumped from 0 successful walks to 1, so the increase is Inf)

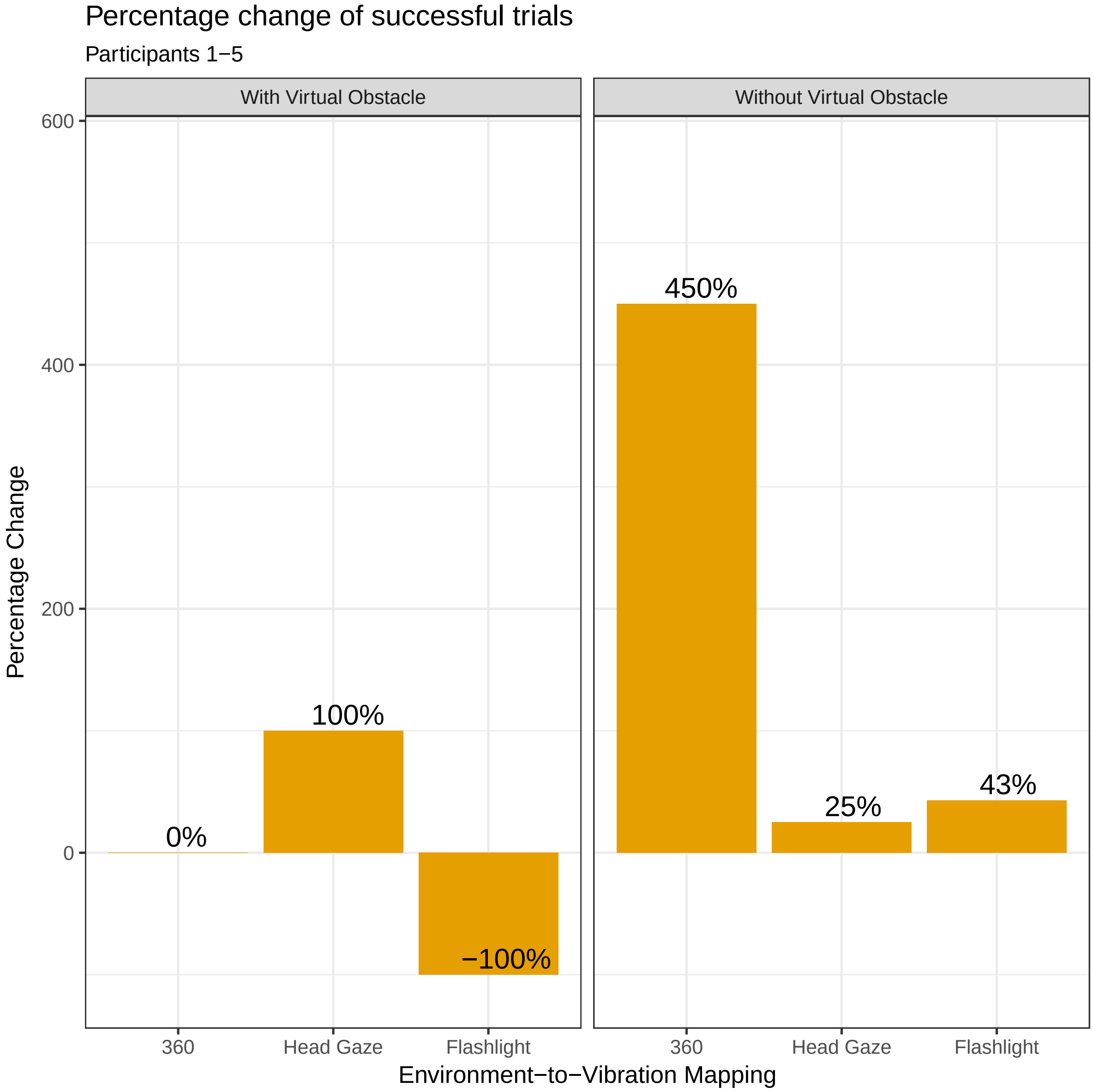


Figure 47. Number of Valid and Invalid Trials per *Environment-to-Vibration Mapping* for Participants 6-16

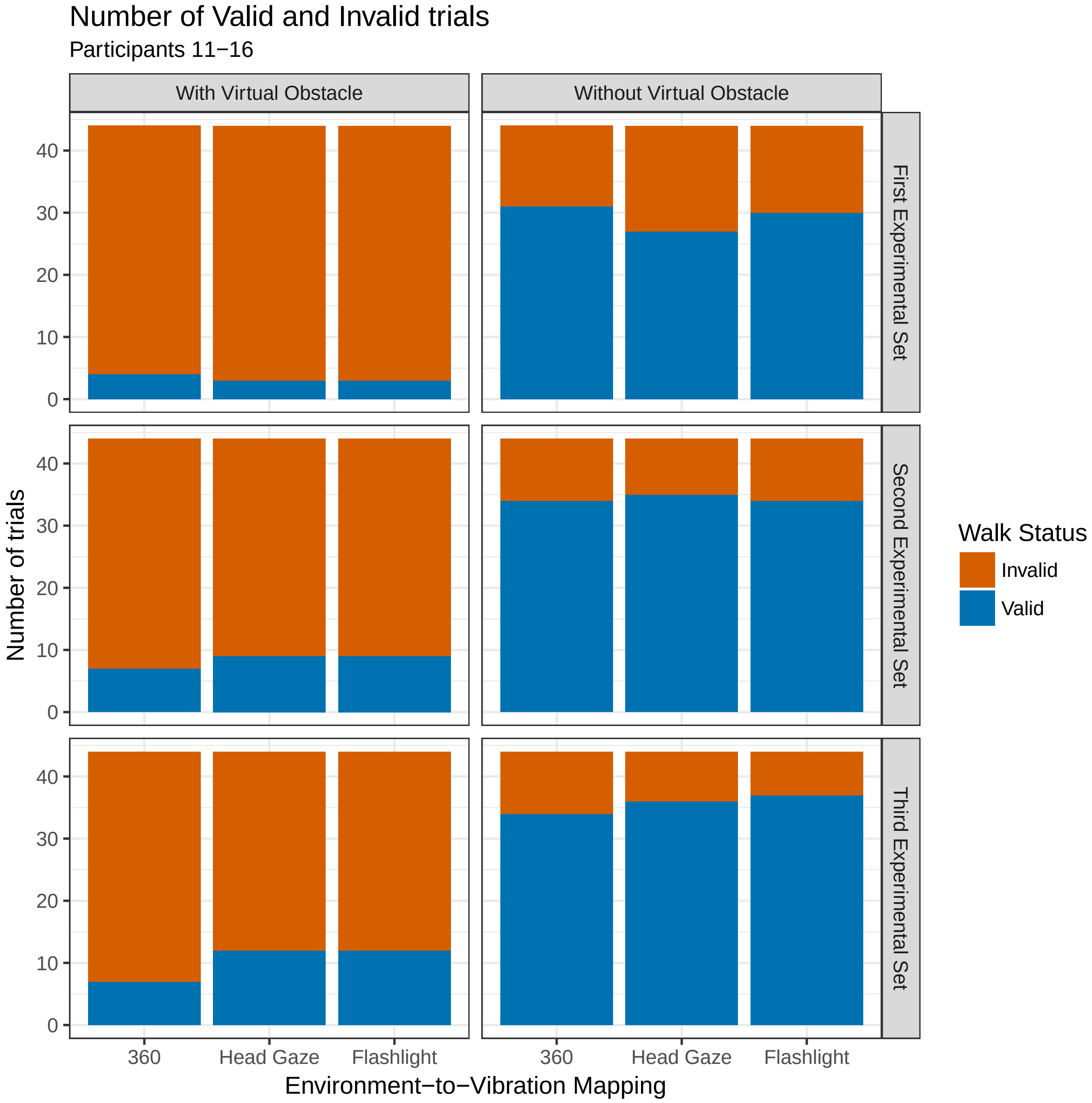


Figure 48. Percentage Change of Number of Valid Trials between Experimental Sets for Participants 6-16

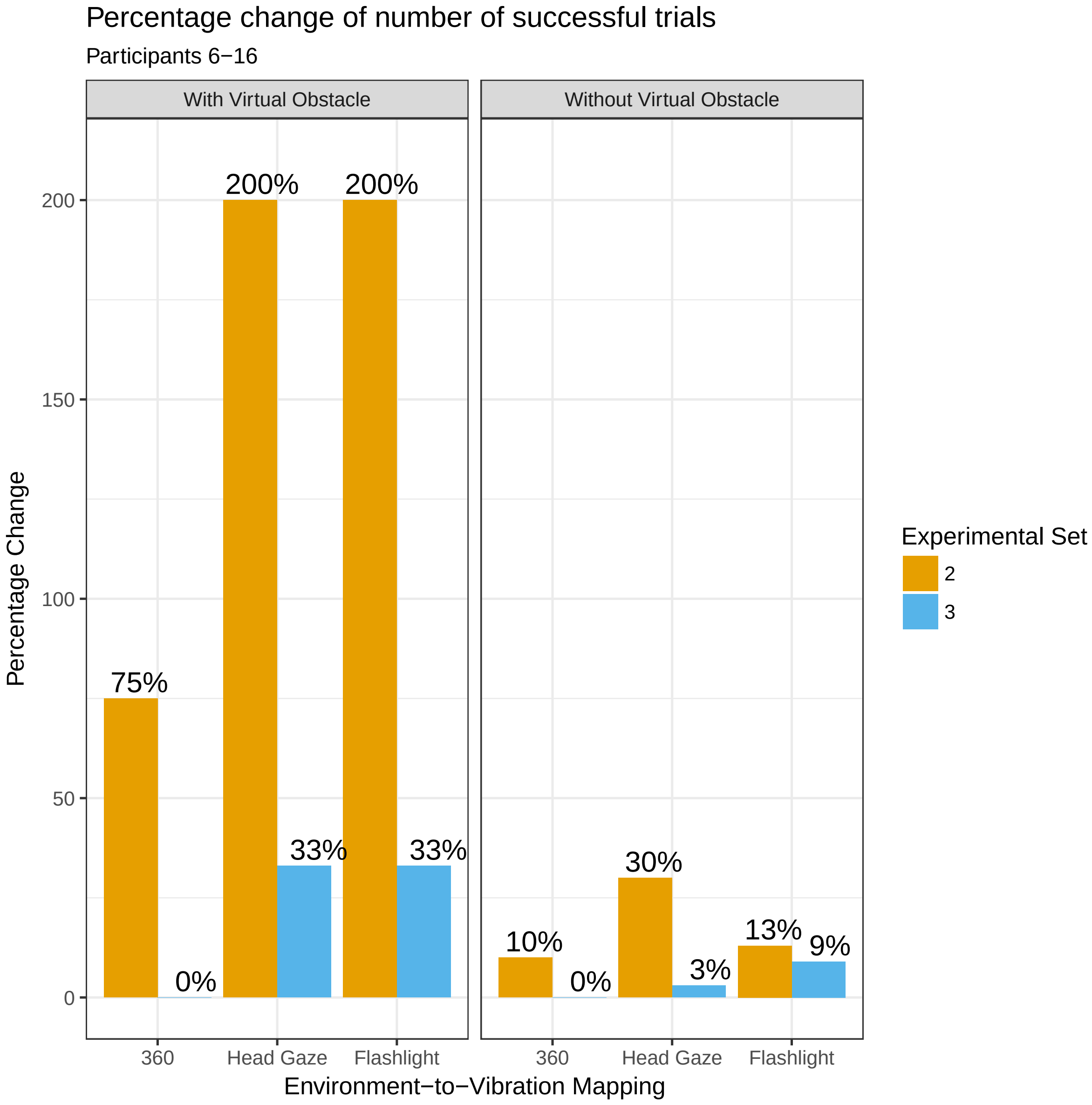


Figure 49. Fitted Line Plot of Relationship between Experimental Set and Number of Valid Trials

