Haptic Vision: Augmenting Non-visual Travel Tools, Techniques, and Methods by Increasing Spatial Knowledge Through Dynamic Haptic Interactions

by

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ABSTRACT

Access to real-time situational information including the relative position and motion of surrounding objects is critical for safe and independent travel. Object or obstacle (OO) detection at a distance is primarily a task of the visual system due to the high resolution information the eyes are able to receive from afar. As a sensory organ in particular, the eyes have an unparalleled ability to adjust to varying degrees of light, color, and distance. Therefore, in the case of a non-visual traveler, someone who is blind or low vision, access to visual information is unattainable if it is positioned beyond the reach of the preferred mobility device or outside the path of travel. Although, the area of assistive technology in terms of electronic travel aids (ETA's) has received considerable attention over the last two decades; surprisingly, the field has seen little work in the area focused on augmenting rather than replacing current non-visual travel techniques, methods, and tools. Consequently, this work describes the design of an intuitive tactile language and series of wearable tactile interfaces (the Haptic Chair, HaptWrap, and HapBack) to deliver real-time spatiotemporal data. The overall intuitiveness of the haptic mappings conveyed through the tactile interfaces are evaluated using a combination of absolute identification accuracy of a series of patterns and subjective feedback through post-experiment surveys. Two types of spatiotemporal representations are considered: static patterns representing object location at a single time instance, and dynamic patterns, added in the HaptWrap, which represent object movement over a time interval. Results support the viability of multi-dimensional haptics applied to the body to yield an intuitive understanding of dynamic interactions occurring around the navigator during travel. Lastly, it is important to point out that the guiding principle of this work centered on providing the navigator with spatial knowledge otherwise unattainable through current mobility techniques, methods, and tools, thus, providing the *navigator* with the information necessary to make informed navigation decisions independently, at a distance.

DEDICATION

Dedicated to my children Chloe, Xander, and Seth for making me a proud father and allowing me to be a role model who demonstrates what hard work, dedication, and overcoming adversity can accomplish. To my parents who gave me unconditional love, to my family and friends for always being there to help me decompress, and to Hayley for her endless patience, selfless support, and abundance of encouragement which got me through the long nights, early mornings, and ultimately to the finish line! Finally, I could not forget about my best friend and life long companion, Dixon who was with me through it all!

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TABLE OF CONTENTS

Page

LIST OF TABLES viii

LIST OF FIGURES ix

CHAPTER

1 INTRODUCTION 1

- 1.1 Breaking down Design Requirements for Effective Electronic Travel Aids 3
  - 1.1.1 Requirement of Safety 3
  - 1.1.2 Requirement of Non-intrusive 4
  - 1.1.3 Requirement of Real-time Feedback 5
  - 1.1.4 Requirement of Discreet 6
  - 1.1.5 Requirement of Intuitive 6
  - 1.1.6 Requirement of Hands Free 7
- 1.2 Summary 8
- 1.3 Conclusion 8

2 NON-VISUAL TRAVEL OVERVIEW 11

- 2.1 Definitions 11
  - 2.1.1 Cognitive Load Theory 11
  - 2.1.2 Cognitive Load 11
  - 2.1.3 Mental Load 11
  - 2.1.4 Mental Effort 11
  - 2.1.5 Performance 11
- 2.2 Cognitive Load and Mental Performance 12
- 2.3 Haptics as a Sensory Organ 13
- 2.4 Spatial Reference Modalities 15
- 2.5 Egocentric Vs Allocentric Reference, Does Sight Matter 15

2.6 Types of Assistive Travel Aids 18
2.7 Non-visual Travel Need Finding Study 19
2.7.1 Survey Findings 20
3 RELATED WORK 22
3.0.1 Smart Cane Augmentation 22
3.0.2 Audio Devices 23
3.1 Indoor applications 24
3.2 Outdoor applications 25
3.3 The Paradigm Shift, Wearables 26
3.4 Computer Vision Implementations 28
4 HAPTIC VISION: AUGMENTING NON-VISUAL TRAVEL 30
4.1 Aim 30
4.2 Hardware Design 31
4.3 Software Implementation 32
4.4 Experimental Design 40
4.5 Procedure 40
4.6 Results 43
4.7 Discussion 47
4.8 Conclusion 48
5 THE HAPTWRAP 51
5.1 Transition To Wearable Haptics 51
5.2 Background and Approach 52
5.3 Apparatus 53
5.4 Hardware Design 54

- 5.5 Software Design 54
  - 5.5.1 Static Patterns 56
  - 5.5.2 Dynamic Patterns 58
- 5.6 Experimental Design 61
  - 5.6.1 Procedure 62
  - 5.6.2 Human Subjects and IRB Approved Study 63
  - 5.6.3 Study Implementation 63
- 5.7 Results 66
- 5.8 Discussion 66
- 5.9 Conclusion 68
  - 5.9.1 Overview 68
  - 5.9.2 Future Work 69

6 THE HAPBACK 70
- 6.1 The HapBack 70
- 6.2 The HapBack 71
  - 6.2.1 Background 71
- 6.3 Apparatus 72
  - 6.3.1 Hardware Design 73
  - 6.3.2 Software Design 74
  - 6.3.3 Software To Hardware Mappings 74
  - 6.3.4 Mapping Distance - Absolute and Relative 76
- 6.4 Evaluation 78
  - 6.4.1 Procedure 78
  - 6.4.2 Results and Discussion 80

CHAPTER Page

6.5 Conclusion 82

7 SYNTHESIZED DESIGN GUIDELINES 84

7.1 The Purpose 84

7.2 Synthesized Hardware Design 85

7.2.1 Apparatus 85

7.2.2 System Input, Hardware 86

7.3 Synthesized Design , Software 92

7.3.1 Prioritization Of OIs In The Navigator's Environment 92

7.3.2 Design Guidelines For Multiple Objects 93

7.3.3 Human In The Loop 94

7.3.4 Haptic Speed, Fast Moving Objects 96

7.4 Conclusion 99

8 FUTURE WORK 100

8.1 Assistive Technology In The Future 100

8.2 Haxels, The Haptic Pixel 102

8.3 Conclusion 107

BIBLIOGRAPHY 111

APPENDIX

A UNIVERSITY APPROVAL FOR HUMAN TESTING 121

LIST OF TABLES

Table Page

4.1 Situational Metaphors for Mapping Elevation/Height to an Object. 34

4.2 Responses to Questionnaire. 46

5.1 Survey Responses for the HaptWrap. 65

6.1 Post-Experiment Questionnaire Responses on Perceived Intuitiveness. 81

LIST OF FIGURES

Figure Page

4.1 Haptic Chair 32

4.2 Mapping of Elevation (Object) to a Two-dimensional Vibrotactile Array. . . . 35

4.3 Mapping of Angles to a Two-dimensional Vibrotactile Display. 36

4.4 Vibrotactile Rhythms for Communicating Object Distance. 38

4.5 Three Examples Demonstrating Display of Multidimensional Patterns. 39

4.6 Mean Recognition Accuracy per Elevation (Object). 45

4.7 Mean Recognition Accuracy per Angular Direction. 45

4.8 Mean Recognition Accuracy per Distance. 45

5.1 A Model Demonstrating the HaptWrap. 56

5.2 An Artist's Rendition of the HaptWrap. 59

5.3 An Artist's Rendition of the HaptWrap for Elevation. 60

5.4 Artist's Eendition of Tactile Rhythms. 61

5.5 Static and Dynamic Mean Recognition Accuracy for the HaptWrap. 64

6.1 Prototype of the HapBack. 72

6.2 Illustration of Five Absolute Feedback Patterns. 76

6.3 Illustration of Relative Feedback Pattern Sequence for 5 Feet. 76

6.4 Identification Accuracy in Absolute and Relative Distance Encoding. 80

7.1 The HaptWrap 3.0 Apparatus 88

7.2 HaptWrap 3.0 Back View Worn. 89

7.3 HaptWrap 3.0 From the Front. 90

7.4 HaptWrap 3.0 Side Views. 91

8.1 Haxel PCB Actuator. 104

8.2 Haxel in Stages. 105

8.3 Haxel Motor Bump. 106

Chapter 1

INTRODUCTION

In 2019 the World Health Organization published the World report on vision [1]. According to the report, it is estimated that 2.2 billion people worldwide are blind or low vision, though approximately 1 billion of these cases are suspected to be preventable or treatable. For the estimated one third of the global population who are blind or low vision Population Reference Bureau (2019) World Health Organization (2018), non-visual navigation is a daily challenge. Even for sighted individuals, characteristics of the environment may obscure vision, making information about obstacles, landmarks, other objects and people very difficult to access through the visual sensory modality. This spatiotemporal information plays a crucial role in the formation of spatial awareness, a necessity for safe and efficient navigation especially through dynamic environments Giudice (2018). For individuals who live or work in non-visual conditions, mobility and an independent lifestyle require the use of sensory substitution such as audio, touch or other senses for building spatial awareness during navigation.

While specialized training is available to equip someone who is blind with the skills and confidence necessary to live an independent life, there are still limitations present by the nature of a visual disability where assistive technology is critical. For example, there are three primary methods of orientation and mobility for non-visual navigators which include: the long white cane, guide dog, and human guide. However, these methods each have significant limitations: For example, white cane users interact with their immediate surroundings through the sweeping and probing of their cane (tool) to locate objects within their reach. Consequently, this process requires travelers to collide with objects in their path

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[1] https://www.who.int/blindness/publications/globaldata/en/

prior to obtaining identifiable information about objects such as texture, size, slope, and position. Furthermore, the white cane has a limited reach for detecting and interrogating objects at a distance (e.g. roughly 5 feet) or above waist height, undoubtedly posing safety concerns stemming from insufficient alert time and leading to reduced response time that may result in collisions. Consequently, a collision of this type often results in injury to areas of the body such as the head (Manduchi and Kurniawan (2011)). Similarly, a guide dog has the primary job of avoiding obstacles. However, by avoiding obstacles, users are unable to obtain useful information regarding their surroundings, limiting their access to landmarks used for wayfinding. Furthermore, a guide dog and human guide both direct the navigator, signaling him or her on which actions to take, rather than providing the navigator with information to allow him/her to maintain autonomy and control over path planning and movement decisions while navigating.

These challenges have resulted in the development of technological solutions designed to assist travel, called Electronic Travel Aids (ETAs). Yet, despite decades of research and development in this field, the adoption rate of ETAs remains quite low relative to traditional approaches. To determine the reasons for these shortcomings, a survey was conducted of 80 individuals who self identify as blind or low vision on the topic of nonvisual travel outlined in Chapter 2. This preliminary survey revealed that, indeed, the long white cane (63%), guide dog (30%), and sighted human guide (5%) were overwhelmingly popular as the three primary forms of assistance used during travel. Where technological solutions were used, often they were abandoned within five or fewer uses due to several limitations, which have been presented as requirements for an effective ETA here:

- *Safety*: The safety of the navigator should be the primary focus of all ETAs to instill confidence in its use.

- *Non-intrusive*: does not disrupt the user's focus (e.g. block a remaining sensory input used for safe travel).

- *Real-time feedback*: provides timely alerting to objects or obstacles (context specific) quickly to maximize action or reaction time.
- *Discreet*: able to be embedded in clothing, worn under clothing, or designed in such a way as to be fashionable without drawing negative attention;
- *Intuitive*: such that the human-computer interactions are ubiquitous, limit the cognitive load placed on the user, and deliver information in real-time in a manner that does not overstimulate the user's senses.
- *Hands-Free*: ETAs which require constant usage of the hand are non-ideal as the hands are necessary for other tasks such as opening doors, and interacting with cross walk signs or other pedestrians.

1.1 Breaking down Design Requirements for Effective Electronic Travel Aids

1.1.1 Requirement of Safety

The primary focus of any travel aid should be on safety of the user. That said, devices that attempt to direct or drive the navigator in a step by step manner, or claim to provide obstacle avoidance, creates a situation where the user has a false sense of security in the assistive technology resulting in potential danger or risk of injury. For example, when the traveler is relying on the ETA for navigation, wayfinding, or obstacle avoidance, any inaccuracies could result in a decision being made based on incorrect or inaccurate information, thus, subjecting him or her to significant danger. Therefore, the optimal approach for implementing a safe, effective, and efficient travel aid is to focus more on information gathering and delivery, rather than directing the user where safety of the individual is at risk. By focusing on gathering information pertaining to the objects or obstacles (depending on the context) then conveying the information to the user, this approach not only increases the navigator's spatial knowledge, but also eliminates the element of danger introduced by claiming to provide obstacle avoidance. More pointedly, if the aim of an ETA is to increase spatial knowledge by localizing Obstacles of Interest (OIs) in the navigators vicinity rather than attempting to direct him or her around said OI, the autonomy to make independent and educated travel decisions is empowered to the user.

1.1.2 Requirement of Non-intrusive

In terms of an assistive travel aid, the aim should first and foremost be centered on safety of the individual using the device. Subsequently, there are many potential barriers to safe travel for non-visual navigators such as the limiting or blocking of one of the remaining sensory inputs critical for obtaining perceptual information. In fact this is a significant design flaw in the majority of electronic travel aids; the design leverages verbal or non-verbal audio as a form of human computer interaction, blocking the primary modality for obtaining environmental information: the sense of hearing. Consequently, a device delivering feedback through the auditory channel disrupts the sense of hearing, effectively rendering it unavailable for other essential tasks such as listening for the flow of traffic, identifying way points (e.g. bus stops, local businesses, or street crossings), and interactions with fellow pedestrians. Although the sense of hearing is an effective modality for communicating detailed information in substitution of the sense of vision, audio and speech are not the only mediums capable of serving as a sensory substitute for vision. In fact, the human body is equipped with several biological sensory organs, but the sense of touch in particular offers a promising alternative modality for discreetly communicating spatial and situational information. The skin has impressive temporal and spatial acuity Van Erp (2005), and is the largest sensory organ found on the human body Montague (1986), capable of providing an expansive surface area as well as multiple locations around the body for mapping visual information to tactile stimulation.

1.1.3 Requirement of Real-time Feedback

Certainly individuals who are blind or low vision are fully capable of traveling safely and efficiently without the aid of an ETA if they have proper training. On the other hand, there are significant limitations inherent in current non-visual travel tools, techniques, and methods where the use of an electronic travel aid could augment the process. For instance, when moving through a confined environment (e.g. store, mall, hotel) having access to near real-time spatial information about objects/obstacles in the vicinity could be the difference between a collision occurring, or being avoided. In other words, timely information pertaining to OIs in the navigators environment, at a distance beyond what the current mobility aid is capable of obtaining, (e.g. long white cane, or guide dog) remains the aspect of travel currently unattainable for someone without the sense of vision. An important point to mention here is the usage of the term *near real-time*. Certainly the human body is equipped with biological sensory inputs for receiving perceptual information including the sense of hearing or touch; however, merely substituting one sensory modality for another does not imply a direct one to one correlation between capabilities. In this way, the usage of *near real-time* was purposeful to indicate the understanding that while the sense of touch is a viable modality for receiving information in the absence of sight, it is not capable of inducing the same reflex response as vision, therefore, the aim of an ETA should be to deliver a *near real-time* solution to maximize the reflex response time afforded to the navigator. Although vision is faster and provides a high resolution of data, results from the experiments conducted by D'Angiulli *et al.* (1998), Lebaz *et al.* (2010), Postma *et al.* (2007), and Arditi *et al.* (1988), suggest that the haptic sense is the optimal modality to communicate visual information to non-visual persons. Moreover, evidence indicates there are no significant impediments to an individual's haptic recognition corresponding to the age of onset of blindness. Finally it should be pointed out that these findings hold true regardless of age of the individual.

1.1.4 Requirement of Discreet

While the stereotypes and stigmas associated with having a disability are outside the scope of this work, it is important to acknowledge the fact that they exist and play a significant role in the cultural norms that influence the thoughts, feelings, and decisions of society. For the sake of this work, it should be stated: the individual should have the choice to decide if they will disclose or not disclose the usage of an electronic travel aid in addition to the cane or guide dog they currently use for a mobility aid. That said, the term discreet here, assumes two different connotations: the first is that of discreet: hidden (e.g. embedded in clothes, under clothes, or otherwise out of sight); and that of discreet: hidden in plain sight (e.g. worn as a fashionable garment, or item to be proud of). The important thing to emphasize in the two connotations outlined here is the choice one has to use the technology as they choose. In making the ETA discreet it affords the user the opportunity to avoid any and all unsolicited, undue, and unwanted discrimination associated with using an assistive technology outside the norms of society and/or the public eye.

1.1.5 Requirement of Intuitive

In the case of a sensory substitution device (SSD), intuitive pertains to the manner in which information is translated, mapped, or otherwise communicated from the source modality to the substitute modality. More pointedly, for the mapping to be intuitive the information being communicated must be easy to understand, natural, and intelligible in the substituted modality as it would have been in the source modality. It should be noted that this does not mean it has to be represented the same way across modalities. For example, the use of situational metaphors could be employed to depict objects in three-dimensional space as in the HaptWrap wearable device by Duarte *et al.* (2019a). The HaptWrap leveraged the egocentric point of reference of the human body in conjunction to the spatiotemporal capabilities of the sense of touch to intuitively represent the distance, angular direction, and elevation or height of an object in a users vicinity through vibrotactile haptic feedback. Additionally, the analogy of a heartbeat rhythm to communicate interpersonal distance by McDaniel *et al.* (2009), identified the impressive recognition accuracy of the haptic system when mapping distance to a familiar rhythm such as a heartbeat. Finally, there are feelings, experiences, and instincts which can be exploited for the purpose of inducing an intuitive mapping. For instance the sensation of chills running up the back of the neck to communicate distance as in the HapBack by Duarte *et al.* (2020). Regardless of the sensory modality being substituted, or the stimuli being employed to convey information, if the mappings are intuitive the recognition and intelligibility will be exceptional.