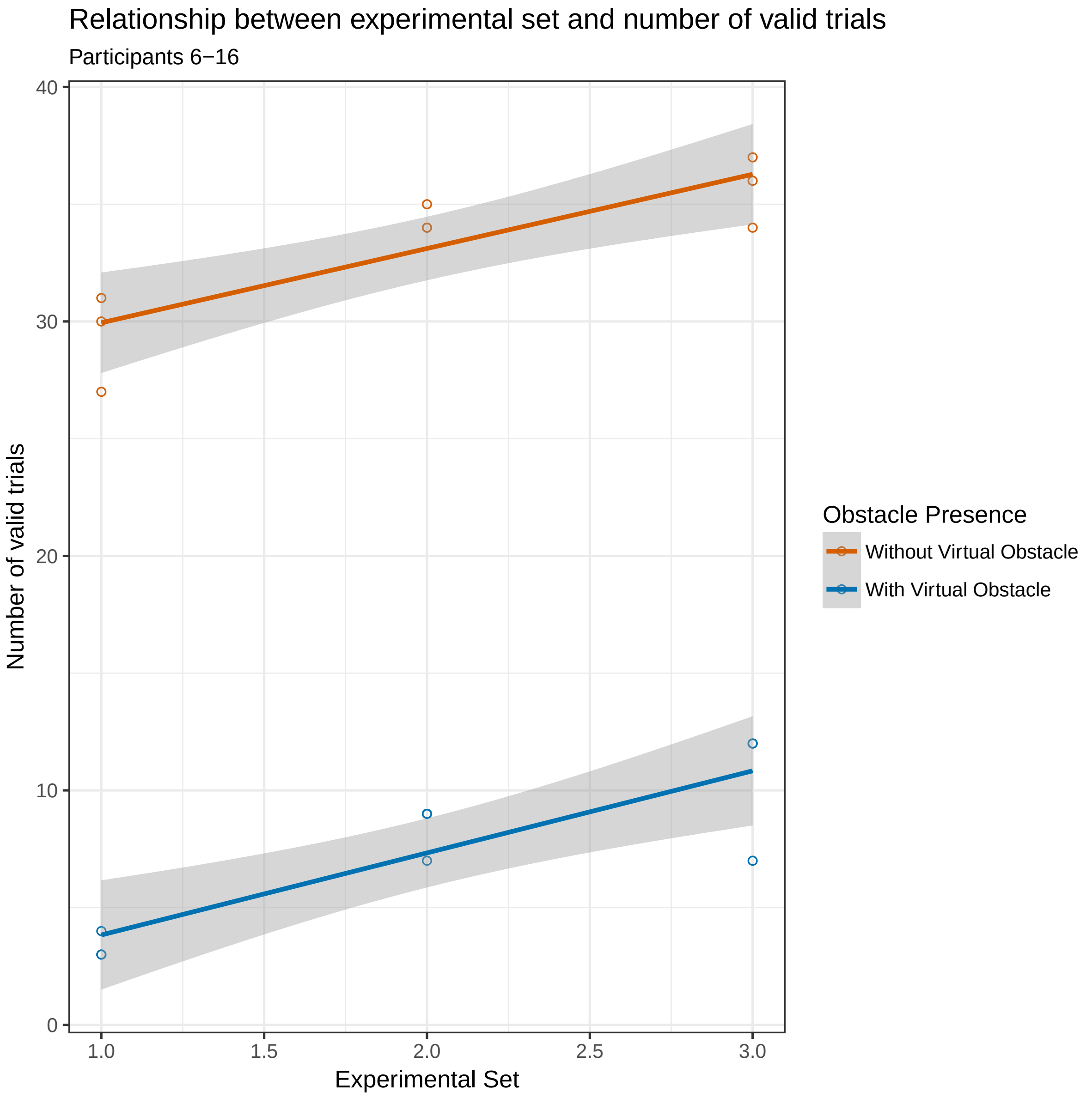


TABLE XXVII

REGRESSION COEFFICIENTS AND STANDARD ERRORS FOR MULTIPLE LINEAR REGRESSION

	Sum		
	B	***CI***	***p***
(Intercept)	26.44	23.97 – 28.92	$< .001$
attempt	3.33	2.26 – 4.41	$< .001$
Virtual Obstacle (True)	-25.78	-27.53 – -24.03	$< .001$
Observations		18	
R^2 / adj. R^2		.986 / .984	

ings we run a multiple regression model that statistically significantly predicted the number of successful trials based on the number of experimental sets. Please note that the improvement will plateau as the number of valid trials approaches the total number of this study's trials. These findings, however, support our second hypothesis—that the participants' efficiency and precision is related to their experience with the tactile display and would significantly improve over time. Therefore, the participants' *Situation Awareness* is associated with experience and would significantly improve over time.

5.2.4 Obstacle Detection Results

As mentioned in section 4.3.2, half of the trials within an experimental set, have a *Virtual Obstacle* at head height appearing at random path locations. As seen in Figure 46, Figure 47, Figure 48, Figure 49, Figure 51 and Figure 52 significantly more invalid walks occurred, in trials with *Virtual Obstacles*.

However, most participants significantly improved over the course of the 3 experiments, as their third attempt, would reveal the highest number of successful walks, contrasted to their previous 2. Our multiple regression model (section 5.2.3) also statistically significantly predicted the number of successful trials based on the presence of *Virtual Obstacles* and number of attempts. Among trials within the same experimental set, those with *Virtual Obstacles* yield on average 25.8 less valid walks than those without. However, as seen in Figure 50, the fitted line's slope is positive, meaning that given more attempts the participants would improve in the given task.

Figure 50. Number of Valid and Invalid Trials per Path Type and *Environment-to-Vibration Mapping* for Participants 1-5

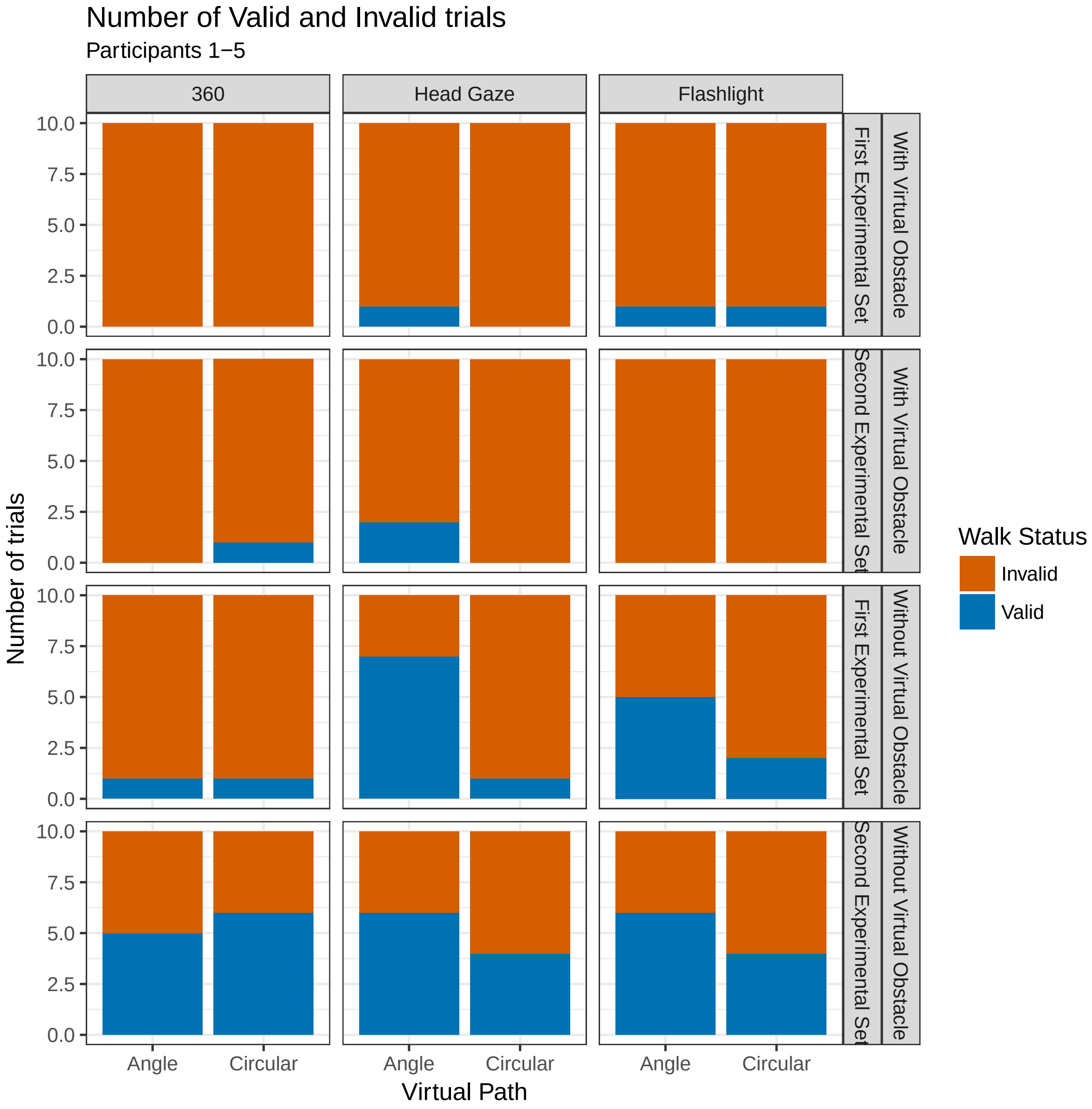
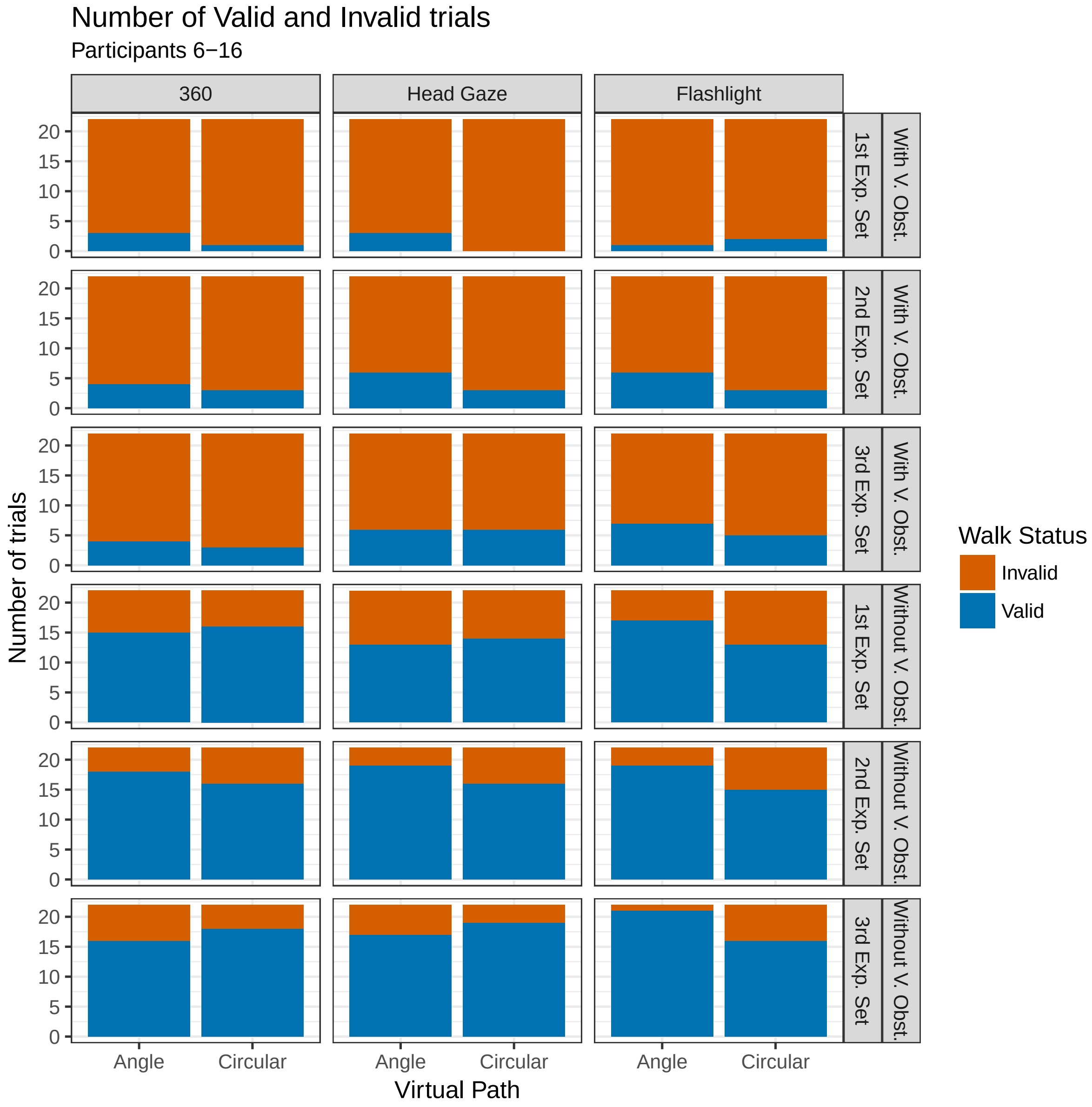


Figure 51. Number of Valid and Invalid Trials per Path Type and *Environment-to-Vibration Mapping* for Participants 6-16



All participants agreed that the *Virtual Obstacles* were by far the most challenging part of this study and the majority was unable to correctly identify and avoid them. After analyzing the video recordings of the experiments, we managed to identify the most common ”mistakes” that occur in a *Virtual Obstacle* setting. Our results can be found below:

1. The user feels the Virtual Obstacle vibration, but is unable to successfully identify it as such. As they try to avoid it by backtracking, they now find themselves ”trapped” in walking back and forth.
2. The user—using *Flashlight* Mapping— points their hand too low. As a result, they miss the *Virtual Obstacle* completely.
3. The user identifies the *Virtual Obstacle*, however is not successful in crossing it. We found that the challenge in this case, is incorrect alignment to the *Virtual Path* and by extension to the *Virtual Obstacle*. In other words, the participant needs to be in the middle of the *Virtual Path*, in order to have the *Virtual Obstacle* perpendicular to their crossing direction. Otherwise there is a great chance of hitting one of the virtual walls.
4. The user finds the *Virtual Obstacle*, however underestimates the distance and ends up touching it with their head.

5.2.5 Virtual Room Results

At the end of the last experimental set, a more complex navigational scenario was tested. As described is section 4.3.2.1.4, participants had to find the open door inside a 2x3m Virtual Room. 2 obstacles were also present. Goal of this experiment was to investigate whether the acquired knowledge from the path navigation experiments was transferable to more complex navigational scenarios. Please note that the participants did not go through any additional training for this specific scenario.

Overall, the success rate was 15%, with participants mostly using the *Head Gaze Mapping* (Table XXVIII). During the exit interviews participants reported that their navigating strategy was to randomly select a direction and attempt to find the open door. In the case their path selection resulted in a dead end, they then tried to backtrack and head a different way. None of the participants tried to create a mental map of the room, and none was able to recall its shape or the position of the obstacles. Regarding the *Environment-to-Vibration Mapping*, most of the participants did not have a specific strategy either. They said that they would start by selecting their personally preferred *Environment-to-Vibration Mapping* (usually *Flashlight* or *Head Gaze*) and if they got stuck, they would then try the other ones. Only 2 participants reported having a very specific strategy that included using the 360° for general navigation and then switching to *Flashlight* or *Head Gaze* to get more information about a specific spot. In other words, they were using 360° *Environment-to-Vibration Mapping* to create a macro image of the environment, and they would then switch to the other *Environment-to-Vibration Mappings* to collect a more specific, micro image of the environment.

In conclusion, the Virtual Room experiments further support our first hypothesis—that minimally trained vision deprived individuals can efficiently use tactile displays for completion of navigational tasks. While the success rate was relatively low (15%), we can see from Table XXIX that one user was successful in 4 out of 5 attempts. More specifically, the participant finished each attempt with a different *Environment-to-Vibration Mapping* and successfully used *Head Gaze Mapping* twice. When interviewed, they named *Head Gaze* as their least favorite and they reportedly saw it as a challenge. Please note that the same participant (ID: 8) was our second best subject as they had the second best number of valid walks, mean duration and mean distance (see Table XIX, Table XX, Table XXI, Table XXII, Table XXIII and Table XXIV).

TABLE XXVIII

MODES AND PATHS PER EXPERIMENTAL SET

Environment-to-Vibration Mapping	**Total Seconds**
360°	338
Head Gaze	573
Flashlight	266

TABLE XXIX

MODES AND PATHS PER EXPERIMENTAL SET

Subject	**Total Valid Attempts**
1	1
2	0
3	0
4	1
5	1
6	0
7	0
8	4
9	1
10	0
11	0
12	2
13	1
14	0
15	0
16	1

CHAPTER 6

CONCLUSION

Bourne et al. (80) estimate that 253 million people in the world are blind and visually impaired. Visual impairments can significantly lower one's quality of life as they hamper the ability to perform otherwise simple tasks, like cooking a meal, walking to the bedroom or enjoying the outdoors. Similarly, people working in high-risk low-visibility environments, like firefighters and soldiers, might temporarily lose their vision when they need it the most. And while Tactile Visual Substitution Systems (*TVSS*) have been designed to aid in situations with vision loss, their use in navigation scenarios is very limited.

This dissertation has sought to investigate different environment-to-vibration mappings while assessing one's *Situation Awareness*. Furthermore, we sought to understand whether one's experience with a tactile display would affect one's *Situation Awareness*. Finally, we investigated how different vibration configurations, patterns and environment-to-vibration mappings would affect one's navigation. As we have demonstrated through experimental studies, tactile displays significantly increase one's *Situation Awareness* while facilitating successful navigation. These results provide insight and design implications for creating more complex navigational tactile displays.

This chapter concludes the dissertation by outlining the main contributions as well as providing potential areas of future research that would continue to improve navigational tactile displays.

6.1 Discussion

We subconsciously continually process information from our sensory channels and after much internal filtering, decide what is worth attracting our attention. For instance, car drivers do not pay attention to the license plate numbers of the car in front of them–even though that information is right there—but would (hopefully) never miss a red light. Our senses continuously compete with each other to inform us of the environment around us, while keeping us safe. However, due to the overwhelming amount of data of the visual and auditory systems, the sense of touch is often underestimated. While, however, we have lost touch with our sense of touch, it is becoming increasingly clear that this largest organ of the human body can be utilized for hands-free communication of vital information. For example, one of the modern cars' latest safety feature is the feeling on the steering wheel—through vibration—of the presence of cars at their blind spots.

This new sensory modality requires a new type of haptic language or encoding that will be seamless and natural as verbal communication. More specifically, how does information get efficiently communicated to the user and how can the human-computer loop be minimized? Based on the results of this dissertation as well as research by Jansen et al. (70), McGrath et al. (72) and Novich and Eagleman (81) we envision that there will be a different haptic encoding or language for each specific task. For instance, a tactile navigation display, like *SpiderSense*, will have a different haptic language than an audio-to-tactile display. For each of those specific use cases, scientists need to find the best way to encode and communicate information while maintaining or increasing *Situation Awareness*. Haptic knowledge will not transfer from device to device, however, we hypothesize that familiarity with tactility will improve the learning curve. Our last point derives from the observation that people speaking multiple languages or playing a plethora of musical instruments are, in general, better at learning a new language or instrument.

Going a step forward, one might ask whether this new sensory modality can integrate with the sensory system, thus becoming a *sixth sense.* While a longitudinal user study is needed to investigate this type of sensory integration, some of the results of this dissertation hint towards that direction. People are exceptionally good at learning new skills, which once perfected, are executed subconsciously. For instance, a guitar player ”feels” the music and is not actively thinking of his finger positions on the fretboard; a hockey player controls the hockey stick as an extension of his arms; and a Kung-Fu master blocks and attacks faster than the blink of an eye. Furthermore, these skills produce structural and functional changes in areas of the brain due to the formation of new neurons and synapses. While no longitudinal study investigates whether tactile displays produce those types of changes, experimental results hint that it might be possible. For instance, in Bach-y-Rita's experiments (6), experimenters—after extensive training—describe the haptic sensation as ”seeing” instead of ”feeling” the objects. Similarly, in our experiments, we have observed that the ”expert” users of our system were able to navigate more efficiently than their counterparts while improving their performance with every run.