1.1.6 Requirement of Hands Free

As demonstrated in Chapter 3, there are several form factors by which ETAs have been designed to support non-visual travel. In particular the long white cane form factor has received considerable attention, yet due to the manner the cane is used the smart cane still is not widely adopted as an effective ETA. However, the smart cane form factor does attempt to address the final requirement of being hands free by taking the primary mobility aid (e.g. long white cane) and embedding technology. While this application makes sense it does not take into consideration the substantial beating the cane takes when being used to interrogate OIs, thus, resulting in inaccurate information, broken technology, or unintelligible feedback. In contrast to the smart cane approach, other ETAs attempt to provide spatial knowledge through less ideal form factors such as a smart phone, which requires the navigator to occupy the remaining hand not already occupied by the mobility device being used. Similar to the ears for receiving critical travel information, the hands serve as a sensory input modality used for obtaining tactile information; therefore, devices which occupy the user's hand obstruct his or her ability to interact with objects such as doors or traffic lights. In summary, to effectively augment non-visual travel, a discreet and nonintrusive solution should provide details about the environment at a distance greater than the user already has access to through current non-technical methods, while not intruding on the navigators remaining methods for interaction (e.g. remaining hands free).

1.2 Summary

Although the proposed technology has been designed and tested for individuals who are blind and low vision, the application of this work extends far beyond a non-visual mobility aid. The HaptWrap could be used to provide real-time threat awareness to police officers, fire fighters, or even soldiers as they perform their civil and national duties. In each example men and women are risking their lives to protect and serve others. These situations require intense focus, making them vulnerable to danger outside of their primary focus area. Certainly a visual disability creates a barrier to accessing physical objects present in the environment; situations that require one's full attention and focus also have the ability to impact spatial awareness to immediate surroundings.

1.3 Conclusion

Non-visual travel is a complex task which requires a significant amount of skill, technique, and real-time information to execute safely. A non-visual navigator is confronted with numerous safety concerns every time they set out on a travel route. For example, consider the dynamic nature of a city block where vehicles are passing by, construction is underway, ambient sounds from local businesses are being admitted, and other pedestrians are all around: this type of environment presents several barriers to safe and successful travel. In particular this situation hinders the individual's ability to utilize their primary sensory input for gathering environmental information: the sense of hearing. Consequently individuals who are blind or low vision have the opportunity to learn skills and techniques for interrogating their environment in spite of these environmental barriers. Mino (2011), and Mettler (1994), describe a non-visual travel technique called structure discovery as the ability of the individual to gain a first hand experience of their environment rather than a second hand understanding offered by a third party. Moreover, these authors present structure discovery as not only a travel method, but a problem solving method. When confronted with a seemingly impossible situation where someone's safety is in jeopardy, this is where experience, confidence in one's skills, and the ability to problem solve is critical. In addition to the cane travel skills a non-visual traveler can learn and utilize, assistive technology can also be employed to convey essential information about the environment. For instance, central to the design requirements of the HaptWrap, (Duarte *et al.* (2019b)), and HapBack (Duarte *et al.* (2020)) are to gather real-time information about the user's surroundings, then provide an intuitive mapping of the objects in the user's vicinity through a vibrotactile haptic representation. Specifically these mappings are designed to communicate the distance, angular direction, and height of an OI as it relates to the user's orientation and position. It is important to note that not all individuals will interpret spatial information the same. For example, someone who became blind later in life may have access to spatial knowledge comprised of both an egocentric and allocentric sense of reference; where as, their early blind peers may only have access to an egocentric sense of reference, Ruggiero *et al.* (2009), Postma *et al.* (2007), Arditi *et al.* (1988), and Schinazi *et al.* (2016). Consequently it is critical that the vibrotactile haptic mappings are designed with a primary focus of being intuitive based on human perception and natural instinct. For example, by leveraging the human torso as the interface, the HaptWrap can provide angular direction to the user based on a fundamental ability of the human body, an egocentric point of reference. Furthermore, distance is represented by simulating the familiar sensation of chills up the back by aligning vibrotactile motors along the spine then mapping distances far from the user lower on the back, while distances near the user are up around the neck. In this way we can ensure every user regardless of their age of onset of blindness has access to the spatial knowledge they require to travel efficiently, confidently, and most of all, safely. The work presented in this dissertation documents several iterations of hardware and software developed to address limitations set forth by gaps in the literature pertaining to ETAs claiming to provide spatial knowledge for non-visual travelers.

An overview of the chapters covered in this dissertation are as follows: Chapter 2 begins with a background on non-visual travel; in particular the travel aids used for orientation and mobility, then concludes with findings from the non-visual travel survey and interviews conducted to gain a deeper understanding of the tools, techniques, and methods used from a navigators and professionals perspective. Chapter 3 discusses related works in the field according to form factor, target modality for human computer interaction, and how it aligns with the design requirements for an effective electronic travel aid as introduced above. Chapter 4 introduces the Haptic Chair, which investigates the effectiveness of substituting the sense of vision for the sense of touch in receiving, processing, and identifying objects in three-dimensional space. Chapter 5 presents the HaptWrap, a novel description of haptics in motion through a wearable form factor worn around the torso. Chapter 6 proposes the HapBack, a novel approach for employing an intuitive analogy to represent distance along the spine. Chapter 7 introduces synthetic design guidelines for augmenting non-visual travel by increasing spatial knowledge through the use of dynamic haptic interactions, and Chapter 8 concludes the dissertation and highlights areas of future research to continue building on this work.

Chapter 2

BACKGROUND INFORMATION AND NON-VISUAL TRAVEL OVERVIEW

2.1 Definitions

2.1.1 Cognitive Load Theory

Cognitive Load Theory (CLT) is focused on the optimal methods for transferring newly acquired knowledge and skills to new situations given the limited cognitive processing capacity of the human mind, Paas *et al.* (2003).

2.1.2 Cognitive Load

When the cognitive processing effort exceeds the available cognitive capacity for a given task, Mayer and Moreno (2003).

2.1.3 Mental Load

The aspect of cognitive load pertaining to the performance on a given task based on the subject's prior knowledge of, or experience with said task, Mayer and Moreno (2003).

2.1.4 Mental Effort

The cognitive resources allocated to accommodate the cognitive load required to complete the given task, Mayer and Moreno (2003).

2.1.5 Performance

The measurable aspects of completing a given task characterized by correct or incorrect responses and the time spent on each task, Mayer and Moreno (2003).

2.2 Cognitive Load and Mental Performance

The human body is equipped with five biological sensory organs including: the nose for the sense of smell, ears for the sense of hearing, tongue for the sense of taste, eyes for the sense of vision, and skin for the sense of touch. Each of these sensory input modalities provide the individual with multiple channels for obtaining essential information necessary for interacting with their environment, family and friends, as well as the tools to complete daily tasks. Certainly access to the sensory data the ears, nose, tongue, eyes, and skin provide is critical to the quality of life of humans; however, there is a threshold for the amount of sensory information someone can receive, process, and retain during a single task, which is referred to as the cognitive load, Paas *et al.* (2003). For instance, reading a book while listening to music containing lyrics will quickly overload the mental capacity by stimulating both the auditory and visual channels simultaneously. Similarly to the auditory and visual channels, it is also possible to overload other sensory modalities such as the haptic system. In fact, Traylor and Tan (2002) in an experiment with the NASA KC-135A reduced gravity aircraft found that someone's ability to interpret vibrotactile haptic stimuli in zero-gravity was decreased due to the required mental effort necessary to constantly monitor the position and motion of their body in space. However, the significance of these findings have more to do with the mental processes required with orienting the human body in space when gravity is not applying force, than someone's inability to recognize and process haptic feedback. Moreover, further results show the haptic sensations were received, recognized, and responded to in spite of the burden placed on the individual's cognitive faculties resulting from the sensory overload exerted on the kinesthetic component of the haptic system.

In addition, Cao *et al.* (2007) explored the effects on cognitive load resulting from haptic feedback being applied during surgery with both novice and expert surgeons. The results from their experiment show that subjects performed 36 percent faster and 97 percent more accurately when haptic feedback was provided versus when it was absent. Further observations suggest that haptic feedback can enhance performance, while mitigating the effects of cognitive load when completing a task. It should be noted that each of the aforementioned studies offered support for the use of haptics as a viable modality for communicating critical information in spite of cognitive constraints. Further studies suggest that the haptic system can operate independently in spite of simultaneous stimuli being received from the auditory system, whereas the visual system seems to distract or disrupt the processing capability of the haptic system, Geitner *et al.* (2019). Certainly cognitive load is an essential component to be accounted for in the design, development, and method of human computer interaction employed in the application of an assistive device. Furthermore, there is ample support for leveraging the haptic system as an optimal modality for communicating task specific information, with minimal increase placed on the cognitive load of the individual. Finally, evidence shows that the haptic system operates independently of the auditory system, further suggesting that assistive technology utilizing haptics is an optimal sensory modality for conveying dynamic information without increasing mental processing, thus decreasing cognitive performance of the user.

2.3 Haptics as a Sensory Organ

The human body is equipped with biological sensory organs which can be used to gather sensory information from the environment. However, in the case where one or more of the senses are impaired, the human body has the unique ability to utilize alternative sensory input modalities in place of the impaired sense, by way of sensory substitution. For example, reading is a task primarily done using visual input from the eye(s); however, individuals who are unable to read visually can utilize their tactile sense to read Braille with their fingers. In fact, studies have shown that the occipital lobe, the region of the brain primarily responsible for processing visual information, is activated as a response to reading Braille Théoret *et al.* (2004), Belardinelli *et al.* (2009).

In addition to the sensory substitution that occurs when a blind person reads Braille, there is a similar substitution between hearing and haptics that takes place through the tactile method of communication used in deaf-blindness. More pointedly, deaf-blindness is a dual modal sensory disability in which the individual is both deaf and blind; alternative methods of communication have been developed using a tactile language comprised of gestures and movements Auer Jr *et al.* (2007), Sigafoos *et al.* (2008), Monti and Delnevo (2018). Finally, studies have shown activation of the auditory cortex of the brain in subjects engaged in tactile language, further supporting the human ability to learn and adapt through sensory substitution Bavelier *et al.* (1998), Kujala *et al.* (2000).

Research has shown that there is a cross-modal transformation or reorganization that occurs in the brain when one or more biological sensory inputs is impaired or incapacitated. Additional results suggest that due to the neuroplasticity of the human brain, humans have the ability to exploit alternative sensory input to receive information in spite of having an impairment impacting one or more of their senses Théoret *et al.* (2004), Bavelier and Neville (2002), Kujala *et al.* (2000), Amedi *et al.* (2007), Obretenova *et al.* (2010), Auer Jr *et al.* (2007). Although sensory substitution most notably occurs when one or more of the sensory modalities are impaired or incapacitated, studies have shown there is no significant difference between a participant who is sighted or who is blind in their ability to recognize information through haptic sensory input, Théoret *et al.* (2004). In fact, the haptic system opens up vast potential for sensory substitution technology due to its large coverage area and keen ability to recognize spatial and temporal information. The haptic system, composed of the epidermis and the musculoskeletal system, is responsible for all tactile interactions, movements, and position in space Hale and Stanney (2004). The haptic system combined with the neuroplasticity of the brain and the dynamic nature of the sensory organs make it possible to train the human body to receive and respond to cross-modal stimuli.

2.4 Spatial Reference Modalities

Two frames for the representation of object locations exist: allocentric, wherein an object's location is described relative to that of another object in the environment, or egocentric, wherein an object's location is described relative to the subject McNamara (2003). It has been shown in studies of spatial representation that while individuals with vision utilize both for spatial awareness, those who do not have access to vision generally rely on the latter (egocentric) representation for spatial awareness Ruggiero *et al.* (2009); Patla *et al.* (1991). A growing body of evidence supports that access to spatial information is amodal, in that it does not necessarily require the use of a specific modality such as vision and can be abstracted from this sensory mechanism, allowing for sensory substitution strategies to be employed Schinazi *et al.* (2016). In fact, with proper sensory substitution, it has been shown that individuals who are congenitally blind can reach equivalent spatial representation to their sighted peers Chebat *et al.* (2018).

2.5 Egocentric Vs Allocentric Reference, Does Sight Matter

The ability to obtain spatial knowledge about an indoor or outdoor environment is essential for safe and effective travel. Environmental information consists of knowledge obtained prior to the journey from sources such as a web search, friend or family member sharing information, or viewing a topographic map of the area of interest, and/or during the travel route by tracking landmarks, waypoints, or interacting with objects in the environment. Primarily humans perform navigation using a combination of their egocentric and allocentric sense of reference aggregated from the interaction and interrogation of their surroundings. Although the acquisition of spatial knowledge favors the visual sense, methods, techniques, and tools exist to allow individuals who are blind to efficiently and independently obtain the environmental data they need to navitate effectively. Moreover, research shows individuals who are born blind, or became blind later in life are capable of receiving, retaining, and recalling visual information presented in a tactile format. For instance, D'Angiulli *et al.* (1998) investigated the tactile perception of seven congenitally blind children, and two groups of seven sighted children who were blindfolded, all between the ages of nine and thirteen. Each child was presented a tactile raised line image depicting common objects such as scissors, cup, umbrella, or person, then asked to interrogate the image using their fingers, and finally, were asked to identify it. Results from their studies indicate that much like the sighted children, blind children possess cognitive and perceptual abilities that can be leveraged to recognize an object solely through touch. Further findings revealed that blind children are capable of discriminating between different vantage points of the object when presented tactically. Similarly, Lebaz *et al.* (2010) conducted a study with 20 congenitally blind individuals whose onset of total blindness ranged from birth to 25 years of age. The aim of this work was to investigate the effects on someone's tactile perception based on blindness onset: early or late. An analysis of their results indicated that haptic recognition and the participants' age at onset of blindness were not significantly related. On the other hand, they did discover a correlation between age at onset of blindness and the method used to process the images: visual or non-visual. The discoveries from both of these experiments support the cognitive capability and haptic recognition of spatial depictions, non-figurative images, as well as their ability to discriminate between different vantage points of these tactile representations by children and adults with a varying age of onset of blindness.

This section investigated the tactile perception of congenitally blind children and adults, from both an early onset and late onset perspective of blindness. The goal was to determine the effects of haptic perception as it corresponds to the length of time someone had vision before they became totally blind. In fact results from the experiments conducted by D'Angiulli *et al.* (1998), Lebaz *et al.* (2010), Postma *et al.* (2007), and Arditi *et al.* (1988), suggest that the haptic sense is the optimal modality to communicate visual information to non-visual persons. Moreover, evidence indicates there are no significant impediments to an individual's haptic recognition corresponding to the age of onset of blindness. Finally it should be pointed out that these findings hold true regardless of age of the individual.

The capability of obtaining spatial knowledge is one that favors the sense of vision, yet can be achieved through the sense of touch. This section identifies the methods used to obtain spatial knowledge by individuals who became blind early in life or had a late onset to blindness. Additionally, an examination of the different approaches used to process spatial information (e.g. visual or non-visual), and if there are significant advantages for someone who has had vision versus someone who has never seen to obtain spatial information through the sense of touch. Postma *et al.* (2007), examined how the experience of vision can influence someone's ability and method of processing objects in peripersonal space through haptics. The study evaluated 13 early blind, 17 late blind, and 16 blindfolded sighted individuals. Each participant was required to perform four distinct tasks across five different studies. The first task was to place ten abstract shaped objects into their corresponding holes on a board. This task was performed twice and the participant was timed to correlate efficiency and time to completion. Next the board was rotated and once again the participant was asked to match all ten objects with its corresponding hole, this task also was timed. The third task returned the board to its original position although the board was substituted with one that was absent of holes. In place of the holes the new board had cut outs of the shapes in the same location as they were on the cut out version. The participants were asked to place the objects on the board solely from memory. The final task required the individual to verbalize where each object goes on the board, again from memory.

The aim of this section was to examine and compare the approach used in recognizing, retaining, and recalling objects in peripersonal space by groups of individuals who are blindfold sighted, early blind, or late blind. Across all trials the groups of blind participants scored much higher than the group of blindfolded sighted participants. In the task where the individual was required to describe where the objects were placed there were two striking discoveries. The first was that the late blind group performed better than the early blind group which suggests that the experience of vision in someone's life can improve their ability to recognize, retain, and recall spatial knowledge. The second point to note is in how the late blind and blindfolded sighted groups approached the task of describing the position of where the shapes go on the board; they employed an allocentric approach, whereas the early blind group described the position of each shape from an egocentric perspective. More pointedly these findings imply that vision may play a role in the ability to use allocentric points of reference. Egocentric coding is said to be employed during quick reaction tasks involving movement, while allocentric coding tends to occur in tasks pertaining to conscious perception and spatial memory, Postma *et al.* (2007). Moreover, individuals who become blind early in life, i.e. no visual memory, rely on an egocentric, rather than allocentric sense of reference due to the limited spatial information a non-visual traveler can aggregate from the environment at a distance, Ruggiero *et al.* (2009). Finally, visual experience did not appear to obstruct the participants egocentric sense of reference, nor did there appear to be any correlation between the early or late blind groups and their ability to employ a visual or non-visual method of recognizing, retaining, or recalling the objects along with their positions.