Physical and functional constraints of vibration motors, like for instance their size, weight, and power draw, have limited their practical use in everyday objects. However, recent changes in technology miniaturization have yielded a plethora of small, efficient vibration motors which can be integrated into electronic and wearable devices. As these devices become ubiquitous, we will need a governing body to set the safety standards and assure for homogeneity. This new tactile consortium will share information about tactile technologies and agree on common haptic languages/encodings, best practices, and safety standards. For instance, a haptic jacket from a company should use the same haptic language/encoding with another's. Another consideration is that devices should follow safety standards and include design considerations for people with sensory sensitivity as to not to disturb them.

6.2 Contributions

This dissertation aimed to explore two main research questions regarding the use of tactile displays in navigation:

- Could tactile displays be used to increase *Situation Awareness* of visually deprived individuals?
- To what extent would *Situation Awareness* be associated with experience when using a tactile display?

In order to answer these questions, we designed and performed a pilot study that was used to evaluate and compare different ways of mapping environmental cues to vibration patterns. During the study we tested 14 different Environment-to-Vibration Patterns and found statistical significance when comparing their performance. Additionally, we designed and performed a user study to uncover the effectiveness of various *Environment-to-Vibration Mappings* during vision deprived navigation. During the study we tested 3 different *Environment-to-Vibration*

Mappings in various navigational scenarios and found statistical significance when comparing their performance. These studies allowed us to gain an understanding on how to better design tactile displays for navigational tasks.

Firstly, we sought to investigate how to effectively communicate the environment onto one's skin. As one's *Situation Awareness* is tightly related to perceiving and comprehending environmental cues, we had to explore whether there is a difference in comprehension of different tactile stimuli. Our experiments showed that the way of coding the environment onto haptic patterns will affect their comprehension (and therefore their *Situation Awareness*) and can either increase or decrease their performance in a specific navigational task. Coding here refers to the participants' perceived feeling of an object on their bodies (pattern-wise) and how the haptic sensation changes when they move around.

Secondly, we explored different ways of mapping the environment onto one's skin and tested whether participants can recognize and use different vibration levels to avoid obstacles at head height. Mapping here refers to the mapping of an object onto the vibration motors of the tactile display. Our experiments showed that there was a difference in performance between different mappings and that, while challenging, obstacles at head height can be recognized and avoided. Furthermore, a more complex navigational scenario also showed that minimally trained vision deprived individuals can use tactile displays to successfully navigate complex environments. Finally, we also found that all participants regardless of mapping and obstacle presence significantly improved in performing the navigational tasks. This showed us that, when using tactile displays, experience is associated with *Situation Awareness* and that some users can achieve Endsley's "mark of an expert" given enough training.

Finally, through the iterative design process and user feedback of *SpiderSense 1* and *SpiderSense 2*, we discovered the sheer number of variables when designing and evaluating a tactile navigation display, and the difficulty in their quantification and interpretation. For instance, a user walking into a wall was due to not feeling the vibration, or due to not interpreting it? Did they not feel it because it was too soft, or was it due to decreased *Situation Awareness*? Were the sensors correctly aligned right before the impact and was the wall in their FOV? Right from the beginning, it became evident the need for an experimental environment that allowed the control of the variables so we can focus on our research questions. Our final contribution is the design of a virtual reality experimental setup that allows researchers to design and evaluate tactile displays and haptic sensations while performing complex user studies in dynamic environments.

The proposed system consists of two main parts: the tactile display and the dynamic virtual environment, each being interchangeable and dynamic. The untethered tactile display allows freedom of movement, while its flexible tactor design enables reconfiguration and fitting on all body types. The modularity of the vibration motors enables testing of different motor configurations, like for example having an additional row of motors. In fact, the hardware design of *SpiderSense 3* can support up to 48 vibration motors, even though only 24 were used in the user studies. Additional flexibility is also provided by the firmware design that is sensor-agnostic and therefore can support a variety of inputs (for instance replacing the VR environment with actual depth sensors).

Similarly, the use of a virtual environment that simulates spaces and obstacles enables researchers to test—in a controlled environment—a variety of experimental scenarios while keeping the participants safe. The possibilities here are endless: the spaces can be simple or complex; they can have one or multiple obstacles; there are no (reasonable) space limitations as other Virtual Environments with bigger tracking space can be used (like for example the CAVE2 (82)); different *Environment-to-Vibration Patterns* and *Mappings* can be tested as well as other types of vibration motors.

We hope that other scientists will adopt this modular experimental setup, allowing them to a faster iterative design process, better quantitative results and more robust experimental design.

6.3 Areas of Future Research

The work done in this dissertation does have certain limitations. Firstly, the 3 *Distance-to-Vibration Mappings* (*Smooth*, *Power*, *Exponential*) performed equally well and therefore a more thorough user study, with more participants is needed. During the exit interviews participants agreed on disliking intense vibrations and prefered modes with less intense vibration. This leads us to believe that for similar navigational tasks a power mapping with a k-constant value bringing it closer to linear might be preferable. Our rationale is that a power mapping gives the participants more space to walk without any vibration feedback, while still alerts them on time in case of an obstacle.

Alarm Mode proved to be a very good mechanism for drawing attention and making the users stop and change their course. While in the pilot study experiments, *Alarm Mode* signalled that they were already touching a wall, it would be interesting to investigate whether it could be used as a last minute alert (signaling right before touching a wall). Additionally, users complained that while *Alarm Mode* was very effective in drawing their attention towards the presence of a wall, they were still unaware of its exact location and orientation—a consequence of continuous vibration on the entire torso band surface. An area of future study would be to further experiment with different methods of localizing the *Alarm Mode* sensation so that one gets more information of their whereabouts.

While *Follow Vibration Mode* proved to be the least successful during the pilot study, the concept of following the vibrations is, due to its simplicity, still very appealing. A possible future research study could further test *Follow Vibration Mode*, possibly having only one vibration column vibrating at once. In this scenario the system would work similar to a guide-dog, where the user blindly follows the vibration, completely unaware of their surroundings.

In this study, modulating either the frequency or the amplitude of vibration, results in perception of its magnitude. A more complex tactile synthesis of both (amplitude and frequency) modulations, however, might yield different results and might allow for more complex tactile sensations.

During the user study, the obstacles at head height proved to be the most challenging task throughout the experiment. Showing that the task is possible, 3 participants, whose performance significantly improved over time, were able to successfully detect and avoid obstacles at a high percentage rate. Based on our discussions with the participants, we believe that spacing out the rows of motors might improve obstacle detection, however we recognize that further studies are needed.

The analysis of the user study demonstrated participant's significant improvement over the course of the three experimental sets for all *Environment-to-Vibration Mappings*, regardless of *Virtual Obstacle* presence. While all experimental sets were performed sequentially with 5-minute breaks in between, a longitudinal user study would uncover how people improve over a longer period of time; whether the improvement is permanent; and the improvement's margins when using a similar tactile display. Additionally, going back to the *Virtual Obstacle*, a longitudinal study could investigate whether participants performance with the obstacle would improve, given enough time and training. It is important to note that our proposed navigational tactile display required minimal training, unlike other *TVSS* systems, like the *Tactile Image Projection* system (6), that required hours of training and even then, only a few expert users were able to use it effectively.

Trials with 360° *Mapping* were statistically significantly faster but also lengthier, hinting that people might be more comfortable in using this *Environment-to-Vibration Mapping* in a more exploratory way. Our interpretation is that due to it's 360° coverage, individuals are more aware of their surroundings and, as a result, walk faster. More studies are needed to further understand how, why and when 360° *Mapping* might be preferable to the other *Environment-to-Vibration Mappings*, to further compare the *Flashlight* and *Head Gaze Mappings* and to investigate what other new *Environment-to-Vibration Mappings* could be beneficial. Finally, due to the nature of our research questions, the experimental setup had to be very controlled. Further studies using a larger more complex environment could investigate how vision deprived individuals navigate in such spaces. Another area of future research is integration of sensors and overcoming the sensor limitations that were described in sections 3.1.4 and 3.2.3. Furthermore, we believe that the addition of real physical obstacles will increase the learning curve, due to reinforced learning effects. Concluding, we hope that this dissertation would instigate young future researchers' minds and open a door for further research studies and opportunities.

APPENDICES

Appendix A

PILOT STUDY MATERIALS

Appendix A (Continued)

A.0.1 Pilot Study Recruitment Document

Recruitment Document:

A team of researchers at the University of Illinois at Chicago is looking for individuals to participate in a research project at the Electronic Visualization Laboratory (“EVL”), to examine how different vibration patterns affect navigational tasks when other senses are blocked.

The experimental session involves wearing a Virtual Reality Head Mounted Display and our haptic system and walking in an empty space while feeling different vibration patterns on your torso.

You must be over 18 years old to participate in this study and cannot have a disability that would hamper the use of/response to the devices being tested.

A trial for this study will take you approximately 120 minutes to complete. The study will be audio recorded and videotaped for data analysis. Data collected through this study will remain confidential.

People interested in participating should contact Viktor A. Mateevitsi by responding to this e-mail vmatee2@uic.edu or contact him directly at (312) 996 3002.

Questions and concerns regarding this research should be directed to:

Principal Investigator:
Viktor A. Mateevitsi
Vmatee2@uic.edu
Phone: (312) 996 3002

Faculty sponsor:
Andrew E. Johnson
ajohnson@uic.edu
Phone: (312) 996 3002

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8/18/2017 — 8/18/2018
UNIVERSITY OF ILLINOIS AT CHICAGO
INSTITUTIONAL REVIEW BOARD

Appendix A (Continued)

A.0.2 Pilot Study Consent Document

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INSTITUTIONAL REVIEW BOARD

University of Illinois at Chicago
Consent for Participation in Research
“A Study on Vibration Feedback Mechanisms”

Why am I being asked?

You are being asked to be a participant in a research project about the effects of vibration patterns on navigation when other senses are blocked, being conducted by Viktor A. Mateevitsi with a team of other researchers at the University of Illinois at Chicago. You have been asked to participate in the research because you responded to our request for participants and may be eligible to participate. We ask that you read this form and ask any questions you may have before agreeing to be in the research.

To participate in this research you have to be an adult and do not have any disability that could hamper the use of/response to the devices being tested. Your participation in this research is voluntary. Your decision whether or not to participate will not affect your current or future relations with the University. If you decide to participate, you are free to withdraw at any time without affecting that relationship.

Why is this research being done?

This study is designed to determine the key vibration characteristics and patterns for conveying environmental information using haptic interfaces. The insights of the research will allow researchers to build better haptic interfaces that can communicate haptic messages more efficiently.

What is the purpose of this research?

The goal of the experiment is to observe which vibration patterns and mechanisms work best for navigational tasks and to enable the future development of specialized software and hardware tools to assist people through the use of haptics.

What procedures are involved?

You will be asked to wear a Virtual Reality Head Mounted Display, a pair of over-the-ear headphones, and our haptic system that consists of a torso band equipped with vibration motors

Appendix A (Continued)

and a backpack that houses the batteries and the electronics. You will also be using up to two Virtual Reality controllers.

During the experiment, we will ask you to do the following:

- Respond to a Demographic Survey.
- Follow a short training by walking around to acclimate yourself to the vibration patterns and what they mean
- When the experiment starts, the display will be disabled and you will hear background noise. The headphones are connected to 2-way communication system and therefore the experimenter can talk to you at any time.
- You will need to do a series of walks down invisible corridors. The experimenter will walk you to a starting point and then you will need to find your way by using the haptic feedback you are getting. Once you successfully get to the finish point, the experimenter will let you know and a new walk will begin.
- During the study, you will be video and audio taped.
- If you have questions during the study, please feel free to ask the researcher at any time.

Participation in the experiment will take approximately 120 minutes.

What are the potential risks and discomforts?

To the best of our knowledge, the things you will be doing have no more risk of harm than you would experience by using a consumer Virtual Reality head mounted display. There is a risk of feeling Virtual Reality sickness, and a minor risk of tripping due to the use of the Virtual Reality headset. We are mitigating those risks by taking regular schedules brakes and having a Safety Assistant that will monitor the experiment and be responsible for your safety. Another risk of this research is a loss of privacy (revealing to others that you are taking part in this study) or confidentiality (revealing information about you to others to whom you have not given permission to see this information). Your information will remain confidential, and is not linked to your performance with the University of Illinois at Chicago.

Are there benefits to taking part in the research?

There are no direct benefits to you for participating in this study but will increase our understanding of how to effectively use haptic interfaces to communicate environmental and navigational information.

What other options are there?

You do not have to participate in this program. In the event that you do not participate or withdraw during the experiment, there will be no penalty.

What about privacy and confidentiality?

Appendix A (Continued)

The people who will know that you are research participants are members of the research team. No information about you, or provided by you during the research will be disclosed to others without your written permission, except:

- if necessary to protect your rights or welfare (for example when the State of Illinois auditors or UIC Institutional Review Board monitors the research or consent process); or
-if required by law.

When the results of the research are published or discussed in conferences, no information will be included that would reveal your identity. If photographs, videos, or audiotape recordings of you will be used for educational purposes, your identity will be protected or disguised. Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law.

- All identifying data, including images, recordings, and questionnaires will be kept under lock and key at the Electronic Visualization Laboratory (room 2032 ERF) at UIC for the duration of the study. Access to this data will be restricted to the principal investigator, *Viktor Mateevitsi*, and his co-investigators.
- All other information that might identify you, will be labeled with a numerical identifier to maintain your anonymity. The index of study participant names and numbers will be kept under lock in the Electronic Visualization Laboratory (room 2032 ERF) at UIC.
- We will request additional consent from you if we desire to use identifying images or recordings of you in a publication or for public presentation.
- All identifying images, recordings, and questionnaire results will be destroyed once the data has been fully analyzed.

What are the costs for participating in this research?

There are no costs for you to participate in this program.

Will I be reimbursed for any of my expenses or paid for my participation in this research?

There is no reimbursement for your participation in this research.

Can I withdraw or be removed from the study?

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you do not want to answer and remain in the study. The investigator may withdraw you from this research if you cannot follow the instructions needed to conduct these experiments such as stand, walk, and sit.

Appendix A (Continued)

Who should I contact if I have questions?

You may ask any questions you have to the researcher now. If you have questions later, you may contact Viktor A. Mateevitsi at:
Phone: (312) 996 3002, or through e-mail: vmatee2@uic.edu

In addition, you may contact Professor Andrew Johnson at:
Phone: (312) 996 3002, or through e-mail: ajohnson@uic.edu

What are my rights as a research participant?

If you have any questions about your rights as a research subject, you may call the Office for Protection of Research Subjects at (312) 996 1711 or e-mail: uicirb@uic.edu.

What if I am a UIC student?

You may choose not to participate or to stop your participation in this research at any time. This will not affect your class standing or grades at UIC. The investigator may also end your participation in the research. If this happens, you class standing or grades will not be affected. You will not be offered or receive any special consideration if you participate in this research.

What if I am a UIC employee?

Your participation in this research is in no way a part of your university duties, and your refusal to participate will not in any way affects your employment with the university, or the benefits, privileges, or opportunities associated with your employment at UIC. You will not be offered or receive any special consideration if you participate in this research.

Remember: Your participation in this research is voluntary. Your decision whether or not to participate will not affect your current or future relations with the University. If you decide to participate, you are free to withdraw at any time without affecting that relationship.
You will be given a copy of this form for your information and to keep for your records.

Appendix A (Continued)

Signature of Participant

I have read (or someone has read to me) the above information. I have been given an opportunity to ask questions and my questions have been answered to my satisfaction. I agree to participate in this research. I have been given a copy of this form.

______________________________ ____________
Signature Date

____
Printed Name

______________________________ ____________
Signature of Researcher Date (must be same as participant's)

Appendix A (Continued)

A.0.3 User Study Recruitment Document

Recruitment Document:

A team of researchers at the University of Illinois at Chicago is looking for individuals to participate in a research project at the Electronic Visualization Laboratory ("EVL"), to examine how different vibration mappings affect navigational tasks when other senses are blocked.

The experimental session involves wearing a Virtual Reality Head Mounted Display and our haptic system and walking in an empty space while feeling different vibration patterns on your torso.

You must be over 18 years old to participate in this study and cannot have a disability that would hamper the use of/response to the devices being tested.

A trial for this study will take you approximately 120 minutes to complete. The study will be audio recorded and videotaped for data analysis. Data collected through this study will remain confidential.

People interested in participating should contact Viktor A. Mateevitsi by responding to this e-mail vmatee2@uic.edu or contact him directly at (312) 996 3002.

Questions and concerns regarding this research should be directed to:

Principal Investigator:
Viktor A. Mateevitsi
Vmatee2@uic.edu
Phone: (312) 996 3002

Faculty sponsor:
Andrew E. Johnson
ajohnson@uic.edu
Phone: (312) 996 3002

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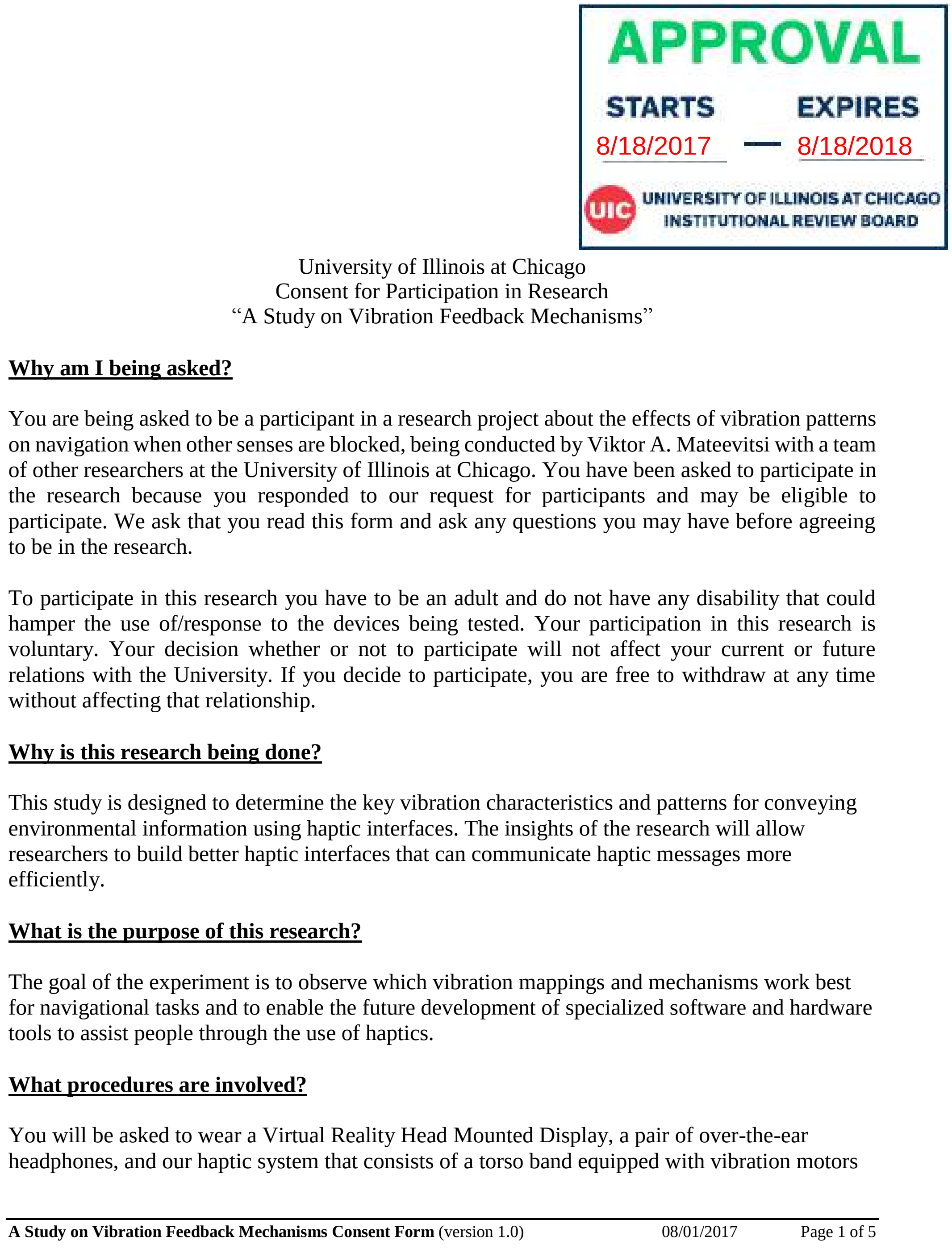
Appendix A (Continued)

A.0.4 User Study Consent Letter



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University of Illinois at Chicago
Consent for Participation in Research
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To participate in this research you have to be an adult and do not have any disability that could hamper the use of/response to the devices being tested. Your participation in this research is voluntary. Your decision whether or not to participate will not affect your current or future relations with the University. If you decide to participate, you are free to withdraw at any time without affecting that relationship.

Why is this research being done?

This study is designed to determine the key vibration characteristics and patterns for conveying environmental information using haptic interfaces. The insights of the research will allow researchers to build better haptic interfaces that can communicate haptic messages more efficiently.

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Appendix A (Continued)

and a backpack that houses the batteries and the electronics. You will also be using up to two Virtual Reality controllers.