2.6 Types of Assistive Travel Aids

There are three subcategories of assistive technology (AT) designed to augment non-visual travel including: navigation, way-finding, and structure discovery. The most common devices are Electronic Travel Aids or ETAs which are primarily used to gather real-time information about the environment, such as object detection or obstacle avoidance, before presenting the visual information to the user through an alternative modality such as speech, audio, and/or haptic feedback. A low-tech method for augmenting travel is an Electronic Orientation Aid or EOA, similar to a compass, which can be used to provide the navigator with essential orientation information prior to or during travel. Position Locator Aids or PLAs utilize Global Positioning Systems (GPS) to provide way-finding or step-by-step directions to a specified destination, primarily conveyed through speech.

2.7 Non-visual Travel Need Finding Study

Little work has been done to gain an in-depth understanding of the techniques, methods, and tools involved in safe, effective, and independent travel for someone who is blind or has low vision. To address the needs of the target demographic, a human centered study was conducted with 80 individuals who self-identify as blind or low vision, as well as one-on-one interviews with orientation and mobility (O&M) professionals. The aim of this study was to gather a first hand perspective of the techniques, methods, and tools that are used by the navigators themselves. Additionally, the O&M professionals who all hold a certification from an accredited university in orientation and mobility for non-visual travel, provided a theoretical and professional insight on how each tool, technique, and method is used. For the purposes of this work the three terms *tool*, *technique*, and *method* are defined as follows:

- *Tools*: Are the mobility aids used for object detection, obstacle avoidance, and structure discovery such as a long white cane, guide dog, or human guide.
- *Technique*: is the process of gathering navigational information such as locating landmarks, identifying objects, interpreting weather indicators (e.g. sun position or wind), or leveraging ambient sounds in the environment for positioning.

- *Methods*: Are the learned skills used for traveling safely, effectively, and independently, structure discovery, street crossings, and orientation during travel.

2.7.1 Survey Findings

Obstacle avoidance (85%) and the location of landmarks (90%) were the two most common categories of information gathered by responses about their environment when using traditional cane and guide dog travel aids. Sighted/human guides were listed as the second most commonly used resource (71%) for travel behind the cane (94%). Only a few responses indicated the use of ETAs with a human remote assistant (RA), such as Be My Eyes, indicating a large degree of hesitance to adopt technological solutions over traditional devices for obtaining spatial knowledge. When asked about the use of a human guide, (29% sometimes, 28% often, 4% all the time) indicated that this method of travel would be most often utilized in busy environments where a cane or guide dog alone would be difficult. However, miscommunication, inconsistency of communication, missed information from the guide's perspective, and other issues occur, causing many responses to indicate that a cane is often used to add tactile information to the interaction. Many of these comments relate to what can be referred to as the ”intuitiveness” of information provided by a resource; tools whose information is readily and quickly understood with high accuracy by the navigator are generally considered more reliable and used more often. For this reason, 63% of responses rely on the cane as their primary tool of travel, 30% on a guide dog, only 5% on a sighted/human guide and even fewer (1%) on other methods including GPS or other ETA.

It should be stated that the need-finding results obtained in this study guided the research and development of the proposed technologies documented herein, by carefully ensuring that design decisions appropriately addressed the desires and concerns of the target population, as well as adherence to the techniques, methods, and guidelines taught by orientation and mobility professionals.

Chapter 3

RELATED WORK

3.0.1 Smart Cane Augmentation

Although the field of non-visual travel aids has received considerable attention in the past two decades, there remain significant gaps in the limited modalities for which solutions were developed for effective and efficient human computer interaction. For example, the first and one of the most commonly used sensory substitution devices for nonvisual acquisition of spatial knowledge is the cane, which demonstrated the effect of neuroplasticity on spatial learning Nau *et al.* (2015). Consequently, many ETA research approaches attempt to augment the cane with additional spatiotemporal information in order to overcome its limited range and height of detection. These approaches generally augment the white cane with technology such as sonar modules, ultrasonic range finding sensors, or cameras to extract real-time data Zeng *et al.* (2012), Maidenbaum *et al.* (2014), Abeysiriwardhana W.A *et al.* (2018), Chen *et al.* (2017), and Salat and Habib (2019). However, the long white cane was designed as a tool used to collide with poles, trees, chairs, doors, and other OOs the navigator comes in contact with; therefore, the smart cane application fails to be the ideal choice for implementing ETA solutions. Furthermore, the Smart Cane notion carries with it an implication that the tool used to collide with objects, people, and environmental elements is the source of intelligence, when in fact it is nothing more than a low tech tool in comparison to the human user. Nevertheless, the Smart Cane form factor is one area of research and development with no shortage of implementations. For example, one recent approach by Rahman *et al.* (2019) utilizes a laser and camera mounted on the cane for the purpose of detection of obstacles, holes, stairs and other OIs while the individual navigates. Once an OI is detected, a vibrotactile signal is emitted from the cane and felt by the individual. The closer an individual moves to said obstacle, the greater the frequency of vibration. In this case, the laser and camera mechanism improve the sensing range while a simple tactile signal is used to augment spatial awareness.

Additionally, there are Smart Cane devices which utilize audio or speech Sheth *et al.* (2014), Gupta *et al.* (2015), and Saaid *et al.* (2016). Likewise, there are Smart Cane designs implementing haptic feedback applied to the hand, wrist, and/or waist WA *et al.* (2018), Wang and Kuchenbecker (2012), and Faria *et al.* (2010).

Generally, however, smart canes do not provide significantly higher performance at the detection of most obstacles over traditional canes dos Santos *et al.* (2020). Several factors may contribute to this observation. One is that when using the cane to send tactile feedback, the interface is limited to the contact between the hand and cane, which is a rather small surface area with relatively low resolution for a tactile display. Hence, sensitivity to distinct signals may be reduced, and many smart cane approaches instead turn to audio for feedback, the limitations of which are discussed below. Another is that the design and usage of a cane make it difficult to implement technology directly within or on the cane for this purpose as the weight of the cane must be kept to a minimum Arefin *et al.* (2020) and the cane is constantly being swung left and right while walking, making it difficult to use a camera or other sensing mechanism on the device. In summary, the Smart Cane concept has never been an ideal design strategy since the long white cane is used in a very specialized manner and attaching additional hardware to it disrupts the way the cane can be used by non-visual travelers.

3.0.2 Audio Devices

Alternative solutions have utilized audio or audio-haptic cues for the delivery of real-time feedback on spatiotemporal data Hoffmann *et al.* (2018); Metsiritrakul *et al.* (2017);

Presti *et al.* (2019). The advantage of audio as a target modality is that it is highly attuned to distance recognition. Echolocation, for example, is the act of bouncing audio signals off of objects in the environment and using the acoustic properties of the sound's echo to determine size, distance and other attributes of these objects. Echolocation is a commonly used mechanism for audio-based distance detection Thaler *et al.* (2019). Some recent approaches Syed *et al.* (2019); Ye *et al.* (2019) have even chosen to leverage echolocation with audio feedback as an ETA, in an attempt to build upon an existing skill set of a non-visual navigator.

Unfortunately, all interfaces which use audio as a modality for feedback and cueing in the context of nonvisual navigation share one massive pitfall: individuals who are blind or low vision typically utilize hearing as their main sensory channel by which to interact in their environment in the absence of vision, making audio a less than ideal modality for guidance Bharadwaj *et al.* (2019). For example, while navigating outdoors, an individual may be listening for audio cues at a pedestrian crossing or relying for ambient sounds immeted from his or her environment for navigation. In each of these cases, audio cues from the ETA may obstruct the interactions occuring in this sensory channel or induce unnecessarily high cognitive load Martinez *et al.* (2014).

3.1 Indoor applications

The primary objective of indoor navigation is obstacle avoidance in a confined environment. Although the risk of injury is slightly reduced in an indoor environment, the amount of OOs present in a close proximity to the navigator is significantly higher than that of an outdoor environment. Consequently, an ETA providing indoor obstacle avoidance to a non-visual navigator has the task of not only detecting OIs, but also conveying a high volume of information to the user without overwhelming his or her cognitive capacity. One approach for how this could be accomplished is in Drishti by Ran *et al.* (2004) which was proposed for both indoor and outdoor navigation using voice commands and speech output to independently guide non-visual navigators through familiar and unfamiliar settings. Tian *et al.* (2013) incorporated computer vision with Text To Speech (TTS) to assist the user in locating objects such as doors, elevators, and restrooms, in order to familiarize them with their environment. Similarly, D. Jain Jain (2014) deployed a mobile application in a New Delhi national museum to provide step-by-step navigation through the displayed artifacts using audio and speech guidance. Never the less, safe indoor navigational assistance comes with unique challenges not encountered in an outdoor environment since access to the Global Positioning System (GPS) architecture is not available indoors. Lastly, a system capable of providing the precision and accuracy necessary for safe and efficient indoor travel assistance is expensive and difficult to scale.

3.2 Outdoor applications

Outdoor navigation has the added advantage of being able to utilize Global Positioning Systems (GPS) in applications, yet it is not without challenges resulting from the dynamic and fast pace of the outdoor environment. For example, when traveling on busy streets or residential walkways, an assistive device must take into account potential hazards to the navigator such as low-hanging tree branches or traffic markers, and path barriers such as benches, street signs, curbs, stairs, or construction work. The University of Santa Cruz surveyed 300 individuals who identified as blind or low vision to learn the dangers encountered during non-visual travel. The results clearly identified head level accidents as the most significant danger to the individual's' safety; they found that "86 percent of the head-level accidents happened outdoors, with 8 percent of the respondents reporting accidents both indoors and outdoors, and 6 percent only indoors" Manduchi and Kurniawan (2011). The survey results also revealed that tree branches were the majority of outdoor accidents, but vehicles, construction equipment, poles and signs commonly caused accidents as well.

Similarly, work has been done to explore solutions for real-time detection of head-level obstacles using haptic feedback in particular Mann *et al.* (2011), Jameson and Manduchi (2010), and Cassinelli *et al.* (2006). Certainly, head level obstacles are always a concern, but when the navigator has no forewarning of the eminent threat approaching, the concern becomes especially dangerous. Consequently, the field of electronic travel aids is primarily focused on solving these two problems in non-visual travel: obstacle avoidance, and reducing or eliminating head level accidents.

3.3 The Paradigm Shift, Wearables

The last decade has given rise to a paradigm shift which began with heavy handheld devices which gave way to discreet wearable technologies. This shift to wearable technology has introduced new avenues for designing and applying haptic feedback. Initially, wearable haptic technology consisted of bulky factors most commonly worn around the waist in the form of a belt Hao and Song (2010), Rivière *et al.* (2018). However, considerable work has been done to decrease the size and weight of the technology while increasing comfort, ubiquity, and fashion. At the present time haptic wearable devices are smaller than ever and have the potential to be discreet or fashionable. For example, a number of electronic travel aids (ETA) have taken the form of a wristband Wang *et al.* (2016), Kuc (2002), or ring worn around the finger Gaudeni *et al.* (able). Furthermore, work is being done to develop technology that can be worn under clothes, or embedded in clothes as the haptic feedback is applied to the torso of the user as Duarte *et al.* (2019b), Katzschmann *et al.* (2018), and Wang *et al.* (2017b) have shown. Due to the dynamic manner in which the haptic system can receive stimuli, the door has been opened for sensory substitution technology to take the form of discreet wearable devices hidden beneath clothing, or perhaps worn proudly as a fashionable garment.

For example, tactile ETAs outside of cane augmentation have emerged to assist with the task of nonvisual navigation Wang *et al.* (2017a), van Erp *et al.* (2017), Pissaloux *et al.* (2017), Scheggi *et al.* (2014), Lisini Baldi *et al.* (2018). These interfaces, often implemented as wearables, are designed to leverage the spatial acuity of the body's surface at various sites toward touch stimuli Collins *et al.* (2001) to deliver information discreetly. A majority of these implementations either implement static spatial representations such as room layouts as tactile maps on a display (for example, the refreshable top-down display style of Pissaloux *et al.* (2017)) or calculate the optimal path for the navigator to take and then utilize tactile signals to direct the navigator past obstacles (for example, the *turn left*, *turn right*, and *go straight* metaphors in approaches such as Wang *et al.* (2017a)).

However, many of these methods each have significant challenges for adoption. Tactile map views utilize survey-style (allocentric) reference frames which contradict the egocentric preference of spatial mapping Postma *et al.* (2007), such that when used in conjunction with the traditionally egocentric cane, guide dog or human aid, these devices require simultaneous use of both reference frames for navigation. Furthermore, they require that a reliable and sufficiently informed sensing infrastructure is in place for retrieving the entire spatial layout of the environment prior to and during navigation Real and Araujo (2019), which may be impractical when used to navigate outdoors in dynamic environments including traffic, people and other moving parts. Tactile interfaces which provide directions for navigation focus on directing, rather than informing the navigator. In this case, the locus of navigational decision making is on the device rather than the user. These interfaces may be undesirable in that they reduce the autonomy of the navigator Parasuraman *et al.* (1993), Risko and Gilbert (2016), Brunyé *et al.* (2018), and further disrupting the ability to independently form a cognitive map of the environment.

Perhaps the most promising method, based on the requirements for ETA use, is that of van Erp *et al.* (2017), who focused on the provision of spatiotemporal information exhibiting the location of OIs in multiple dimensions: horizontal direction (simply referred to here as direction), distance from the navigator (simply referred to as distance), height (a reference of the height of the OI relative to the navigator) and ID (classification of the OI among several commonly encountered objects during navigation such as stairs). A two-dimensional wearable vibrotactile display on a belt was implemented and utilized to evaluate a tactile language wherein rows, columns, temporal patterns and frequencies were utilized to encode each dimension of this information. It was found that an intuitive depiction of this information requires the design of dimensional encodings that are not only intuitive on their own, but also maintain distinctiveness when combined into multidimensional representations.

3.4 Computer Vision Implementations

Speech, audio, and haptics have all been explored for interacting with the user; however, to develop a complete system, a reliable source for input is essential for it to be successful. Although many sources of input have been explored for gathering environmental information, computer vision (CV) shows promise in that it can quickly and efficiently process real world scenarios with an ever-improving accuracy. Additionally, computer vision algorithms are capable of being applied to a variety of tasks such as: object detection, identifying where an object is in a frame; object recognition ,classifying the type or description of a detected object in a frame; and depth, how far an object is from the lens. The "Rollator Structured System" combined a roller stability device with computer vision mounted cameras and incorporated a haptic belt for communication with the traveler Ni *et al.* (2015). Similarly Limin Zeng Zeng *et al.* (2017) utilized computer vision algorithms to indicate ground or head level obstacles in the user's path of travel. Again, haptics were selected to interact with the user, though audio was also introduced in the form of an audio tone used as a subsequent alert to indicate low hanging obstacles. In addition to computer vision, range finding sensors are often integrated to lessen the processing load of the CV algorithms and provide a much faster response time Mulford *et al.* (2017), Chun *et al.* (2019), Bai *et al.* (2019). In summary, CV algorithms are becoming increasingly more powerful making computers capable of accomplishing feats today which previously were only possible by the human brain, body, and sensory organs.

Chapter 4

HAPTIC VISION:AUGMENTING NON-VISUAL TRAVEL AND ACCESSING ENVIRONMENTAL INFORMATION AT A DISTANCE

4.1 Aim

Independent travel is an essential component of an individual's ability to lead a healthy, successful, and fulfilling life. For individuals who are blind or low vision: however, access to critical safety and way-finding information is limited to the objects within their immediate vicinity. Due to ease of use and potential for identifying obstacles, the long white cane remains the preferred orientation and mobility device for non-visual travel. Moreover, the long white cane is a low-tech mobility aid used to navigate environmental structures present in a traveler's path. For example, the long white cane is held directly in front of the traveler while being swept side to side, tapped, and probed, for the purposes of extracting perceptual information about objects or obstacles (depending on the context) which allows them to identify physical characteristics such as distance, angular direction, texture, and slope. In spite of being able to obtain structural information with the use of the white cane, it should be noted that this information is only available via direct contact with said object since the average length of the cane depends on the height of the individual, (roughly five feet in length). Clearly this poses significant risk of injury to the traveler should the object/obstacle be out of reach of the probing cane, or above the path of the sweeping motion. To address these risks, this work aims to augment current methods of non-visual travel to extend the distance at which a non-visual traveler can obtain information pertaining to the environment for which they are traveling. More pointedly, a two-dimensional matrix of haptic (vibrotactile) actuators were proposed to provide a relative mapping between the angular direction and distance of an object with respect to the orientation and position of the traveler. A preliminary experiment designed to assess the effectiveness of applying haptic stimulation to the lower back in an effort to convey the position of an object in three-dimensional space, suggests haptics as a viable modality to substitute the sense of vision with regard to obtaining spatial knowledge.

4.2 Hardware Design

The Haptic Chair depicted in Fig. 4.1 consists of an ergonomic mesh chair embedded with a 6x8 two-dimensional array of 3 V DC pancake (ERM) motors. Motors are spaced 2 cm horizontally and 4 cm vertically (measured center-to-center). This spacing was chosen based on results of Van Erp's Van Erp (2005) study exploring vibrotactile spatial acuity on the abdomen and back. Actuators are attached to custom printed circuit boards, which are connected over I2C, and controlled using an Arduino FIO.

Figure 4.1: Haptic Chair with close-up of two-dimensional vibrotactile display consisting of six rows and eight columns of vibrating pancake motors.

4.3 Software Implementation

The design of the haptic patterns deployed on the Haptic Chair for the purposes of communicating objects in three-dimensional space to a non-visual traveler through the sense of touch were developed with four primary requirements in mind:

1. Be intuitive and intelligible.
2. Leverage the human body's fundamental ability of egocentric reference as a focal point allowing for angular direction to be perceived relative to the user's orientation.