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- Follow a short training by walking around to acclimate yourself to the vibration mappings and what they mean
- When the experiment starts, the display will be disabled and you will hear background noise. The headphones are connected to 2-way communication system and therefore the experimenter can talk to you at any time.
- You will need to do a series of walks in virtual spaces while avoiding virtual objects and obstacles. The experimenter will walk you to a starting point and then you will need to find your way by using the haptic feedback you are getting. Once you successfully get to the finish point, the experimenter will let you know and a new walk will begin.
- During the study, you will be video and audio taped.
- If you have questions during the study, please feel free to ask the researcher at any time.

Participation in the experiment will take approximately 120 minutes.

What are the potential risks and discomforts?

To the best of our knowledge, the things you will be doing have no more risk of harm than you would experience by using a consumer Virtual Reality head mounted display. There is a risk of feeling Virtual Reality sickness, and a minor risk of tripping due to the use of the Virtual Reality headset. We are mitigating those risks by taking regular schedules brakes and having a Safety Assistant that will monitor the experiment and be responsible for your safety. Another risk of this research is a loss of privacy (revealing to others that you are taking part in this study) or confidentiality (revealing information about you to others to whom you have not given permission to see this information). Your information will remain confidential, and is not linked to your performance with the University of Illinois at Chicago.

Are there benefits to taking part in the research?

There are no direct benefits to you for participating in this study but will increase our understanding of how to effectively use haptic interfaces to communicate environmental and navigational information.

What other options are there?

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What about privacy and confidentiality?

The people who will know that you are research participants are members of the research team. No information about you, or provided by you during the research will be disclosed to others without your written permission, except:

- if necessary to protect your rights or welfare (for example when the State of Illinois auditors or UIC Institutional Review Board monitors the research or consent process); or
-if required by law.

When the results of the research are published or discussed in conferences, no information will be included that would reveal your identity. If photographs, videos, or audiotape recordings of you will be used for educational purposes, your identity will be protected or disguised. Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law.

- All identifying data, including images, recordings, and questionnaires will be kept under lock and key at the Electronic Visualization Laboratory (room 2032 ERF) at UIC for the duration of the study. Access to this data will be restricted to the principal investigator, *Viktor Mateevitsi*, and his co-investigators.
- All other information that might identify you, will be labeled with a numerical identifier to maintain your anonymity. The index of study participant names and numbers will be kept under lock in the Electronic Visualization Laboratory (room 2032 ERF) at UIC.
- We will request additional consent from you if we desire to use identifying images or recordings of you in a publication or for public presentation.
- All identifying images, recordings, and questionnaire results will be destroyed once the data has been fully analyzed.

What are the costs for participating in this research?

There are no costs for you to participate in this program.

Will I be reimbursed for any of my expenses or paid for my participation in this research?

There is no reimbursement for your participation in this research.

Can I withdraw or be removed from the study?

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you do not want to answer and remain in the study. The investigator may withdraw you from this research if you cannot follow the instructions needed to conduct these experiments such as stand, walk, and sit.

Who should I contact if I have questions?

You may ask any questions you have to the researcher now. If you have questions later, you may contact Viktor A. Mateevitsi at:
Phone: (312) 996 3002, or through e-mail: vmatee2@uic.edu

In addition, you may contact Professor Andrew Johnson at:
Phone: (312) 996 3002, or through e-mail: ajohnson@uic.edu

What are my rights as a research participant?

If you have any questions about your rights as a research subject, you may call the Office for Protection of Research Subjects at (312) 996 1711 or e-mail: uicirb@uic.edu.

What if I am a UIC student?

You may choose not to participate or to stop your participation in this research at any time. This will not affect your class standing or grades at UIC. The investigator may also end your participation in the research. If this happens, you class standing or grades will not be affected. You will not be offered or receive any special consideration if you participate in this research.

What if I am a UIC employee?

Your participation in this research is in no way a part of your university duties, and your refusal to participate will not in any way affects your employment with the university, or the benefits, privileges, or opportunities associated with your employment at UIC. You will not be offered or receive any special consideration if you participate in this research.

Remember: Your participation in this research is voluntary. Your decision whether or not to participate will not affect your current or future relations with the University. If you decide to participate, you are free to withdraw at any time without affecting that relationship.
You will be given a copy of this form for your information and to keep for your records.

Appendix A (Continued)

Signature of Participant

I have read (or someone has read to me) the above information. I have been given an opportunity to ask questions and my questions have been answered to my satisfaction. I agree to participate in this research. I have been given a copy of this form.

Signature Date

Printed Name

Signature of Researcher Date (must be same as participant's)

A.0.5 Media Consent Document

APPROVAL
STARTS — EXPIRES
8/18/2017 — 8/18/2018
UNIVERSITY OF ILLINOIS AT CHICAGO
INSTITUTIONAL REVIEW BOARD

University of Illinois at Chicago
Consent to Use Identifying Media from

“A Study on Vibration Feedback Mechanisms”

Why am I being asked?

We would like to use images, video, or audio recordings of your participation in the study for publication or presentation. We seek your consent to use this media in unaltered form that may allow others to identify you. We ask that you read this form and ask any questions you may have before giving consent.

Your decision to give this consent is voluntary. Your decision whether or not to give consent will not affect your current or future relations with the University or your grade in any courses.

What will this media be used for?

We wish to use images, video, or audio recordings that include your likeness in a publication about the results of our study. This may also lead to opportunities to present the results of the study in a conference setting. The media selected with your likeness or voice has not been altered to prevent others from identifying you. The media will only be used to support arguments regarding the hypothesis of our study within the publication or at the presentation. The media will not be used to convey any personal information about your individual mannerisms, personality, or behavior traits.

Can I review or edit the media before they are used?

You have the opportunity to review the images, video recordings, and audio material bearing your likeness at this time. You may decline to give your consent for individual media items if you so desire. Once you have reviewed the media items and signed this consent agreement, you will not have another opportunity to edit or review the images, video, or audio content before publication or conference presentation.

Who should I contact if I have questions?

The researcher conducting this study is *Viktor Mateevitsi*. You may ask any questions you have now. If you have questions later, you may contact him at:
Phone: 312-996-3002, Email: vmatee2@uic.edu

The faculty sponsor of this research is Associate Professor *Andrew E. Johnson*. You may contact him at:
Phone: 312-996-3002, Email: ajohnson@uic.edu

Appendix A (Continued)

What are my rights as a research subject?

If you have any questions about your rights as a research subject, you may call the Office for Protection of Research Subjects at 312-996-1711.

Remember: Your participation in this research is voluntary. Your decision whether or not to participate will not affect your current or future relations with the University. If you decide to participate, you are free to withdraw at any time without affecting that relationship.
You will be given a copy of this form for your information and to keep for your records.

Signature of Subject

I have read the above information. I have been given an opportunity to ask questions and my questions have been answered to my satisfaction. I agree to participate in this research. I have been given a copy of this form.

Signature	Date
Printed Name	
Signature of Researcher	Date (must be same as subject's)

A.0.6 Demographic Survey

Demographic Questionnaire

"A Study on Vibration Feedback Mechanisms"
University of Illinois at Chicago
Department of Computer Science

1. What is your age?
   a. 18 – 24 years old
   b. 25 – 34 years old
   c. 35 – 44 years old
   d. 45 – 54 years old
   e. 55 – 64 years old
   f. 65 – 74 years old
   g. 75 or older

2. What is your gender?

3. What is your waist circumference (will be measured by the experimenter)?

4. What is your experience level with a body haptic interface (like the one you will be wearing today)?

1	2	3	4	5	6	7	8	9	10
Never used before									Used frequently

5. What is your experience level with VR HMDs (like the one you will be wearing today)?

1	2	3	4	5	6	7	8	9	10
Never used before									Used frequently

Appendix B

PERMISSIONS FOR REUSE

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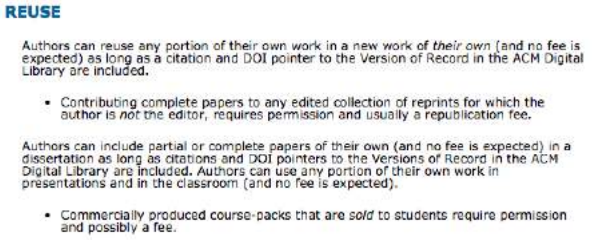

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Mateevitsi, Victor, Brad Haggadone, Jason Leigh, Brian Kunzer, and Robert V. Kenyon. ”Sensing the environment through SpiderSense.” In Proceedings of the 4th augmented human international conference, pp. 51-57. ACM, 2013.

communication+1

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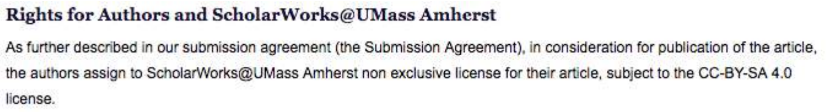

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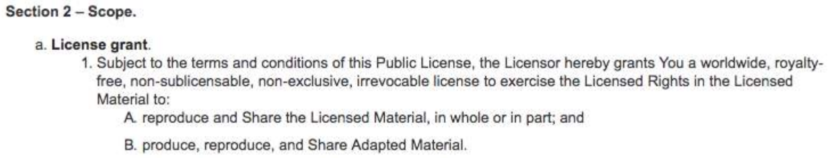

Section 2 – Scope.

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Novak, John; Archer, Jason; Mateevitsi, Victor; and Jones, Steve (2016) "Communication, Machines & Human Augmentics," communication +1: Vol. 5, Article 8.

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VITA

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EDUCATION

Ph.D., Department of Computer Science **2009 – 2018**
University of Illinois at Chicago Chicago, IL
Advisor: Andrew Johnson

Bachelors of Science, Computer Science and Technology **2002 – 2007**
University of Peloponnese Tripolis, Greece
Advisors: George Lepouras, Costas Vassilakis

AWARDS AND HONORS

Alien of Extraordinary Ability	US Green Card	**2016**
Dean's Scholar Award	University of Illinois at Chicago	**2015**
20 in their 20s	Crain's Chicago Business	**2014**
Best Paper Award	IEEE CollaborateCom	**2014**
Fifty For The Future®	Illinois Technology Foundation	**2013**
Certificate of Appreciation for outstanding performance and lasting contribution to Wearable Technology	MIT Enterprise Chicago	**2013**
Best Augmented Reality Hardware (Finalist)	Augmented World Exposition	**2013**
Image of Research (Finalist)	University of Illinois at Chicago	**2013**

WORKING EXPERIENCE

University of Illinois at Chicago **2009 – 2018**
Research Assistant – Electronic Visualization Laboratory (advisor: *Andrew Johnson*) Chicago, IL

- Co-invented *SpiderSense*, an innovative Human Augmentation device that has been featured in more than 200,000 press outlets.
- Developed software for 3D rendering of terrain and maps in a CAVE2.
- Developed 3D Visualization Software for the US Air Force medical researchers. Expedited biology experiment analysis by 800% introducing automatic video processing and tracking for field biologists at Princeton University.
- Invented the *HealthBar*, an ambient persuasive technology reflecting the health status of an office worker.
- Developed a client-server application enabling medical researches to upload image datasets to a remote database.