3. Communicate three-dimensions of spatial attributes through the sense of touch.

4. Provide near real-time feedback to allow for a maximized response time

Software to control the Haptic Chair consists of three separate components; embedded firmware, backend logic with actuation scripts, and client-side Graphical User Interface (GUI). The embedded firmware operates on an Arduino Fio micro processor and is responsible for receiving data, parsing the data into serializable strings, and producing the specified haptic pattern. The backend logic which controls the Haptic Chair is written in the Python programming language, and is responsible for parsing the JSON encoded actuation script, generating a serializable string based on a predefined scenario, and sending the packet to the embedded system for deployment. To convey three-dimensional data through a two-dimensional interface, the following dimensional components were leveraged to create situational metaphors in order to simulate an object in the user's vicinity and indicate where it is located in space;

- *Distance*: 10 ft., 15 ft., 20 ft., 25 ft.

- *Angular Direction*: 90° Left, 45° Left, 0°, 45○ Right, 90° Right

- *Elevation or Height*: Waist Height, Chest Height, Head Height

Each pattern was composed of an integer value corresponding to a distance in feet, angular direction in 45 degree increments, and elevation or height, and stored then in a JSON formatted flat file for rapid prototyping.

Furthermore, the mappings were designed based on situational metaphors first described in terms of dimension: distance from the user, angular direction relative to the user's orientation, and elevation level or height of the object, then further described in metaphorical terms where each elevation is then associated with an object corresponding to its height.

To achieve the highest quality of haptic mappings capable of accurately depicting an object in the traveler's vicinity, each pattern combines a three-dimensional representation of the object described by directing a vibrotactile haptic rhythm to a focused point on the individual's back. For example, three levels of elevation depicted by the rows of the vibrotactile matrix of actuators correspond to three elevations, which then are associated with commonly encountered objects or obstacles depending on the context, during routine travel. More pointedly, these haptic representations are intended to be situational metaphors, and therefore, elevational cues may be mapped to more abstract attributes such as; head height, chest height, and waist height as depicted in Table: 4.1 and Fig. 4.2. Additionally, based on the situational context, patterns could further be used to indicate a bench when walking through a park, clothes rack in a store, or low hanging branches on a hiking trail.

Table 4.1: Situational metaphors for mapping elevation/height to an object

Rows	Elevation/height	Object
Top 2	Head Height	Person
Middle 2	Chest Height	Vehicle
Bottom 2	Waist Height	Chair

Next, is the dimension of angular direction, which employs the human body's fundamental ability of egocentric reference to describe the direction of an object relative to the user's orientation, depicted in Fig. 4.3.

1. 0° is described by activating motors directly in line with the spine;
2. 45° angles are described by activating motors just to the immediate left or right of the egocentric center-point of the spine.
3. 90° angles are described by activating motors at the edges, furthest away from the

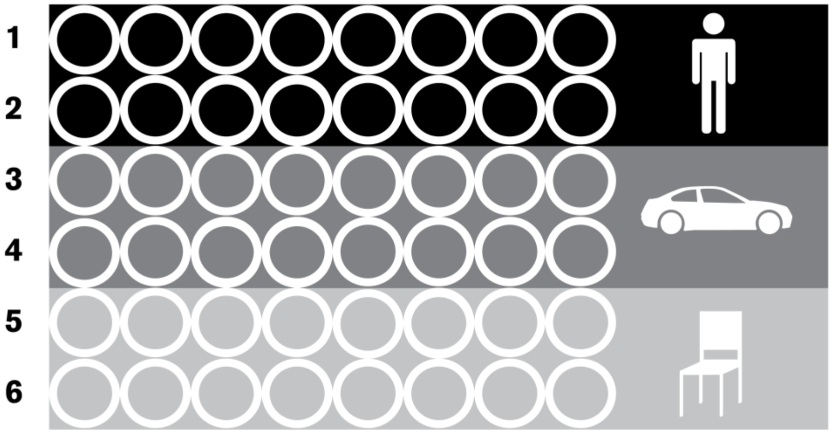


Figure 4.2: Mapping of elevation (object) to a two-dimensional vibrotactile array 'Person', 'Vehicle', and 'Chair' actuate the top (1 and 2), middle (3 and 4), and bottom (5 and 6) rows, respectively.

center-point of the spine.

Finally, distance is represented by a vibrotactile haptic rhythm based on McDaniel *et al.* (2010), where the metaphor of a heartbeat rhythm describes interpersonal distance. According to the heartbeat metaphor, the distance of an object near or far from the individual can be indicated by varying the tempo of the vibrotactile haptic pattern. For instance, objects at a greater distance produce a slower tempo; while, objects nearer to the user increase the tempo, simulating a rapid heartbeat rhythm. It should be noted that on average, non-visual travelers are able to explore the environment five to seven feet at a time, by tapping, probing, and examining objects with the long white cane, although this distance varies since the length of the cane is based on the individual's height.

The study of interpersonal distance across cultures and social groups is known as proxemics Hall (1966). In American culture, there are four zones:

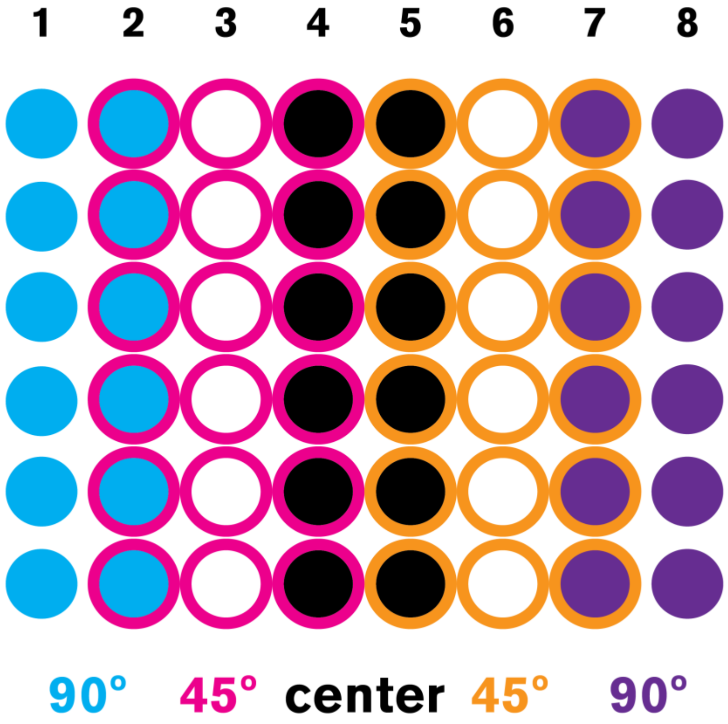


Figure 4.3: Mapping of angles to a two-dimensional vibrotactile display. Assuming number begins at the user's right side when seated in the Haptic Chair, '90° right' actuates the blue columns (1 & 2), '90° right' actuates the pink circled columns (2, 3, and 4), '0°' (center) actuates the black columns (4 & 5). '45° left' actuates the orange circled columns (5, 6, and 7), and '90° left' actuates the purple columns (7 & 8).

1. *Intimate space*: (0-18 inches)
2. *Personal space*: (1.5-4 feet)
3. *Social space*: (4-12 feet)
4. *Public space*: (12 or more feet)

For the purposes of communicating distance while in motion, the above mapping was adjusted to take into account that this work is focused on augmenting current nonvisual travel aids, not replacing them. Furthermore, if an object is within reach of the traveler, it is presumed he or she is already engaged with the object and is no longer in need of the information. Therefore, distance information begins at 10 feet, followed by 15 feet, then 20 feet, and finally, 25 feet, which is no longer conveyed as a heartbeat, but rather, a sonar pulse to convey that the distance of the object is outside interaction space. Fig. 4.4 depicts these heartbeat rhythms.

The aforementioned individual dimensions of distance, angular direction, and elevation are combined using intersection of columns and rows to build a three-dimensional vibrotactile stimulation pattern describing the given object and position. Three examples of how these individual dimensions are combined into a multidimensional representation are shown in Fig. 4.5.

The client side user interface, similar to the backend logic was developed in the Python programming language. The GUI utility was instrumental in executing research studies with individuals who self identified as blind or low vision. In particular, the front end software handled interactions such as triggering patterns to be sent to the Haptic Chair, repeating a pattern, entering the participants response to the haptic pattern, and the loading or saving of the test data.

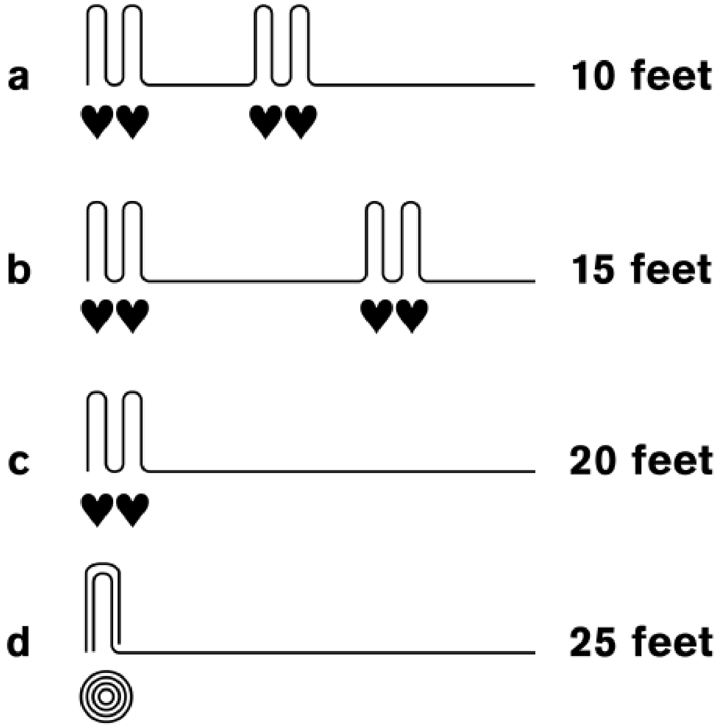


Figure 4.4: Vibrotactile rhythms for communicating object distance. Heartbeat rhythms (a)-(c) consist of a heartbeat separated by varying gaps. A single heartbeat consists of two quick pulses: each pulse is 50 ms separated by a 50 ms gap to simulate a single heartbeat. (a) Heartbeats are separated by a 300 ms gap. (b) Heartbeats are separated by a 650 ms gap. (c) Heartbeats are separated by a 1500 ms gap. (d) Instead of a heartbeat, a single pulse of 50 ms is used to simulate a sonar pulse, with sonar pulses separated by 1500 ms.

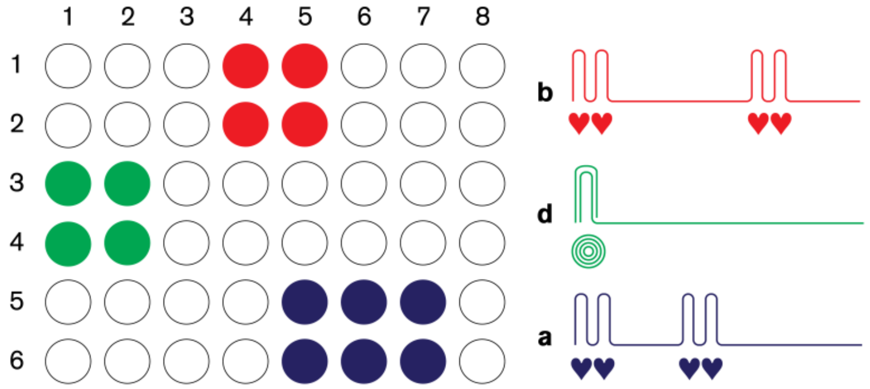


Figure 4.5: Three examples to demonstrate how the proposed multidimensional patterns are displayed. The leftmost motors would be at the left side of your back, and vice versa. The depicted groups of actuated motors (red, green, and blue) each represent a different object at a specific angle and distance. To convey a ‘Person’ at ‘0° (center)’ and ‘15 ft’, motors (red group) at the intersection of rows 1 & 2 and columns 4 & 5 are actuated using rhythm (b). To convey a ‘Vehicle’ at ‘90° left’ and ‘25 ft’, motors (green group) at the intersection of rows 3 & 4 and columns 1 & 2 are actuated using rhythm (d). To convey a ‘Chair’ at ‘45° right’ and ‘10 ft’, motors (blue group) at the intersection of rows 5 & 6 and columns 5, 6, and 7 are actuated using rhythm.

4.4 Experimental Design

The aim of this experiment was to investigate the recognition accuracy of objects positioned in three-dimensional space, when information which is primarily obtained visually is represented tactically. In particular, the study explored how well individuals who are blind or low vision interpret three-dimensional spatial information when communicated through vibrotactile haptic feedback. The preliminary study focused on the recognition of absolute identification (AI), static non-moving objects with the participant seated in the Haptic Chair. By positioning the subject in the Haptic Chair with his or her lower back pressed firmly against the haptic matrix located in the chair back, the experiment could be conducted safely, while testing the hypothesis of how effective and recognizable objects represented in three-dimensional space can be understood when communicated through vibrotactile haptic feedback applied to the lower back. Furthermore, the experiment was only concerned with the recognition of the three-dimensions; distance, angular direction, and elevation, not performance based on the recognition: therefore, it was not necessary to have the individual moving to carry out the study.

4.5 Procedure

Twelve individuals who self-identified as blind or visually impaired were recruited for this IRB-approved research study. Of the 12, 4 were male, 5 were female, and 1 was transgender; 3 acquired blindness later in life, and 7 were born blind.

Individuals participating in the experiment were first introduced to the purpose of the study, given $25 compensation for their willingness to participate, and requested to provide informed consent. Following the introduction to the study each participant completed three stages: familiarization, training, and testing, each described below. In addition to the three stages, participants were asked to complete a post experiment survey to rate the ease of recognition and naturalness of the vibrotactile patterns. The familiarization phase began with introducing participants to the four values indicated for the dimension of distance:

1. '10 ft'
2. '15 ft'
3. '20 ft'
4. '25 ft'

Next, the analogy of a heartbeat was described, and the following example was given: "The heartbeat pattern plays at a faster rate (tempo) the closer an object is to you. For example, at '10 ft', the heartbeat will feel faster than it will at '20 ft'. At '25 ft', the object is so far away, you no longer feel the rhythm as a heartbeat, but instead, a simple sonar pulse." At this time the participant would be presented with all four rhythms in order beginning with a distance of '10 ft' up to '25 ft', with elevation and angular direction remaining constant at Vehicle and 0°, respectively. All three distances were then repeated two more times for a total of three cycles. Participants were permitted to request that a distance be repeated during theE familiarization phase to increase confidence in recognition. The heartbeat rhythm is designed to produce exactly three beats (or in the case of '25 ft', three sonar pulses), to remove the temptation to count beats when determining the distance. Next, the participant was presented the dimension of elevation along with the three associated objects: 'Person', 'Vehicle', and 'Chair'. All three elevations were presented to the user in order from 'Chair' to 'Person' with distance and angle kept constant at '10 ft' and '0°', respectively. All three elevations were then repeated two more times for a total of three cycles. Participants were permitted to request that an elevation be repeated during the familiarization phase to increase confidence in recognition. Finally, participants were introduced to the dimension of angular direction along with the five associated values:

- ‘90° left’
- ‘45° left’
- ‘0° (center)’
- ‘45° right’
- ‘90° right’

All five angles were presented to the user in order from ‘90° left’ to ‘90° right’ with distance and elevation kept constant at ‘10 ft’ and ‘Vehicle’, respectively. All five angular directions were then repeated two more times for a total of 3 cycles. Participants were permitted to request a repeat of an angular direction during the familiarization phase to increase confidence in recognition. Next, the training phase introduced uniquely designed vibrotactile haptic patterns consisting of a combination of the three individual dimensions. All patterns incorporated one component from each of the three dimensions to simulate a situational metaphor commonly encountered during travel, for a total of 60 haptic patterns, (4 distances $\times$ 3 elevations $\times 5$ angles = 60 trials). For example, a distance of 10 feet, angular direction of 0°, and elevation of head height would be conveyed by triggering the vibrotactile actuators directly in line with the spine, in the top row of the matrix, with a rapid heartbeat tempo, depicting a person directly in front of the individual 10 feet away. Finally, each Pattern was randomly selected by the software, then presented as multidimensional stimuli see Fig. 4.5, rather than individual dimensions to assess absolute identification under more realistic conditions such as those that would be encountered in the wild.

The training phase required the participant to evaluate each haptic pattern presented as a situational metaphor, before asserting a response identifying each individual dimension of; distance, angular direction, and elevation encoded in the presented pattern. The experimenter confirmed correct guesses, and corrected incorrect guesses. For incorrect guesses, the pattern was repeated one time before moving to the next trial. A recognition accuracy of eighty percent, (minimum of 48 out of 60 correctly answered), was required before the participant would be permitted to transition to the testing phase. Should a participant not achieve eighty percent or better during the training phase, he or she would be required to complete another bout of training consisting of all 60 trials until the minimum recognition accuracy was achieved, up to three attempts were allowed. The testing phase is similar to training except that all participants complete a single pass of all 60 randomly presented trials, during which the experimenter provides no feedback concerning correct or incorrect guesses, with no repeats allowed.