Developed a plugin that combines the input from multiple Microsoft Kinects.

Summer 2015
Redmond, WA
Microsoft Research
Research Intern (advisor: *Jaron Lanier*)
Worked on project COMRADERIE, developing the largest untethered FOV Mixed Reality Head-Mounted Display. Research on collocated collaboration in untethered Mixed Reality. Research presented at SIGGRAPH 2015.

Pixar Animation Studios **Summer 2013**
Studio Tools Intern (mentor: *Davide Pesare*) Emeryville, CA

Worked on the next generation internal scene description and geometry file format. Developed the plugins for commercial software (Houdini, Mari) to load the in-house file format. Developed plugins were privately demoed to the film industry at SIGGRAPH 2013.

PDI/ DreamWorks Animation **Summer 2012**
Research and Development Animation Tools Intern (mentor: *Bruce Wilson*) Redwood City, CA
Upgraded an internal tool for parallelization accelerating the rendering cycle up to 30%. Improved the code coverage process, resulting in a hundred-fold speedup. Worked on the next-generation animation tool as part of the core development team.

National Technical University of Athens **2006 – 2009**
Research Associate (advisor: *George Stassinopoulos*) Athens, Greece
Research on video and audio search algorithms.

Global Digital Technologies **2006 – 2009**
Advanced Software Engineer Athens, Greece
Developed software for embedded hardware control systems.

FCNet **2007 – 2009**
Consultant Athens, Greece
Installation of PBX phone systems for small businesses.

University of Peloponnese **2002 – 2006**
Network Technician - Telecommunication Networks and Mobile Systems Laboratory Tripolis, Greece
Research on metropolitan wireless networks.

UNDERGRADUATE STUDENTS SUPERVISED

Jagrut Patel **2014**
Built high-resolution video streamer for the Scalable Amplified Group Environment (SAGE2)

Panagiotis Karvounis **2009**
Research on using Google Maps on the .NET platform

Constantinos Kolovos **2008**
Research on Database XML Schemas

MIDDLE-SCHOOL STUDENTS SUPERVISED

Glen Poole, Dexter Wells Co-advised with A. Febretti **2014**
Built an augmented virtual sling game for the CAVE2.

Antwan McBee, Andrew Lewis, Joshua Gartley Co-advised with A. Febretti, K. Reda, G. Thomas-Ramos **2013**
Built a Fruit-Ninja like game for the CAVE2.

TEACHING

Teaching Assistant – National Technical University of Athens **2006 - 2008**
Internet and Applications
Database Systems

PEER-REVIEWED PUBLICATIONS

P17 J. Novak, J. Archer, **V. Mateevitsi**, and S. Jones. "Communication, machines & human augmentics." *Communication+ 1* 1 (2016): 51-35.

P16 J. Lanier, **V. Mateevitsi**, K. Rathinavel, L. Shapira, J. Menke, P. Therien, J. Hudman, G. Speiginer, A. Stevenson Won, A. Banburski, X. Benavides, J. Amores, J. Porras Lurashi and W. Chang. "The RealityMashers: Augmented Reality Wide Field-of-View Optical See-Through Head Mounted Displays." To appear in the 15th IEEE International Symposium on Mixed and Augmented Reality (ISMAR), 2016.

P15 J. Novak, J. Archer, V. Mateevitsi, and S. Jones. "Communication, Machines & Human Augmentics". To appear in the *communication+ 1* journal, 2016.

P14 L. Renambot, T. Marrinan, J. Aurisano, A. Nishimoto, **V. Mateevitsi**, K. Bharadwaj, L. Long, A. Johnson, M. Brown, and J. Leigh. "SAGE2: A collaboration portal for scalable resolution displays." *Future Generation Computer Systems* 54 (2016): 296-305.

P13 **V. Mateevitsi**, T. Patel, J. Leigh, and B. Levy. "Reimagining the microscope in the 21st century using the scalable adaptive graphics environment." *Journal of pathology informatics* 6 (2015).

P12 **V. Mateevitsi**, and B. Levy. "Scalable Adaptive Graphics Environment: A Novel Way to View and Manipulate Whole-Slide Images." Analytical Cellular Pathology 2014 (2014)

P11 🎖 T. Marrinan, J. Aurisano, A. Nishimoto, K. Bharadwaj, **V. Mateevitsi**, L. Renambot, L. Long, A. Johnson, and J. Leigh, "SAGE2: A New Approach for Data Intensive Collaboration Using Scalable Resolution Shared Displays," In Proceedings of the IEEE International Conference on Collaborative Computing: Networking, Applications and Worksharing, 2014. **Best Paper Award**

P10 A. Febretti, A. Nishimoto, **V. Mateevitsi**, L. Renambot, A. Johnson, and J. Leigh. "Omegalib: A multi-view application framework for hybrid reality display environments." In Virtual Reality (VR), 2014 IEEE, pp. 9-14. IEEE, 2014.

P9 **V. Mateevitsi**, K. Reda, J. Leigh, and A. Johnson. "The health bar: a persuasive ambient display to improve the office worker's well being." In Proceedings of the 5th Augmented Human International Conference, p. 21. ACM, 2014.

P8 M.A. Bassiony, B.J. Vesper, **V.A. Mateevitsi**, K.M. Elseth, M.D. Colvar, K.D. Garcia, J. Leigh, J.A. Radosevich, Immunohistochemical Evaluation of Bleeding Control Induced by Holmium Laser and Biolase Dental Laser As Coagulting Devices of Incisional Wounds, Proceedings of the UIC College of Dentristry Clinic and Research Day 2014, Chicago, IL, March 6, 2014

P7 **V. Mateevitsi**, B. Haggadone, J. Leigh, B. Kunzer, and R.V. Kenyon. "Sensing the environment through SpiderSense." In Proceedings of the 4th Augmented Human International Conference, pp. 51-57. ACM, 2013.

P6 C. Offord, K. Reda, and **V. Mateevitsi**. "Context-dependent navigation in a collectively foraging species of ant, Messor cephalotes." Insectes sociaux 60, no. 3 (2013): 361-368.

P5 K. Reda, **V. Mateevitsi**, and C. Offord. "A human-computer collaborative workflow for the acquisition and analysis of terrestrial insect movement in behavioral field studies." EURASIP Journal on Image and Video Processing 2013, no. 1 (2013): 1-17.

P4 K. Reda, A. Johnson, **V. Mateevitsi**, C. Offord, and J. Leigh. "Scalable visual queries for data exploration on large, high-resolution 3D displays." In High Performance Computing, Networking, Storage and Analysis (SCC), 2012 SC Companion, pp. 196-205. IEEE, 2012.

P3 A. Febretti, **V.A. Mateevitsi**, D. Chau, A. Nishimoto, B. McGinnis, J. Misterka, A. Johnson, and J. Leigh. "The OmegaDesk: towards a hybrid 2D and 3D work desk." In Advances in Visual Computing, pp. 13-23. Springer Berlin Heidelberg, 2011.

P2 G. Doumenis, S. Papastefanos, **V. Mateevitsi**, F. Andritsopoulos, N. Achilleopoulos, and A.V. Mikhalev. "Video index and search services based on content identification features." In Broadband Multimedia Systems and Broadcasting, 2008 IEEE International Symposium on, pp. 1-4. IEEE, 2008.

P1 **V. Mateevitsi**, M. Sfakianos, G. Lepouras, and C. Vassilakis. "A game-engine based virtual museum authoring and presentation system." In Proceedings of the 3rd international conference on Digital Interactive Media in Entertainment and Arts, pp. 451-457. ACM, 2008.

WORKSHOPS AND DEMOS

D1 **V. Mateevitsi**, B. Haggadone, J. Leigh, B. Kunzer, and R.V. Kenyon. "Sensing the environment through SpiderSense." In Proceedings of the 4th Augmented Human International Conference, pp. 51-57. ACM, 2013.

PATENTS

P1 J. Lanier, R. Gal, W. Chang, J. A. Porras Luraschi, V. A. Mateevitsi, G. Speiginer and J. Menke. Mixed reality social interaction (2015).

INVITED KEYNOTES, TALKS, PRESENTATIONS, DEMONSTRATIONS

BIOE Class – University of Illinois at Chicago **2017**
Guest Lecture: *SpiderSense.* Chicago, IL. Spring 2017. 60 attendees

Human Augmentics Class – University of Illinois at Chicago **2017**
Guest Lecture: *SpiderSense.* Chicago, IL. Spring 2017. 60 attendees

TEDx University of Illinois at Chicago **2016**
Superpowers are for Everyone 100 attendees

Technori Maker Movement **2016**
SpiderSense 500 attendees

Human Augmentics Class – University of Illinois at Chicago **2016**

Guest Lecture: *SpiderSense.* Chicago, IL. Spring 2016.

Chicago Inno's Innovation U meetup **2015**
Guest Speaker. Chicago, IL. February 26. 60 attendees

Human Augmentics Class – University of Illinois at Chicago **2015**
Guest Lecture: *SpiderSense.* Chicago, IL. Spring 2015.

Workshop at the IEEE Engineering in Medicine and Biology Society **2014**
Recovery Machines. Chicago, IL. August 26. 115 attendees

Adler Planetarium **2014**
Superhero Science. Chicago, IL. July 18. 1,567 attendees

BLUE1647 **2014**
Panel: *emerge/Next U network Event and Entrepreneurship Mini-Hackathon*. Chicago, IL. July 2. 100 attendees

University of Illinois at Chicago **2014**
An Evening with Legacies and Leaders. Chicago, IL. March 4. 425 attendees

MIT Enterprise Forum **2014**
Panel: *Wearable Technology.* Chicago. IL. January 23. 100 attendees

Human Augmentics Class – University of Illinois at Chicago **2014**
Guest Lecture: *SpiderSense.* Chicago, IL. Spring 2014.

Chicago Public Library Innovation Lab Program **2013**
Presentation and Demonstration: *SpiderSense*. Chicago, IL. September 24. 10 attendees

Augmented Reality Chicago Meetup **2013**
Presentation and Demonstration: *SpiderSense.* Chicago, IL. July 29. 30 attendees

Augmented World Expo **2013**
Presentation and Demonstration: *SpiderSense*. Santa Clara, CA. June 4. 1,100 attendees

Processing Chicago Meeting – University of Illinois at Chicago **2013**
Guest Lecture: *openFrameworks.* Chicago, IL. April 2. 20 attendees

E2 Sense Defense Science Research Council **2013**
Electronically Enhanced Sensing Workshop. Presentation and Demonstration: *SpiderSense.* Arlington, VA. March 28. 40 attendees

Human Augmentics Class – University of Illinois at Chicago **2013**
Guest Lecture: *SpiderSense.* Chicago, IL. Spring 2013.

Processing Chicago Meeting – University of Illinois at Chicago **2012**
Guest Lecture: *DIY variable voltage power supply.* Chicago, IL. February 6. 20 attendees

PROFESSIONAL ACTIVITIES

Founding member of the ACM Student Chapter, University of Peloponnese. Tripolis, Greece.
Founding member of the Tripolis Wireless Network. Tripolis, Greece.

SELECTED PRESS

Books

National Geographic Kids - Weird But True! Ripped from the Headlines: Set your "Spidey Sense" tingling. page 56. National Geographic Children's Books. ISBN: 978-1-4263-1514-5 **2014**

Magazines, Newspapers

UIC News: Student's SpiderSense featured on Discovery Science (Vol. 35, No. 20, February 10)	2016
How It Works: Get your SpiderSense tingling (Issue 72, April)	2015
CAP Today: Software expands on 'what you see is what you get (Vol. 28, No 11, November)	2014
Crain's Chicago Business: 20 in their 20s (Vol. 37, No. 18, May 5)	2014
UIC News: EVL's SpiderSense suit grabs attention of National Geographic (Vol. 34, No. 6, October 1)	2014
UIC News: Seeing future of technology in test of Google Glass (Vol. 33, No. 20, February 12)	2014
UIC News: Virtual reality apprenticeships. Cover page (Cover page, Vol 32, No. 13, November 20)	2013
UIC News: Technology's faces of the future. Cover page (Vol.32, No. 12, November 12)	2013
Popular Mechanics (ZAF): Take 'em on, Spidey! (Vol. 11, No. 9, April)	2013
UIC News: With student invention, not seeing is believing (Cover page, Vol. 31, No. 27, April 10)	2013
New Scientist: Virtual Reality creates infinite maze in a single room (Vol. 217, No. 2911, April 06)	
Stuttgarter Zeitung (DE): Technik fur die Sinne (No. 58, March 9)	2013
UIC News: Quotable (Vol.31, No. 22, February 27)	2013
New Scientist: Spidey-Sense Suit Tingles When Someone Gets Too Close (Vol. 217, No. 2905, February 23)	2013

Web

Built in Chicago: Forget Fitbit: these 8 Chicago companies are taking wearables to the next level.	2016
Chicago Inno: The University of Illinois at Chicago Entrepreneurs to Know	2016
Chicago Tribune: Can a Spider-Man-inspired jacket help the blind get around Chicago? (March 23)	2016
UIC News: Student's SpiderSense featured on Discovery Science (February 9)	2016
Chicago Inno: SpiderSense Helps the Blind See, and Caught the Eye of All-American Makers (February 3)	2016
CNET: Microsoft lab working on multiperson augmented reality (October 13)	2015
MIT Technology Review: Microsoft Researchers Are Working on Multi-Person Virtual Reality (October 11)	2015
ChicagoInno: Innovation U: Celebrating the City's Entrepreneurial Pipeline [Event Recap] (February 27)	2015
UIC News: And the Oscar goes to … Larry Hornbeck (February 19)	2015
ChicagoInno: Innovation U: Introducing Chicago Inno's Next Meetup, Presented by the CIE (February 17)	2015
CAP Today: Software expands on 'what you see is what you get (November 17)	2014
ChicagoInno: Are Your Spidey Senses Tingling? This Wearable Tech Lets You Sense When Obstacles Are Near (October 8)	2014
UIC News: EVL's SpiderSense suit grabs National Geographic's attention (October 6)	2014
The Biz Loft Magazine (IT): *SpiderSense*: una giacca dai super poteri (May 6)	2014
Crain's Chicago Business: 20 in their 20s (May 4)	2014
UIC News: Seeing future of technology in Google Glass (February 11)	2014
NewsMonkey (BE): Deze science fictions werden realiteit in 2013 (January 3)	2014
BuzzFeed: 21 Science Fictions That Became Science Facts In 2013 (December 3)	2013
UIC News: Middle-school kids create a virtual future in 3-D (November 19)	2013

UIC News: Computer science students among ‘Fifty for Future’ (November 12)	**2013**
New Scientist: Colour-changing clothes could make tech fashionable (September 19)	**2013**
Deadline: Academy Science and Technology Council Names 2013 Interns (June 19)	**2013**
New Scientist: Virtual reality display lets fire crews see in blaze (June 18)	**2013**
UIC News: UIC computer science student interns at Pixar (April 17)	**2013**
Sohu.com (PRC): 虚拟现实技术将实现有限空间创建“无限迷宫”(April 12)	**2013**
UIC News: With student invention, not seeing is believing (April 9)	**2013**
New Scientist: Virtual reality creates infinite maze in a single room (April 5)	**2013**
The Globe and Mail (CA): Scientists (finally) build Spider-Man suit with ‘SpiderSense’ (March 24)	**2013**
ACM Tech News: Superhero Science: UIC Students Build ‘SpiderSense’ Suit (March 18)	**2013**
Medill Reports Chicago: Superhero Science: UIC students build ‘SpiderSense’ suit (March 13)	**2013**
Gizmag: SpiderSense suit delivers superhuman perception (March 11)	**2013**
An ninh Thủ đô (VN): Quân đội Mỹ sẽ phát triển trang phục "Giác quan thứ sáu"? (March 4)	**2013**
Examiner.com: This suit could have soldiers saying “my spider sense is tingling” (March 3)	**2013**
Engineering.com: SpiderSense: a Suit That Gives Man a ‘Spider Sense’ (March 1)	**2013**
Stuttgarter Zeitung (DE): Technik für die Sinne (March 10)	**2013**
Defense Tech: Researcher develops Spidey-sense suit (February 28)	**2013**
Europa Press (ES): Un traje permite recrear el sentido arácnido de Spider-Man (February 28)	**2013**
CNET: Feel like Spidey in a real-life spider-sense suit (February 27)	**2013**
UIC News: Quotable (February 27)	**2013**
Europa Press (ES): Científicos elaboran un traje que recrea el 'sentido arácnido' (February 27)	**2013**
WP Facet (PL): Sztuczny "zmysł pająka" (February 27)	**2013**
Wired Magazine: Spider-Man Physics: How Real Is the Superhero? (February 26)	**2013**
Mother Nature Network: High-tech Spider-Man suit gives you real-life ‘spidey sense’ (February 26)	**2013**
Digital Trends: We can all be Peter Parker: New suit gives wearer ‘SpiderSense’ (February 25)	**2013**
Bright.nl (NL): SpiderSense-pak laat je je omgeving voelen (February 25)	**2013**
Star.gr (GR): Απόκτησε τις υπερδυνάμεις του Spiderman… φορώντας τη στολή του (February 25)	**2013**
New York Daily News: Scientists create ‘Spider-Man’ suit that gives wearers superhero’s ‘spider sense’ (February 24)	**2013**
Gizmodo (FR): Enfin une vraie combinaison de super-héros (February 24)	**2013**
Gizmodo (DE): Kräfte wie Spider-Man: Ganzkörperanzug verleiht Spinnen (February 24)	**2013**
Gizmodo (AU): You Can Be A Real Superhero With This Spider-Sense Robot Suit (February 24)	**2013**
Gazzetta.gr (GR): Η στολή του Spiderman που σε κάνει... spiderman! (February 24)	**2013**
Forbes: This Suit Gives You A Real Life Spider-Sense (February 23)	**2013**
The Verge: SpiderSense ultrasound suit gives wearers a sixth sense (February 23)	**2013**
Gizmodo: You Can Be a Real Superhero With This Crazy Spider-Sense Robot Suit (February 23)	**2013**
Engadget: SpiderSense ultrasonic radar suit lets you know when danger is near (February 23)	**2013**
Engadget (DE): Sensoranzug SpiderSense verleiht Radar-Wahrnehmung, könnte Radfahrern zugute kommen (February 23)	**2013**
TechnoBuffalo: Amazing SpiderSense Suit Lets You “Feel” Nearby Objects (February 23)	**2013**

Phys.org: Wearable display meets blindfold test for sensing danger (February 23)	2013
Adevarul (RO): Un nou pas spre omul bionic: costumul care ne transformă în omul păianjen (February 23)	2013
Haberler.com (TR): Örümcek Hisleri Gerçek Oluyor (February 23)	2013
Mashable: Body Suit Gives You Real-Life 'Spider Sense (February 22)	2013
The Mary Sue: Grad Student Creates His Own Working Spider-Man Suit (February 22)	2013
Daily Mail (UK): The suit that gives you 'Spidey Sense' just like Spider-Man by tingling when there is impeding danger (February 22)	2013
New Scientist: Spidey-Sense Suit Tingles When Someone Gets Too Close (February 22)	2013
Discovery News: Body Suit Gives You Real-Life Spidey-Sense (February 22)	2013
Medill Reports Chicago: Chicago computer scientists develop tools to help ecologists in Kenya (February 15)	2012
Medill Reports Chicago: Chicago virtual reality lab home to futuristic health class (February 14)	2012

Television, Radio, Podcast

Blind Hour Podcast: w/Victor Mateevitsi (spider-sense.com) Episode 50 (May 11)	2016
Tastytrade: Bootstrapping in America (March 31)	2016
Science Channel: All-American Makers Season 2 Episode 9 (February 3)	2016
ABC7 Eyewitness News: High Tech Tools Used To Fight Crime. Andrew Johnson talks about SpiderSense (September 7)	2014
Fox 32 News: Interview about "Wearable Technology" at the MIT Enterprise Forum (January 24)	2014
NewsTalk 770AM Radio (Calgary, Canada): The Rutherford Show. Interview about SpiderSense (April 2)	2013
CBC Radio (Canada): Eyeopener. Interview about SpiderSense (March 28)	2013
Discovery Channel: The Daily Planet Show. Demoed SpiderSense (March 14)	2013
RuptlyTV: Germany: Spider Sense augmentation lets you react like Spiderman (March 7)	2013
popCultured:Spidey Sense Suit To Make You Like Spiderman? (March 4)	2013
ABC Australia: Gamer News	2013

EXTRACURRICULAR ACTIVITIES

Sail Chicago - Boat Manager for a Colgate 26 boat	2011 - 2012
Chicago Yacht Club – Member of Rhodes 19 racing team	2010 - 2012
Greek National Ice Hockey Team. World Championships Division III. New Zealand	2009
Greek National Ice Hockey Team. World Championships Division III. Luxembourg	2008
National Speed Skating Champion. Athens, Greece	2001
"Cho Dan Bo" belt in Tang Soo Do	

VOLUNTEER WORK

Apprenticeship mentor with SPARK	2013 - 2014

LANGUAGES

Greek
Romanian
English
German