4.6 Results

Of the 12 participants, the data of two participants were omitted due to experimenter error resulting in data loss during Participant 4's study, and equipment malfunction during Participant 9's study. Of the remaining 10 participants, 600 trials were captured, but due to experimenter error, two of these data points were lost, resulting in the successful recording of 598 trials (participant responses). The vibration motor at column 1, second row from the bottom stopped working beginning with Participant 7 due to a hardware failure. Therefore, experiments involving Participant 7 through 12 did not use this motor, but due to the nature of the mapping, redundant information still allowed participants to recognize patterns involving this motor (the vibration motor could not be repaired as it was not a mechanical failure, but rather, an issue with the actuator 's microprocessor, and given that the Haptic Chair uses custom PCBs with surface mounted devices, the hardware could not be easily repaired). Of the 10 participants, 6 passed the training phase on the first try; the remaining 4 participants needed the second training phase before moving to testing. For the purposes of this experiment, recognition accuracy is defined as the percentage of correctly guessed trials out of total trials.

- Recognition accuracy of the complete, multidimensional vibrotactile pattern, averaged across participants, was M: 57
- Recognition accuracy of the individual dimension of elevation, averaged across participants, was M: 91.8
- Recognition accuracy of the individual dimension of angle, averaged across participants, was M: 74
- accuracy of the individual dimension of distance, averaged across participants, was M: 78.2

Individual accuracies of the three elevations are depicted in Fig. 4.6. Individual recognition accuracies of the five angles are depicted in Fig. 4.7. Individual recognition accuracies of the four distances are depicted in Fig. 4.8. No significant differences were found in the recognition of tactile rhythms representing elevation and distance. Moreover, the high subjective ratings for ease of recognition and intuitiveness of mapping observed in the post experiment survey, shown in Table 4.2, support this. While the average recognition accuracy for angle is lower compared to that of elevation, and distance, it is still impressive considering the limited training participants were exposed to, and the difficulty of identifying absolute positioning, compared to relative positioning, i.e. objects in motion.

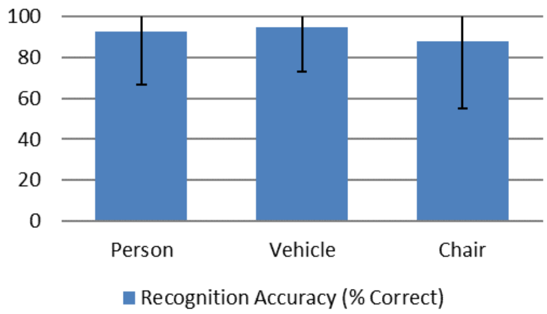


Figure 4.6: Mean recognition accuracy per elevation (object). Error bars are standard deviations.

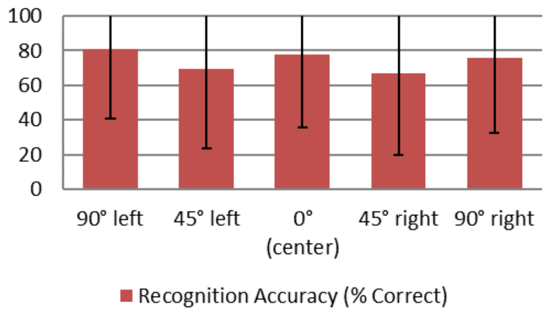


Figure 4.7: Mean recognition accuracy per angular direction. Error bars are standard deviations.

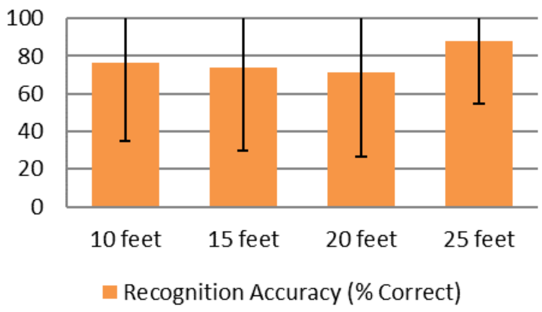


Figure 4.8: Mean recognition accuracy per distance. Error bars are standard deviations.

Table 4.2: Responses to questionnaire. (A) Ease of recognizing individual dimensions. (B) Naturalness of mapping for individual dimensions. Likert scale- 1 (very hard) to 5 (very easy).

Questions	M (A)	SD (A)	M (B)	SD (B)
Chair	4.0	1.0	4.2	1.0
Vehicle	4.4	0.7	4.3	0.6
Person	4.7	0.6	4.3	0.8
90° left	2.9	1.3	3.3	1.2
45° left	2.5	1.1	2.9	1.1
0° (center)	3.9	1.3	4.3	0.9
45° right	2.5	0.9	3.0	1.0
90° right	3.0	1.4	3.5	1.4
10 feet	4.0	1.3	4.3	0.8
15 feet	3.6	0.7	4.0	0.8
20 feet	3.5	0.8	3.7	0.8
25 feet	4.1	0.7	4.2	0.8

4.7 Discussion

Results were computed as follows; a $3 \times 53 \times 4$ design, three-way repeated measures (RM) Analysis of Variance (ANOVA) was conducted to compare the effects of individual dimensions, and interactions between dimensions, on recognition accuracy. All data assumptions for RM ANOVA were met. Three RM ANOVAs were conducted, one for each dependent variable (three recognition accuracies, one for each dimension). An alpha value of 0.01 was selected and divided by the number of dependent variables (k = 3) to account for the multiple significance tests. The final alpha value used was 0.003. For elevation (object) recognition accuracies, no significant differences were found for type of elevation (object), F(2,16) = 4.18, p = 0.035; angle, F(4,32) = 0.65, p = 0.631; or distance, F(3,24) = 0.19, p = 0.902; nor any two- or three-way interactions. These results show that no particular pattern for elevation was more difficult to recognize with respect to other levels. Indeed, the recognition accuracies of Fig. 4.6 corroborate this finding. Moreover, the other dimensions of distance and angular direction had no effect on the perception of elevation, nor were there any interaction effects between dimensions. Overall, participants performed well at recognizing patterns of elevation, indicated by the high subjective ratings for ease of recognition and intuitiveness of mapping, shown in Table 4.2. Once more, no significant differences were found in the recognition accuracies for angular direction, elevation (object), F(2,16) = 1.481, p = 0.257; angular direction, F(4,32) = 1.615, p = 0.194; or distance, F(3,24) = 1.546, p = 0.228; nor any two- or three-way interactions. No main effect for angle type demonstrates that no particular pattern for angular direction was more difficult to recognize, as shown in Fig. 4.7. Still, no main effects for other dimensions, and no interaction effects, demonstrate that variations in other dimensions do not influence the recognition difficulty when variations are introduced in angular direction. While the average recognition accuracy for angular direction is lower compared to that of elevation, these findings are still impressive considering the limited exposure the participant had in interacting with the sensory substitution device (SSD), in addition to the difficulty of absolute identification (compared to relative identification in general), and the number of patterns to recognize (5 angular directions compared to only 3 elevations). In this regard, participants rated the ease of recognition and the naturalness of the mapping lower compared to elevation as indicated in Table 4.2. While recognition accuracy could potentially improve with fewer angular directions, a simplification such as this could increase recognition accuracy, but at the expense of decreasing the system's overall resolution. Lastly, with respect to distance recognition accuracies, no significant differences were found for type of elevation (object), F(2,16) = 0.687, p = 0.517; angular direction, F(4,32) = 2.594, p = 0.055; or distance, F(3,24) = 1.244, p = 0.316; nor any two- or three-way interactions. Similar to the other dimensions, there were no outliers identified as being more difficult to recognize, which is corroborated by Fig. 4.8. Moreover, no main effects for other dimensions, nor interaction effects, were identified, indicating that other dimensions did not influence participants' perception of rhythms. Similar to the average recognition accuracy for angular direction, accuracy is lower compared to that of elevation. Even so, the overall performance is still impressive due to the number of haptic rhythms, limited exposure, and absolute identification task. The average recognition accuracy for distance was higher compared to angular direction (with lower standard deviation), which is indicated by the objective outcome corroborated by the subjective results revealed in Table 4.2. Participants rated the ease of recognizing distance and the naturalness of the haptic mapping higher compared to angular direction on average (M: 3.8 compared to 2.9, respectively.

4.8 Conclusion

The aim of this work was to evaluate the effectiveness of vibrotactile mappings of three-dimensions of spatial information, and the accuracy achieved in recognizing individual dimensions through the haptic modality. To achieve a high recognition accuracy, patterns were composed of situational metaphors describing an object in space in the form of individual dimensions consisting of distance, angular direction, and elevation, applied to the lower back through a two-dimensional matrix consisting of forty-eight vibrotactile actuators. Moreover, each haptic pattern was presented as a combination of dimensions made up from a single component from each of the three aforementioned spatial attributes. For instance, a single situational metaphor pertaining to a person located directly in front of the traveler would be represented by activating the top two rows of the matrix, directly in line with the individual's spine, while simulating a rapid heartbeat rhythm played out through vibrotactile haptic feedback. A preliminary experiment was designed and carried out to assess the viability of the vibrotactile haptic conceptional mappings to represent three-dimensions of an object's position in space relative to the user. Results from this study supports the effectiveness of haptics as a sensory substitution modality for vision when recognizing and understanding static (non-moving objects) in space. Therefore, two primary contributions for future work were identified based on the experimental data:

1. The absolute identification experiment of the current work has shown that the proposed static representations are quickly learned with one or two short training phases, and participant recognition performance demonstrates promise for this design being used in an implementation for relative positioning of moving objects.
2. Furthermore, we suggest static patterns as a foundation for building, training, and recognizing patterns representing objects in motion.

We would like to acknowledge Dr. Troy McDaniel for supporting this research and development through the use of the Haptic Chair. The use of the Haptic Chair proved invaluable to this work for the reason that it was an apparatus which was already developed and allowed for custom software to be developed for individual unique studies. Lastly,

the work conducted with the Haptic Chair made it possible to conduct rapid prototyping of a study which provided a foundation for each subsequent design, development, and experimental research study.

Chapter 5

HAPTWRAP: AUGMENTING NON-VISUAL TRAVEL VIA VISUAL-TO-TACTILE MAPPING OF OBJECTS IN MOTION

5.1 Transition To Wearable Haptics

This work introduces a wearable technology used to augment non-visual travel techniques, methods, and tools through dynamic real-time communication of spatial information at a distance. To address the aforementioned limitations encountered by non-visual travelers this work proposed a wearable vibrotactile haptic device, the HaptWrap, equipped with vibration motors capable of communicating an object's position relative to the navigator's position and orientation, as well as the variation in position as the object moves around the user, Duarte *et al.* (2019b). A preliminary experiment designed to evaluate the effectiveness and recognition accuracy of receiving spatial information from a wearable haptic device worn around the torso, suggests that the sense of touch is an optimal modality for representing objects in motion around a non-visual traveler as a substitute for the visual modality. Furthermore, qualitative results from a post experimental survey suggest that haptic representation of spatial information is not only ideal for representing static and dynamic objects, but also provides the user with a visual understanding of the scenario being depicted through the vibrotactile patterns applied to the body. For example, one participant responded to a pattern titled, "vehicle approaches from left and stops in front", "oh its like my Uber pulling up and I get in." In fact, this was the exact scenario considered when patterns were designed for haptic representation.

5.2 Background and Approach

Duarte *et al.* (2018), previously explored how dimensions of distance, angular direction, and elevation of objects in front of the user could be communicated using haptics applied to the lower back using a two-dimensional array of forty-eight vibration motors (six rows and eight columns). While this previous work was limited to static patterns (not in motion) and an angular direction coverage of 180 degrees in front of the user, results from the pilot study revealed an impressive recognition accuracy when visual information of surrounding objects is mapped to multidimensional vibrotactile patterns for augmenting non-visual travel. To build upon the work done with the haptic chair, while addressing the limitations of the form factor, a wearable device was built to increase spatial awareness in 360° along the horizontal plane and in 3 dimensions: distance, angular direction, and elevation, referred to as the HaptWrap. The apparatus consists of a two-dimensional array of vibrotactile actuators embedded in a waist trainer which is worn around the torso (lower abdomen), Duarte *et al.* (2019b). This work investigates the mapping of objects in three-dimensional space to multidimensional vibrotactile patterns which represent objects in a user's proximity, as a discreet method for increasing spatial awareness and building a cognitive map of his or her environment. It is proposed that by enhancing spatial perception, the HaptWrap will augment non-visual travel by providing a non-intrusive, real-time, and intuitive representation of real world environmental information never before accessible to a blind or low vision traveler.

The sense of touch as an alternative modality for receiving information primarily obtained through the visual modality shows great promise when it applies to discreetly receiving spatial and situational information through haptic (e.g. vibrotactile) stimulation. In particular, the skin as a sensory organ offers a dynamic range of receptors for receiving interactions including; an impressive temporal and spatial acuity, van Erp (2005), and is the largest sensory organ, Montague (1986), providing an expansive surface area for mapping visual information to tactile stimulation. Furthermore, the design of the HaptWrap outlined in this chapter exploits the fundamental egocentric spatial principle, which is the midline plane that divides the human body into bilateral symmetry pertaining to relative left and relative right sides, Vallar *et al.* (1999). Moreover, by leveraging the egocentric frame of reference of the traveler's body, objects can be represented in three-dimensions relative to the user in an intuitive manner. Consequently, this work introduces a novel concept applied to haptic substitution technology: the depiction of dynamic scenes, a novel representation of objects in motion about the user, inspired by the way spatial information is aggregated visually. In fact, experimental results demonstrate the naturalness of the design in intuitive representations of dynamic patterns (e.g. patterns describing movement) compared to static patterns (e.g. patterns describing a stationary object), given the rich complementary and redundant information present in an object's motion as its position varies relative to the user's orientation and position.

5.3 Apparatus

The HaptWrap, depicted in Fig. 5.1 consists of an off the shelf waist-trainer outfitted with a two-dimensional array of haptic (vibrotactile) actuators attached directly to its inner lining. Custom-designed printed circuit boards drive twenty-four (three rows and eight columns) 8 mm eccentric rotating mass (ERM) vibrating motors. A Raspberry PI 3 running custom python code is set up as a server that listens for strings of serial packets sent from a custom built graphical user interface running on the experiment operator's computer. Eight columns of motors are equidistantly spaced horizontally to cover a user's waist in 360°. While horizontal spacing varies based on a user's waist size, vertical spacing of motors remains constant at 2 inches center-to-center. Both horizontal and vertical spacing are well within the limits of vibrotactile spatial acuity for the torso Van Erp (2005).

5.4 Hardware Design

The motors are driven by an 8-bit pulse width modulation (PWM) signal provided by an LED driving integrated circuit (IC) implementing the WS2811 protocol. The PWM signal is connected to the gate of a transistor to increase the amount of current to 80 mA as well as to protect the IC from the back EMF voltages of up to 40 v from the motors. The WS2811 ICs operate on a one-wire repeater protocol, where updates are sent in packets and each IC takes in the first 24 bits through the data-in pin and forwards the remaining through the data-out pin. This allows a large number of motors to be strung together and controlled from a single pin on a microcontroller.

For control, a Raspberry Pi 3 b+ with a quad core arm processor clocked at 1.4 Ghz and 1 GB of SRAM was used. The HaptWrap software was developed using the Python programming language, and interfaces with vibration motors via the NeoPixel library built for the Raspberry PI, distributed by Adafruit.

5.5 Software Design

The HaptWrap, as described under Section 5.3, was used without modification. Custom software was developed in the Python programming language and executed directly on the Raspberry PI. The software consists of backend logic used to randomize and select patterns, execute the patterns, and track results during the experiment. Additionally, a Graphical User Interface (GUI) was designed to ease the experimental procedure as well as allowing for the experimenter to repeat patterns upon request, and to track the participants response. To conduct a controlled study, first static patterns were manually created to represent a single snapshot (frame) consisting of a given object, positioned around the user in a 360° radius, and at a specified distance. Next, a string of static frames were concatenated together to create a series of patterns representative of an object moving through space.

A static pattern was constructed using a list containing three values representing indices identifying an object's distance, angular direction, and elevation or height. For example, each individual dimension is mapped to a haptic actuator as follows:

- *Distance*: is mapped to a tactile rhythm analogous to a heartbeat that varies in tempo
- *Angular direction*: is mapped horizontally, i.e., to one of the eight columns of the HaptWrap
- *Elevation*: is mapped vertically, e.g. to one of the three rows of the HaptWrap

Dynamic patterns were hand-designed to describe real-life situations where objects are encountered by an individual traveling in society. Some examples include a pedestrian walking up behind the traveler and passing to the right around him or her and continuing on; a vehicle passing left to right in front of the user; or approaching a chair in a large room. A total of seventeen dynamic patterns were created and stored as a dictionary containing a list of lists. The construction of a single dynamic pattern was designed by defining individual static patterns that intuitively describe an object in motion. Both static and dynamic patterns were stored in a JSON formatted flat file for rapid prototyping. Finally, all participant data was captured by the software, and written to a separate JSON file vor evaluation. Note, no personal identifiable information was gathered or tracked by the software only data pertaining to the experiment.

Figure 5.1: A model demonstrating how to wear the HaptWrap. Typically, the HaptWrap is worn underneath clothing for discreet use. The HaptWrap is in the form of a waist trainer worn just below the rib cage, and at or above the waist. Based on waist size, the positions of motors are easily adjustable using Velcro.

5.5.1 Static Patterns

Objects in the environment can be stationary (static) or moving (dynamic). For a stationary object's relative position, its static representation for display on the HaptWrap consists of the following: each row of the HaptWrap, from top to bottom, represents a different elevation:

5.5.1.1 Dimensional Mapping of Elevation

- *Head-height*: (e.g., a person)
- *chest-height*: (e.g., a vehicle)
- *waist-height*: (e.g., a chair)

Each column of the HaptWrap represents a different angular direction:

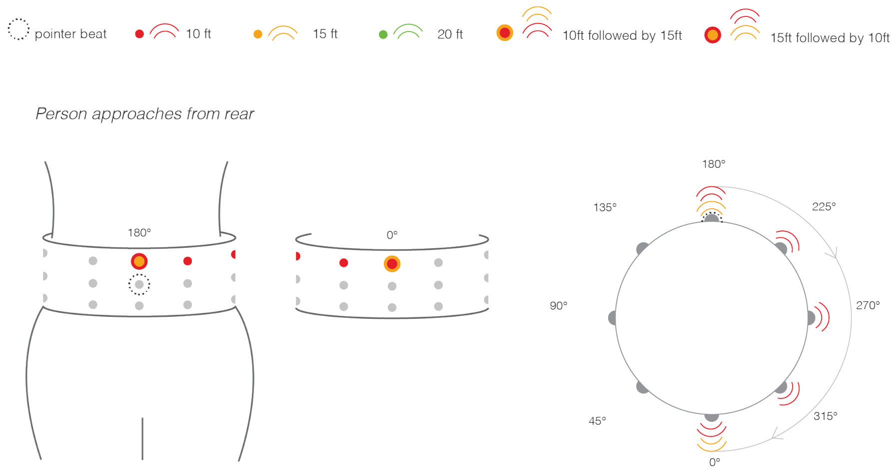
5.5.1.2 Dimensional Mapping of Angular Direction

- 0° (user's midline)
- 45°
- 90° (user's right side)
- 135°
- 180° (user's spine)
- 225°
- 270° (user's left side)
- 315°

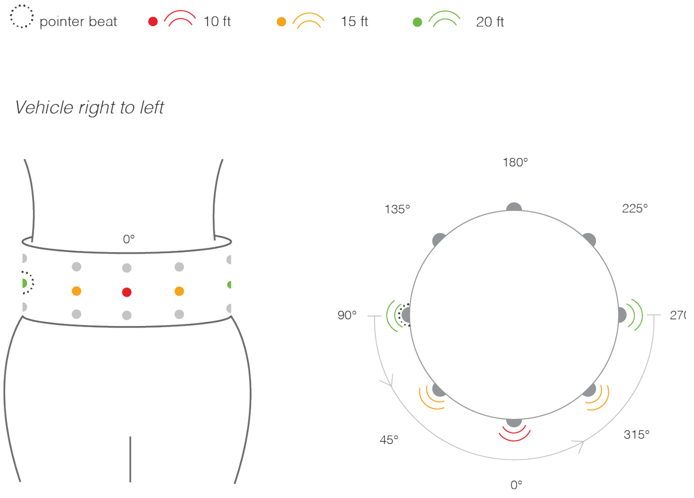
Distance is represented as a tactile rhythm analogous to a heartbeat that varies in tempo inspired by McDaniel *et al.* (2010), where similar patterns were successfully used for conveying interpersonal distance within a vision-based social assistive aid for individuals who are blind. Therefore, three tempos were selected to convey three distances: a slow heartbeat indicates an object is far at 20 feet; a fast heartbeat indicates an object is close at 10 feet; and a heartbeat at a tempo between these slow and fast speeds indicates a distance of 15 feet. Distances of less than 10 feet are not conveyed since the traveler's mobility aid will come into contact with the object at a distance of 5 to 7 feet. In other words, if an object has an elevation of head height (e.g., a low-hanging tree branch), direction of 0° (directly in front of the user), and a distance of approximately 10 feet, the vibration motor at the top row directly in line with the belly-button would execute a heartbeat rhythm with a fast tempo. Fig. 5.4 depicts the mapping of distance to vibrotactile rhythm.

5.5.2 Dynamic Patterns

Objects are considered to be in motion when moving, and/or when the user is moving through his or her environment. Dynamic representations consist of consecutive presentations of an object's position varying relative to the individual's approximate position and orientation, each represented by a series of static patterns executed sequentially. The HaptWrap employs an attention-grabbing vibrotactile pulse, triggered immediately before the presentation of any dynamic pattern. This pointer beat (0.99 s pulse width) serves two purposes: First, the pulse alerts the user of the presence of an object at a specific direction, thereby quickly communicating the "where," followed by information that allows the user to ascertain the "what." Second, the pulse provides a comparative baseline for easing recognition of the different elevations. The pointer beat is always triggered at chest-height. Objects at head-height or waist-height are perceived as shifts upward or downward in elevation, respectively, or no shift when the object's height is waist-height. Fig. 5.2 depicts two examples of dynamic patterns.

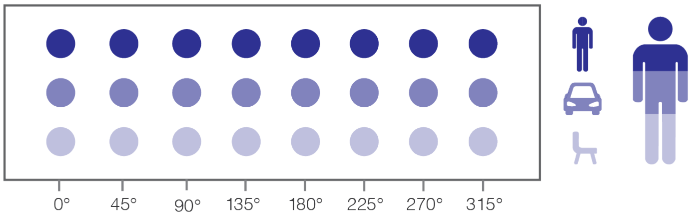


(a) Dynamic Person

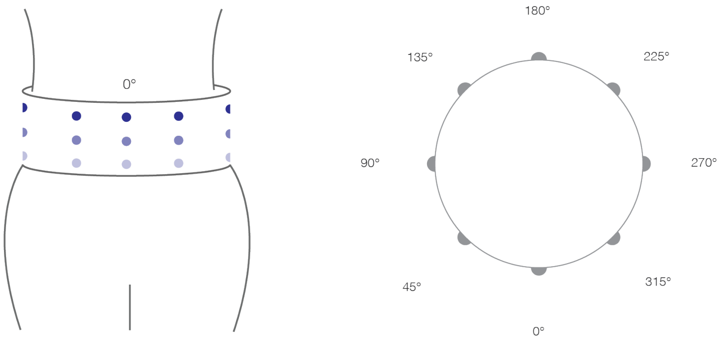


(b) Dynamic Vehicle

Figure 5.2: An artist's rendition of the HaptWrap. In each image, the left side depicts a frontal view of the HaptWrap being worn around the torso; elevation is mapped to vertical body sites. The right depicts a top-view of the layout of actuators around the waist; direction is mapped to equidistantly spaced body sites around the waist in 45° increments.



(a) Elevation mappings



(b) Elevations mapped to rows on the HaptWrap

Figure 5.3: An artist's rendition of the HaptWrap for elevation. The left side depicts a frontal view of the HaptWrap being worn around the torso; elevation is mapped to vertical body sites. The right depicts a top-view of the layout of actuators around the waist; direction is mapped to equidistantly spaced body sites around the waist in 45° increments. The drawing on the right details the mapping of each row of the HaptWrap as it corresponds to elevation; (e.g top row, head-height - person, middle row, chest-height - vehicle, and bottom row, waist-height - chair).

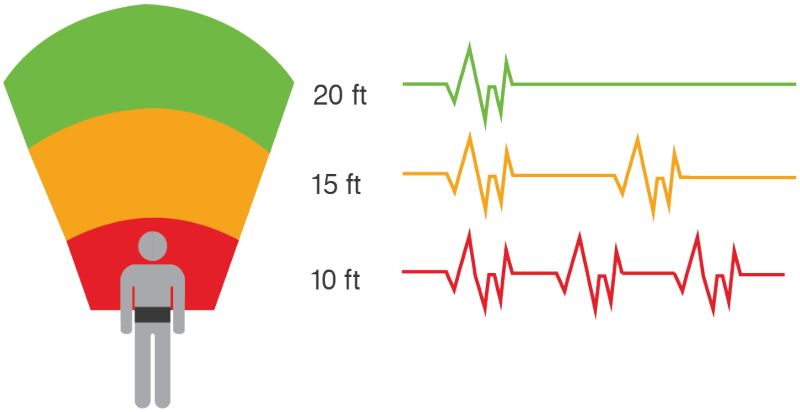


Figure 5.4: Artist's rendition of tactile rhythms. Rhythm design was inspired by the work of McDaniel *et al.* (2010). A single "heartbeat" consists of two beats, each of pulse width 0.55 s, and separated by a gap of 0.06 s. The rhythm for 10 feet separates each heartbeat by a gap of 0.25 s. The rhythm for 15 feet separates each heartbeat by a gap of 0.5 s. The rhythm for 20 feet separates each heartbeat by a gap of 1 s.

5.6 Experimental Design

The aim of this study was to investigate the ease of recognition and intuitive design of the proposed visual-to-tactile mapping of distance, angular direction, and elevation, in both a static and dynamic haptic mapping. In particular, the focus was on identifying any perceptual differences between static and dynamic representations given that most objects in the environment will be encountered under non-stationary scenarios, (e.g. the object and/or the navigator is in motion). With this in mind the study was designed so that participants were randomly presented with seventeen randomly selected dynamic haptic patterns representing the motion of an object around them, or alternatively, his or her motion around a stationary object (depending on the context and/or perception). As described previously, each dynamic pattern depicts a real-life scenario using a series of static patterns, concatenated together to create the situational metaphor, then played consecutively.

5.6.1 Procedure

The experimental procedure consisted of two phases: a static phase followed by a dynamic phase. During the static phase, participants start with a familiarization stage where individual dimensions are introduced (distance, angular direction, and elevation). Next, the participant was presented with twenty-nine static patterns representing an object's position in three-dimensional space, with respect to his or her current orientation and position. Moreover, each pattern was randomly selected by the software for each participant, from a total of seventy-two possible patterns representing all combinations of values for the three dimensions. Upon receiving the static haptic pattern, the subject was asked to identify each dimensional value making up the full multidimensional pattern. Any number of patterns could be repeated upon request, which were tracked by the software to assess performance. Once a response was asserted by the participant, the experimenter would record the response using the GUI to track performance and recognition accuracy. Incorrect guesses were corrected and correct guesses were confirmed to support learning during the static phase in preparation for the dynamic phase.

To assess the naturalness and ease of recognition of dynamic scenes, there was no familiarization phase proceeding the dynamic phase, due to the redundancy between static patterns and dynamic scenes which are composed of a series of static frames. Similar to the static phase, participants were randomly presented with seventeen haptic patterns depicting a real-life scenario commonly encountered in society, then asked to describe the scenario depicted by the haptic interaction in detail, As described previously, each dynamic pattern conveys a real-life scenario using a series of static patterns. Rather than identify each individual dimension, participants were asked to explain, in their own words, what they interpreted. Participants were allowed to request any number of pattern repeats, which were recorded. Accurate descriptions were confirmed, and any inaccuracies were corrected to support recognition during the dynamic phase.

Finally, each participant was asked to complete a post-experiment survey to record subjective feedback regarding the ease of recognizing the situational scenarios depicted, as well as the naturalness of the proposed haptic mappings. The feedback provided from the post-experiment survey was instrumental for analyzing and evaluating subsequent iterations of the technology, haptic mappings, and the effectiveness of the application in terms of communicating apparent motion of OO's through haptic representations.

5.6.2 Human Subjects and IRB Approved Study

A total of eight individuals who self-identified as blind or low vision were enrolled in and completed this IRB-approved research study. One of these subjects became mentally and physically fatigued, therefore was unable to complete the last ten minutes of the study, but the data that had been collected was still usable and therefore included in the analysis. The eight participants consisted of three males and five females, ages ranging from 23 to 74 years old (M: 45, SD: 17). Two participants were born blind, and the remaining acquired blindness later in life. Upon completion of the consent to participate form, the participant was compensated twenty-five dollars for time spent during the study.

5.6.3 Study Implementation

For the purposes of this research study, recognition accuracy is defined as the percentage of correct guesses out of the total number of pattern presentations. For the static patterns, a guess is counted as correct if the participant is able to articulate all individual dimensions (distance, angular direction, and elevation) correctly. Dynamic patterns are counted as correct if the participant is able to accurately describe the change in all dimensions or accurately describe the situational metaphor being depicted:

1. *Distance*: is described correctly (e.g., the person is far away, now walking closer to me, passes me, and is now walking farther away again)

2. *Angular direction*: is described correctly (e.g., the person is at my right side, now moves around me to my front, and now moves around me to my left side)

3. *Elevation*: is described correctly (e.g., person, vehicle, or chair).

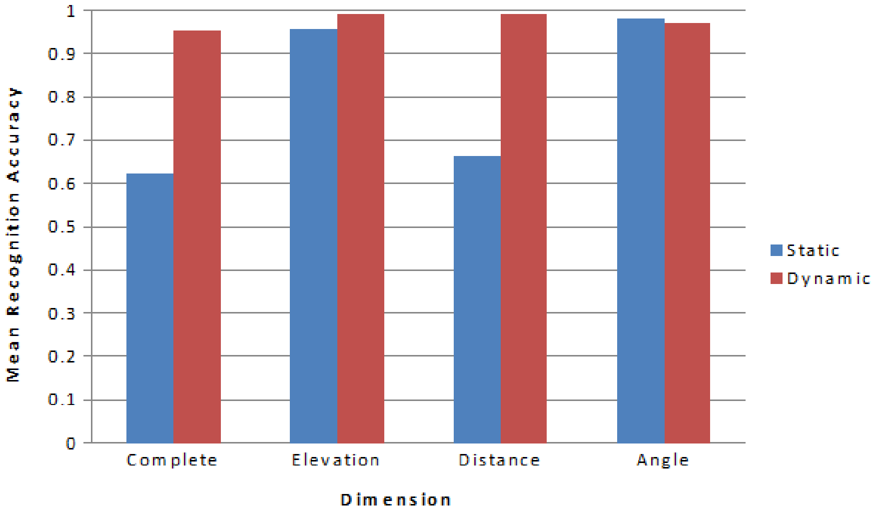


Figure 5.5: Static and dynamic mean recognition accuracy of the proposed multidimensional patterns and each individual dimension including elevation, distance, and angle (direction). Error bars are standard deviations.

Table 5.1: Survey responses. (A) Ease of recognizing individual dimensions. (B) Naturalness of mapping for individual dimensions. Likert scale: 1 (very hard) to 5 (very easy).

Questions	M (A)	SD (A)	M (B)	SD (B)
Waist-Height	4.5	0.7	4.0	1.2
Chest-Height	4.7	0.4	4.2	1.2
Head-Height	4.8	0.3	4.1	1.2
0° (center)	5.0	0.0	4.8	0.3
45° (right, front)	4.7	0.4	4.7	0.4
90° (right side)	5.0	0.0	4.8	0.3
130° (back right)	4.8	0.3	4.7	0.4
180° (back center)	4.8	0.3	4.8	0.3
225° (back left)	4.8	0.3	4.7	0.4
270° (left side)	5.0	0.0	4.8	0.3
315° (front left)	4.7	0.4	4.7	0.4
20 feet	3.4	0.9	3.2	1.2
15 feet	2.5	0.9	2.8	1.5
10 feet	3.0	0.5	3.2	1.2

5.7 Results

For the purposes of the research study, recognition accuracy is defined as the percentage of correct guesses out of the total number of patterns presented. During the static phase, the mean recognition accuracy of the complete, multidimensional vibrotactile pattern (averaged across participants) was M: 62.4

During the dynamic phase, the mean recognition accuracy of the complete, multidimensional vibrotactile pattern (averaged across participants) was M: 95.3

5.8 Discussion

A paired samples t-test was conducted to compare static and dynamic mean recognition performance. An alpha value of 0.01 was used for all tests. A significant difference was found between static and dynamic recognition accuracy for complete, multidimensional patterns, t (7) = -6.717, $p < 0.001$, two-tailed. This result shows that the redundancy inherently embedded in the dynamic scenes becomes more familiar, thus, eases recognition following training on static patterns. While a direct comparison between the recognition of static and dynamic mappings is not possible, (static patterns require participants to recognize exact values of dimensions, e.g., 20 feet, 180°, etc., whereas dynamic patterns require only relative descriptions, e.g., it is farther away, now moving closer, it is to my right side, etc.), this result identifies two key revelations. First, there is a significant correlation between the recognition of the patterns not in motion (static), and those which are in motion (dynamic), about the user, likely due to the redundancy present in the composition of the dynamic scenes. Second, recognition of a dynamic scene did not require a designated familiarization or training phase to foster the learning, recognition, or identification of the situational metaphors being conveyed. Furthermore, while participants are not directly trained to interpret dynamic patterns, they were trained to recognize individual (static) patterns which serve as a familiarization and training of sorts in part to static patterns being employed as the building blocks of dynamic scenes; in other words, all participants completed the static phase before the dynamic phase (i.e., conditions were not counterbalanced). The experiment was intentionally designed to test the recognition of dynamic scenes following a familiarization, training, and testing phase with the static patterns for the purposes of evaluating performance of recognition accuracy of objects in motion based on familiarization with objects not in motion. In fact, this is the use case implementation for the technology,users would receive a small subset of static patterns to familiarize with individual components, then apply the acquired understanding to an infinite set of dynamic scenes. In summary, while learning is taking place between the static and dynamic conditions, and even during the dynamic condition itself due to experimenter feedback, participants are able to achieve a high recognition accuracy in the dynamic condition on complex patterns never encountered previously, demonstrating good generalization between static and dynamic interactions.

There were no significant differences identified in a participants ability to recognize the dimensions of elevation and angular direction between static and dynamic patterns, t (7) = -2.008, p = 0.085, two-tailed, and t (7) = 0.418, p = 0.689, two-tailed, respectively, . These results demonstrate the ease of recognition of dimensions of elevation and angular direction both in isolation or relative to the user's orientation (in motion). On the other hand, a significant difference was identified between static and dynamic recognition accuracy for the dimension of distance, t (7) = -7.372, $p < 0.001$, two-tailed. In particular, participants had difficulty identifying a slight variation in tempo between tactile heartbeat rhythms in isolation, rather, identifying a variation in the tempo of the heartbeat rhythm when presented in relation to other rhythms beating at different tempos, proved to be a much easier task. These results are corroborated by the subjective feedback collected from participants via the post-experiment survey in Table: 5.1. Consequently, these results identified a point of concern in the design of the HaptWrap, in the rhythm used to convey distance in particular. Therefore, the data obtained from the research study and subjective feedback was analyzed and used to design and develop the next iteration of the technology for conveying distance, the HapBack discussed in chapter six.

5.9 Conclusion

5.9.1 Overview

The HaptWrap supported the use of haptics as a substitute modality for conveying spatial awareness to an individual through the sense of touch. Moreover, this work introduced the concept of dynamic objects which are patterns depicting objects in motion around the user. In particular, each of these patterns was composed of three-dimensional components consisting of distance, angular direction, and elevation. Although the Haptic Chair provided support for haptics as a method for communicating objects in space, it presented a gap in intuitively recognizing angular direction. To overcome this limitation in the design of the hardware, a wearable technology was developed capable of representing objects from an egocentric point of reference by applying the haptic stimulation directly to the body wrapped around the torso of the user. In this way the angular positioning of objects was able to be expanded from 180° to 360° around the user. Although the HaptWrap addressed the aforementioned limitation of angular direction from the Haptic Chair, it was not without its own limitations. Distance in particular was identified as the primary dimension users struggled to recognize, specifically, participants reported the heartbeat rhythms with varying tempos were not intuitive to recognize in isolation. In fact, this was a common point of difficulty for the Haptic Chair as well as the HaptWrap, therefore, the next iteration of this work focused on augmenting the manner in which distance was being communicated through intuitive haptic mappings.

5.9.2 Future Work

To overcome deficiencies in the aforementioned technologies, a wearable device referred to as the HapBack was designed to convey distance through discreet, quick, and intuitive haptic mappings. In particular, it was the aim of the HapBack to provide real-time distance information in an intuitive manner: thus, allowing for ease of recognition as well as adequate time to make an informed decision during travel. Following a thorough examination of the literature, no current or former solutions for describing distance using vibrotactile haptic stimulation was discovered. Nevertheless, the results from evaluation of the Haptic Chair and HaptWrap prototypes indicate significant progress toward these goals'. For example, it has been demonstrated how effective haptics are in communicating three dimensions corresponding to an object's distance, angular direction, and elevation in space around the user, through the Haptic Chair study. Additionally, the HaptWrap was able to effectively and intuitively convey static attributes pertaining to an object; as well as dynamic depictions of an object in motion. Finally, this work has yielded promising results for the spatial and temporal accuracy of recognizing multidimensional information through the use of haptic stimulation applied to both the lower back and torso of the user.

Chapter 6

THE HAPBACK: EVALUATION OF ABSOLUTE AND RELATIVE DISTANCE ENCODING TO ENHANCE SPATIAL AWARENESS IN A WEARABLE TACTILE DEVICE

6.1 The HapBack

The HapBack is a device designed to be worn similar to a backpack: wrapped around the shoulders, and positioned down the middle of the back along the spine. The design again leverages the egocentric reference of the body by placing the motors along the center point of the body (along the spine) in the form of 5 rows evenly spaced from the top near the user's neck, down to the lower back just below the ribs, with one motor positioned on either side of the spine. Furthermore, this form factor provides two major points of reference for describing distance: the head and lower back. For example, objects that are far away, i.e. 25 feet, are positioned at the lowest point of the back, while an object positioned close enough to touch, i.e. 5 feet, is located along the user's neck. There were no previous works in the literature designed to communicate haptics in this form factor therefore, two different methods for representing distance were designed to determine the optimal pattern. The first strategy is that of Absolute positioning, which is designed to emit a single vibration at the row corresponding to a given distance, while relative patterns are designed to emit a sequence of vibrations starting from the bottom row, moving up along the back, before ending at the row mapped to the given distance. These two encoding strategies are comparatively evaluated for recognition accuracy and perceived intuitiveness of mapping among ten adult participants who identify as blind or low vision. Following analysis of the results, no significant difference was found between the intuitiveness of the two encodings, thus supporting the hypothesis of distance being conveyed through haptic feedback applied to the back along the spine.

6.2 The HapBack

6.2.1 Background

As outlined in chapter four and five, the Haptic Chair and HaptWrap respectively exposed a critical design flaw in the haptic mapping employed for communicating distance. Specifically, the heartbeat rhythms with the varying tempos used to convey distance was identified in the studies test data, and corroborated by the subjective post-experimental survey as a haptic mapping that was difficult to identify. Furthermore, a second limitation of the haptic mapping used to represent distance was revealed, the heartbeat rhythm took a considerable amount of time to execute, thus, rendering it ineffective as a real-time solution for conveying distance. To address these critical implementation flaws, this study explores the design of an intuitive, discreet, and fast tactile language deployed in a wearable form factor, (the HapBack) for conveying spatiotemporal information to augment spatial knowledge. As a first step in achieving this complex task, the focus of this study was on evaluating the intuitiveness of a novel tactile language capable of communicating the location of an object of interest (OI) in space about the traveler. In particular, two strategies for encoding an OIs distance from the navigator are explored: absolute patterns, which represent an immediate pulse of the object's distance, and relative patterns, which utilize a series of varying pulses in a strategic pattern from a consistent baseline.

As an initial note, the full design of an ETA consists of several components, including a sensing mechanism by which raw visual information is gathered (such as a mounted camera); a processing mechanism by which this information is processed and converted to a multidimensional spatiotemporal representation (such as an image processing mech-

Figure 6.1: Prototype of the HapBack device shown from the front (left) and back (right).

anism which identifies an OI and estimates the distance, angular direction, and height of the OI based on features of the image/video); and finally, communication (the processed spatiotemporal data is communicated to the navigator) through a sensory substitution device (SSD). It should be pointed out that the primary focus of this work is centered on the communication component. Therefore, it should be assumed that at any point, a single OI has been detected and identified, and its egocentric distance from the navigator is known.

6.3 Apparatus

In accordance with the aforementioned requirements for ETA design, a wearable tactile interface was chosen as the design for the current prototype. Named the Hapback, this prototype consists of two back-worn vertical straps each embedded with a single column of five vertically distributed vibrotactile motors as shown in Fig. 6.1. Whereas in the previous HaptWrap implementation, the waist was chosen as the contact site for the haptic display, the back was chosen in this iteration due to the relatively high spatial resolution and stability during motion of the back compared to the waist, forearms and other areas in use while walking Dim and Ren (2017); Karuei *et al.* (2011); Jones *et al.* (2009).

6.3.1 Hardware Design

The HapBack as depicted in Fig. 6.1 consists of ten 3 V. DC pancake (ERM) motors, driven by an 8-bit pulse width modulation (PWM) signal provided by an LED driving integrated circuit (IC) implementing the WS2811 protocol. The PWM signal is connected to the gate of a transistor to increase the amount of current to 80 mA as well as to protect the integrated circuit (IC) from the back EMF voltages of up to 40 v from the motors. The WS2811 ICs operate on a one-wire repeater protocol, where updates are sent in packets and each IC takes in the first 24 bits through the data-in pin and forwards the remaining through the data-out pin. This allows a large number of motors to be strung together and controlled from a single pin on a microcontroller.

The motors are connected in pairs (rows) by one inch elastic bands, draped down the back with one motor on each side of the wearers spine. The vertical straps are connected at the top (near the neck) to shoulder straps similar to the shoulder straps used on a backpack. A one inch elastic band runs along the midline (waist), in addition to a quick release strap located along the chest to ensure all vibrotactile actuators maintain contact with the back of the user. The actuators are attached to custom designed prototype circuit boards (PCB, haxel 8.1), and driven by an ESP-WROOM-32 microcontroller set up as a local server listening for data to be delivered through a serial connection for executing on the HapBack. The system is powered by a portable USB rechargeable battery and can be worn above or underneath clothing to use on-the-go, ensuring discreteness and hands-free portable use.

6.3.2 Software Design

Software to control the HapBack consists of two separate components; embedded firmware, and a client-side graphical user interface (GUI). The embedded firmware operates on an ESP32 micro controlling unit (MCU), and is responsible for receiving data, parsing the data into serializable strings, and producing the specified haptic pattern. Equipped with a hybrid wifi/bluetooth module, low power consumption, and compact design, the ESP32 microcontroller is an ideal choice for interfacing with embedded wearable systems. The role of the ESP32 in the functionality of the HapBack was to set up a local server listening for a connection, authenticating the connection, then receiving data from the target system to execute on the haptic display. Additionally, the embedded firmware handled a significant portion of the logic used to produce the haptic patterns, in particular, the haptic mappings are composed (absolute positioning or relative positioning at a specified distance) based on the string received, then played on the device. The client side user interface was developed in the Python programming language, and was instrumental in executing research studies with individuals who self identified as blind or low vision. In particular, the front end software handled interactions such as triggering patterns to be sent to the HapBack, repeating a pattern, entering the participants response to the haptic pattern, and the loading or saving of the test data.

6.3.3 Software To Hardware Mappings

Distance in this study refers to egocentric distance, measured in feet, from the navigator to an OI. As a continuous measure, this would require an infinite amount of distinct vibrotactile patterns to represent all possible distances. Fortunately, the context of navigation, the length of the long white cane, and the intuitions of proxemics Hall (1962), a study of the regions of interpersonal distance, together form a set of parameters by which this continuous range can be subdivided into discrete categories. Given that the white cane can detect at a range of roughly 4-5 feet, the first distance category represented in this language is 5 feet from the navigator. From there, intervals of 5 feet are used, each representing one full cane length, to reach ranges of the personal, social, public, and beyond public spaces, respectively, as adjustments to the interaction regions defined in American cultural context through proxemics. Therefore, five total distance categories are represented in this approach: 5, 10, 15, 20, and 25 feet. An object's precise location is approximated to the nearest of these five categories. For example, an object at 17.6 feet would be assigned to the 20 ft. distance category. Objects outside of the 5-25 foot range are considered not of interest within the walking context, as anything below 5 feet would be detected by a white cane and anything above 25 feet would require less immediate attention (with the exception of fast-moving objects, which would be moving too quickly for most detection mechanisms to sufficiently warn the navigator). Note that the value of these categories is not itself significant; when applied to a different context, they can be rescaled as necessary.

Each of these five distance categories corresponds to a row of motors on the HapBack device. 5 feet is assigned to the top row, followed by 10 feet in the second row, 15 feet in the third, 20 feet in the fourth, and finally, 25 feet in the bottom row. As the two straps on the hapback are aligned by connecting the motors pairwise on each row, each distance category is therefore mapped to the pair of motors in the corresponding row of the HapBack prototype. When a signal is sent to a particular row, the pair of vibrotactile motors on that row vibrate at the same frequency and amplitude and for the same duration in this implementation. Therefore, the two straps forming the display can effectively be treated as a single column for the sake of mapping.

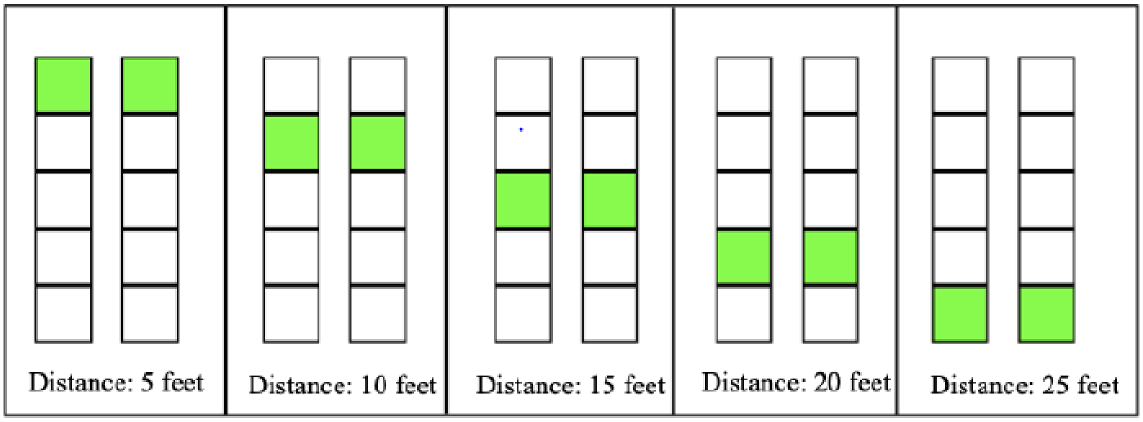


Figure 6.2: Illustration of five absolute feedback patterns.

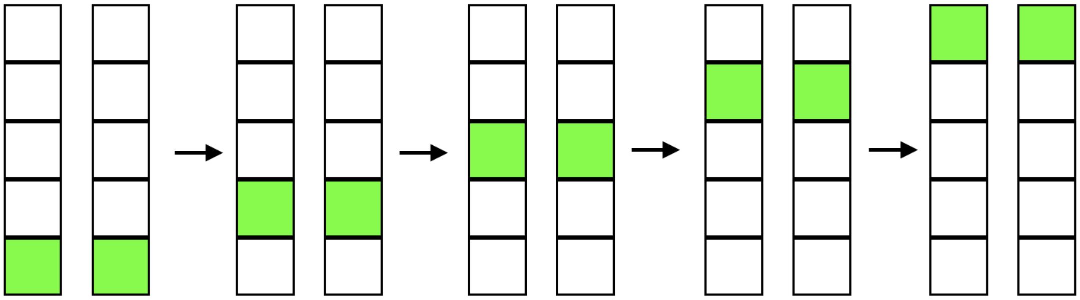


Figure 6.3: Illustration of pattern sequence for 5 feet relative feedback pattern.

6.3.4 Mapping Distance - Absolute and Relative

Two representations are presented in this work to encode a distance in one of the five assigned distance categories: absolute and relative. In the absolute encoding strategy, to communicate a particular distance, the HapBack display pulses its corresponding row once for a preset length of time (roughly 100 ms). For example, to communicate that an object is currently roughly 10 feet away, the second from the top row of the HapBack vibrates a single time. This mapping is shown in Figure 6.2. This representation has the advantage of being rapid as only a single vibration is used in every case, allowing for quick capture of an object's location. However, as the only element distinguishing the five patterns in this case is their vertical location along the spine, it is hypothesized that distinguishing between these patterns, particularly those adjacent to one another, may not be as easy as an implementation in which they were also distinct temporally.

To address this hypothesis, a relative representation was developed as an alternative. The relative representation uses the same mapping of rows to distances, but instead of vibrating only the row corresponding to the communicated distance once, the rows of the HapBack are vibrated in a sequence starting from the bottom row and stopping at the row corresponding to that distance. For example, as shown in Figure 6.3, to communicate that an object is currently roughly 5 feet away, the fifth row is vibrated, followed by the fourth, the third, the second, and finally the top row which is mapped to 5 feet. These vibrations are spaced evenly apart with 0 ms time delay between them (one vibration starts as soon as the previous one stops). In the case of 25 feet, only the bottom row is vibrated, making it equivalent in its absolute and relative representations. The relative encoding therefore allows for a comparative evaluation on the addition of a temporal sequencing element on an individual's ability to distinguish between one distance and another. It should be noted, however, that with the addition of the temporal element in the relative encoding comes two major drawbacks:

1. The spatiotemporal pattern that moves up the back no longer creates a mapping that can be intuitively recognized, instead, requires attention for an extended period of time to track the sequence as it progresses to the given distance mapping. Furthermore, it makes the pattern subject to being counted rather than directly identified which is in contrast to a design requirement for this technology.

2. patterns take longer to present, particularly for 5 feet which is a sequence of five vibrations. This makes the communication of distance significantly slower and may even be impractical when the navigator or OI is in motion. Therefore, a tradeoff of

time consumption for distinctive clarity is hypothesized.

6.4 Evaluation

For this study, the goal of evaluation is to comparatively determine how intuitive the absolute and relative mappings are with respect to the five ranges of distance in the proposed tactile mapping. To assess the effectiveness of the haptic mappings for distance an experimental study was designed to capture both objective and subjective feedback from each participant. For example, objective feedback was measured through recognition accuracy over the range of distances described by the haptic language, and subjectively through a post-experiment survey, as has been shown in previous work McDaniel *et al.* (2009); van Erp *et al.* (2017); Duarte *et al.* (2018).

6.4.1 Procedure

The evaluation was conducted at the Center for Cognitive Ubiquitous Computing laboratory (CUbiC) at Arizona State University along with a private room at SAAVI Services for the Blind in Phoenix. Ten adults (18 years of age or older) who are blind or visually impaired (19 recruited, with 9 dropped due to issues in the experimental setup) participated in the study. All participation was voluntary and each subject signed a consent form prior to participation. The study was approved by Arizona State University Institutional Review Board prior to initiation. All participants were compensated twenty-five dollars for their time spent during the study.

After giving consent, each subject was asked to wear the HapBack device while seated. The experimenter would then transmit tactile patterns directly to the subject through a laptop running the GUI interface, visible only to the experimenter. Each subject was then evaluated on his or her response to two conditions: absolute (in which the absolute pattern mechanism described above was used) and relative (using the relative patterns described above). The ordering of these two conditions were counterbalanced between the subjects to control for ordering effects.

Each condition consisted of a familiarization phase followed by a testing phase. In the familiarization phase, the experimenter presented each of the five patterns in the current condition (corresponding to the five distances) to the subject in an ordered fashion (smallest to largest or largest to smallest). For each pattern, the experimenter first stated the distance that the pattern corresponded to, and then activated the pattern on the subject's HapBack. Once the subject had felt the pattern, he or she could ask for any number of repetitions. For each repetition, the experimenter would once again state the distance of the pattern and then activate it for the subject to feel. No data was recorded during the familiarization phase.

Once all the distances were presented in the familiarization phase, the testing phase would begin. In this phase, a randomized sequence of 15 patterns in the current condition would be presented to the subject, in which each of the five patterns was included exactly three times. Each time a pattern was presented, the subject was asked to identify the distance to which that pattern corresponded. The correct response and subject's response were both recorded. No feedback was given to the subject in this phase, including whether or not the subject's response was correct. A response was scored correct if it matched the intended distance in the mapping, and incorrect if it did not. All requests for a repeat of a given distance during the testing phase was recorded for evaluation of performance on recognition.

Once each subject had completed all four of these phases (a familiarization and testing phase with relative patterns, followed by a familiarization and testing phase with absolute patterns, or vice versa), he or she was then asked to complete a post-experiment questionnaire with four questions, two for each of the testing conditions (absolute and relative). For each condition, the first question asked the subject to rate, on a Likert scale from 1 to 5,

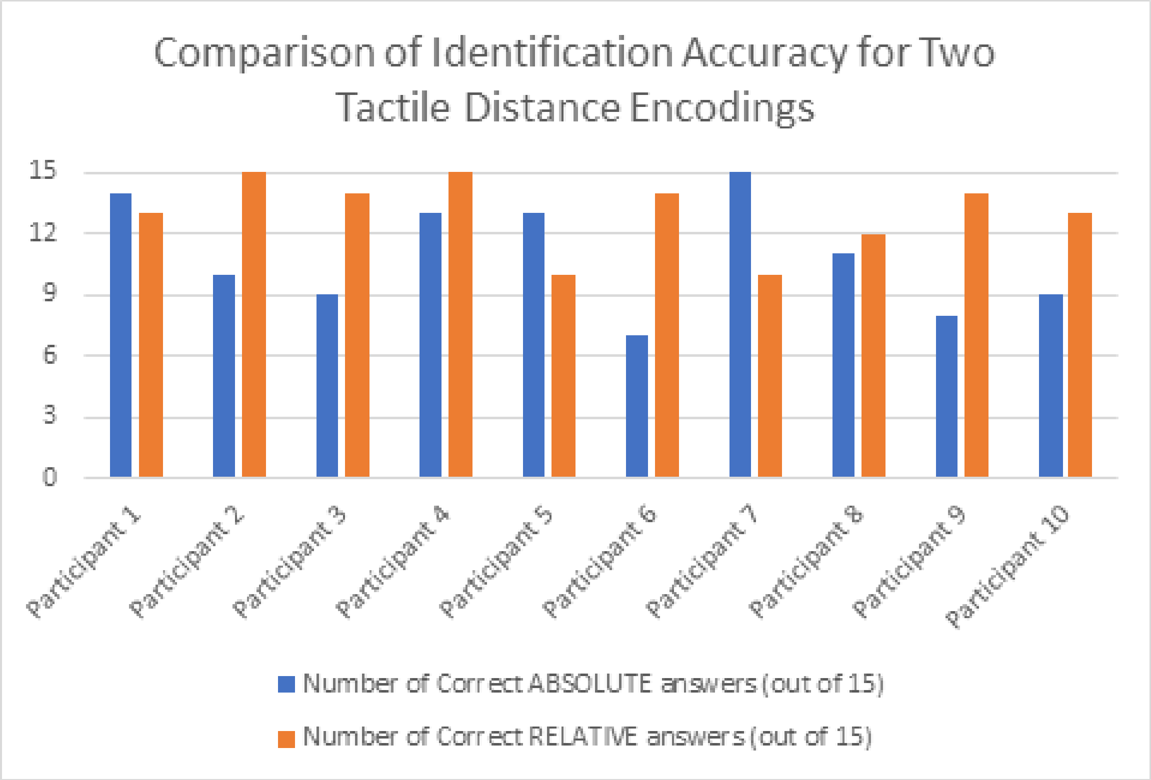


Figure 6.4: Identification accuracy for 10 subjects in absolute and relative distance encoding.

with 1 being *Very Hard* and 5 being *Very Easy*, how natural (intuitive) the mapping was between the vibration patterns for that condition. This was followed by a second question for each condition that asked the subject to explain the ranking he or she chose. This gave each subject a chance to elaborate on why he or she felt a particular mapping was more or less intuitive.

6.4.2 Results and Discussion

The identification accuracy for each subject in each of the two distance encodings, represented as the number of correct distances identified out of fifteen patterns given in each encoding, is shown in Figure 6.4. The average accuracy over all subjects was then col-

Table 6.1: Post-experiment questionnaire responses on perceived intuitiveness of mapping.

Subject	**Absolute**	**Relative**
1	4	5
2	3	5
3	2	5
4	5	5
5	3	5
6	4	5
7	4	3
8	4	1
9	4	4
10	4	4

lected for each condition and used to determine the intuitiveness of that encoding. Results indicated that both absolute and relative encodings were quite intuitive, with 73% response accuracy (st. dev. 0.182) for absolute patterns and 87% accuracy (st. dev. 0.122) for relative patterns. These are impressive response accuracies given that the subjects did not receive any prior training other than the brief familiarization phase to learn the mappings. No statistically significant difference was found in response accuracy between the two modes based on a paired two-sample t-test (P = 0.135 two-tail, $\alpha = 0.01$), suggesting that both approaches were equally viable for the subject sample.

Post-experiment questionnaire responses (out of 5) for perceived intuitiveness of mapping are shown in Table 6.1. Subjects reported an average intuitiveness score of 3.7 (st. dev. 0.823) for absolute patterns and 4.2 (st. dev. 1.317) for relative patterns. No statistically significant difference was found in perceived intuitiveness of mapping between the two modes based on a paired two-sample t-test (P = 0.380 two-tail, $\alpha = 0.01$), supporting the findings from the experimental phases. However, subject explanations for their questionnaire scores in the open-ended questions provided some further insight into the differences between how the two were felt. Some subjects reported some difficulty in discerning between adjacent patterns/distances in the absolute condition, but found it easier in the relative condition because they could count the number of vibrations and use that as a backup strategy to identify the distance in that condition. Many reported that this difficulty was alleviated over the course of the experiment as they found it easier to identify the patterns that were presented later in each phase.

6.5 Conclusion

Based on the results shown during evaluation, the HapBack prototype and tactile language presented serve as an intuitive method by which distance can be communicated in real-time as a part of a novel ETA for spatial awareness. Furthermore, the wearable, discreet, hands-free and non-audio nature of the HapBack prototype, as well as the provision of spatiotemporal information rather than predetermined path directions, afford the navigator a greater sense of control, privacy and usability. Given that no significant difference could be found between absolute and relative encodings, and both were considered highly intuitive on first use by subjects, it is proposed that the absolute encoding be utilized in most cases as it has the advantage of utilizing only a single tactile pulse for each distance, ensuring speed of delivery and allowing for more practical use in dynamic environments. Also the goal is to reduce cognitive load by requiring metal processing when using the device, therefore if navigators are counting beats to identify distance the haptic mapping is not adhering to the design requirements.

The evaluation performed here serves a preliminary purpose in the intuitive encoding of a single dimension of spatiotemporal information. However, to achieve spatial awareness, this dimension of tactile patterns must be integrated with other dimensions of information (direction, height) to form complete, multidimensional representations of OI location. Integration of this mapping with the effective components of the previous mapping used in the HaptWrap requires careful consideration of the role of rows in the tactile display, as both distance in the HapBack and height in the HaptWrap are mapped to rows in their corresponding tactile language. Future work will evaluate how it might be possible to combine these elements while maintaining intuitiveness without the use of a temporal element on a two-dimensional display. The integration of multiple wearables (the HapBack in combination with the HaptWrap) is also under consideration, with careful attention toward the effect of multiple displays on cognitive load during a navigation task. The following chapter will present synthetic design guidelines for an effective electronic travel aid including a description of a synthesized prototype composed of the HaptWrap and HapBack integrated into a single form factor. Lastly, the design guidelines presented will cover how the integration of these two devices can be combined while maintaining minimal mental processing during use.

Chapter 7

SYNTHESIZED DESIGN GUIDELINES FOR INCREASING SPATIAL KNOWLEDGE THROUGH DYNAMIC HAPTIC INTERACTIONS

7.1 The Purpose

This journey began with one main goal: to augment non-visual travel by increasing spatial awareness through real-time and intuitive haptic representation of objects in the user's environment. In particular, the aim of this technology was to be *non-intrusive*, e.g. not to hinder another sensory modality necessary for safe travel; *discreet*, e.g. able to be embedded in or worn under clothing for comfort and concealment; *real-time*, e.g. to rapidly alert the user to maximize response time; and *intuitive*, e.g. not to increase the user's cognitive load. To accomplish this, three separate devices have been proposed to fulfill these requirements as well as address the gap in the literature for ETAs designed to augment non-visual travel. Moreover, each iteration focused on resolving limitations identified in the previous design, always moving toward the primary goal of augmenting non-visual travel by increasing the distance at which spatial knowledge of objects and their position located in the environment can be obtained. The natural next iteration of this technology is to combine the HaptWrap (Chapter 5), and HapBack (Chapter 6) into a single wearable design capable of delivering discreet, near real-time, and intuitive mappings of OIs in the navigator's vicinity. Thereafter, the synthesized technology should be deployed to a limited number of participants to test the technology over an extended period of time in a longitudinal study. The purpose of this chapter is to outline the successful components of the technologies documented in this dissertation, then, synthesize the observed key components into design guidelines for developing an effective electronic travel aid capable of increasing spatial knowledge at a distance through the use of dynamic haptic interactions.

7.2 Synthesized Hardware Design

The HaptWrap 3.0 is an electronic travel aid designed to incorporate the successful components identified from each iteration of the haptic vision work presented in the chapters of this dissertation. The HaptWrap 3.0 apparatus is a synthesized wearable form factor composed of two separat devices synthesized to produce a single solution: the HaptWrap, (e.g. worn around the torso between the ribs and waist line) and HapBack, (e.g. worn down the center of the back along the spine). Results from research studies designed to test the effectiveness, naturalness, and ease of use for both devices, identified each as optimal form factors for discreetness, comfort, and non-intrusive placement on the body. More pointedly, each of these points adhered to the design requirements for an effective ETA outlined above.

7.2.1 Apparatus

The HaptWrap 3.0 as depicted in Fig. 7.1, is constructed of a three inch nylon elastic band, with twenty-four haxels embedded in three rows and eight columns along the inner-lining, to be worn around the torso between the ribs and waist line, per the users preference for comfortability.

In addition, there are one inch nylon elastic bands running vertically along the left and right side of the spine, fastened to the waistline component, and attached to three inch nylon bands that drape around the shoulders similar to backpack straps. Embedded in the vertical straps are five rows of two haxels (total of ten actuators), evenly spaced, beginning from the neck-line and extending along the spine to the lower back. Each row of the vertical section corresponds to a distance beginning at five feet (e.g. along the neck-line), up to twenty-five feet (lower back), with ten, fifteen, and twenty feet values evenly spaced between. The vertical straps with the horizontal rows used to communicate distance can be seen in Fig. 7.2, and the straps that run along the user's torso use to communicate direction and height are depicted in Fig. 7.4. In addition to the custom haptic actuators, the HaptWrap 3.0 incorporated state-of-the-art microcontrollers and a mobile graphic processing unit (GPU) in the form of four Raspberry PI 0W's, and a Jetson Nano single board GPU.

7.2.2 System Input, Hardware

The Raspberry PI 0W board is equipped with a 1GHz, single-core CPU, 512MB RAM, 802.11 wifi and bluetooth (BLE) module, and a CSI camera connector which is instrumental in the live video capture task it is intended for. Additionally, a 120 field of view (FOV) camera module is connected to the onboard CSI header of all PI microcontrollers. The Jetson Nano consists of a 128-core Maxwell GPU, Quad-core ARM A57 @ 1.43 GHz CPU, and 4 GB 64-bit RAM. The Nano single board GPU is tasked with executing deep convolutional neural-network models trained for object detection, person detection, and pose estimation to identify the orientation of the actor relative to the user. A combination of the video capturing of four PI boards positioned on the chest, left and right shoulder, and back of the user, and the execution of powerful computer vision algorithms processed on the Nano provides a complete system capable of capturing live video feed of a navigator's environment in a full 360° around the user.

This combination of hardware, and software attempts to answer a critical question: "how does the system know which OI to indicate to the user when there are multiple OI's in the user's vicinity?" Certainly there are technologies and methods for conveying a single object, but as pointed out this is not an accurate scenario when traveling on public streets where there are multiple OI's present. For instance, a public street introduces external distractions in addition to potential obstacles such as: vehicular traffic, pedestrian foot traffic, sidewalk clutter, and ambient sounds. To safely and efficiently navigate through this type of environment the navigator would require three essential pieces of information: a target destination, path of navigation, and objects/obstacles (e.g. context specific) which could pose as barriers along the route. Consequently this is not an easy task due to the dynamic aspect of the environment which increases the potential for collision based accidents, and obstructions in the travel route. In particular this environment introduces the situation where not only a single object is present: but rather, several objects around the user all of which could pose as obstacles in the traveler's path. At this point it should be stated that the purpose of this work is not to serve as an obstacle avoidance solution as many related works have attempted, De Felice *et al.* (2007), Tan *et al.* (2003), Baldi *et al.* (2017), and Forsyth and MacLean (2005). On the contrary the aim of this work is to augment non-visual travel by increasing spatial awareness by gathering real-time information about the traveler's environment then conveying the distance, angular direction, and height of objects in their vicinity through an intuitive mapping of vibrotactile haptic feedback. Although obstacle avoidance will be achievable through interaction with the proposed solution, it is merely a side effect resulting from the spatial knowledge being obtained by the user not the primary focus.

Figure 7.1: The HaptWrap 3.0 is built using three inch elastic band to wrap around the shoulders of the user. Around the torso are two inch elastic bands equipped with three rows of vibration actuators positioned in 45° increments around the wearer's torso, and fastens with an adjustable plastic clip at the front.

Figure 7.2: The HaptWrap 3.0 worn with straps running along the center of the wearer's back with vibration actuators positioned along either side of the spine.

Figure 7.3: The HaptWrap3.0 worn with three inch elastic bands wrapped around the shoulders similar to back pack straps and fastened around the waist with an adjustable band and plastic clip.

(a) Left Side (b) Right Side

Figure 7.4: The HaptWrap 3.0 viewed from the left and right side with vibration actuators positioned along the navigator's torso in 45° increments.

7.3 Synthesized Design , Software

7.3.1 Prioritization Of OIs In The Navigator's Environment

To address the situation when there are multiple objects present in the user's environment, a solution including input derived from live video feed, and an output capable of mapping multiple objects around a user through vibrotactile haptic patterns is proposed. The design incorporates four cameras all with a 120-degree field of view (FOV) along the horizontal plane allowing for a coverage area of 360° with some overlap. Furthermore, a 120-degree FOV camera has been identified as the optimal frame size to capture the navigator's surroundings while maintaining a clear resolution allowing it to be processed by a computer vision algorithm. The final component of the input system is the implementation of a deep convolutional neural network (CNN) designed to perform pose estimation on objects detected and recognized as human. In particular pose estimation will provide a method for classifying the orientation of human actors in the environment relative to the user's orientation and position: thus, serving as a discriminator for prioritizing alerts. For example, if a human actor is recognized in a frame and he or she is classified as facing away from the user, this actor will be prioritized lower than an actor classified as facing toward the user. In addition to the pose estimation and prioritization, the system will also use object recognition to discriminate between low and high priorities for generating alerts. For instance, if a human actor is recognized and he or she is positioned near an inanimate object the algorithm will compare the pose classification with the second object to determine which is a higher priority. Similarly, stand alone inanimate objects will be recognized and alerted if present in the frame. To conclude the input component of the proposed guidelines, two options for detecting distance of OI's as well as how distance data will factor into the prioritization algorithm is discussed in further detail. First is the MegaDepth computer vision model developed by Li and Snavely (2018) which calculates the distance an object is away from the camera based on the size of the object detected in a frame. Although this approach does not require any additional hardware it is not the most efficient or accurate method for determining distance. There are many factors that could affect the accuracy of a camera based method for calculating distance though it is not an ideal method due to the additional processing load it places on the hardware. The second method requires additional hardware but the trade off is speed and accuracy. By implementing range finding sensors such as an ultrasonic, ultrasound, or even a LiDAR sensor the accuracy and speed at which distance could be calculated would be increased significantly. Finally, distance would be factored into the prioritization algorithm to further discriminate between objects to generate an alert. For example, consider two human actors recognized in a frame and both have been classified as facing toward the user. Consequently without distance data there is no clear method for prioritizing the actors. On the other hand, when distance data is provided: actor one is at a distance of twenty feet, and actor two is at a distance of thirty feet, now there is sufficient information to identify actor one as a higher priority. In summary, the proposed guidelines for accurately prioritizing multiple objects in a user's environment consists of a combination of live video capturing cameras with a 120-degree FOV along the horizontal plane, powerful machine learning algorithms to perform object recognition as well as pose estimation, and the integration of range finding sensors to accurately calculate distance. Although cameras, algorithms, and sensors gather information about the user's environment alone it is only one piece of the system. Next, design guidelines for mapping environmental information (e.g. input) to vibrotactile haptic patterns including the prioritization of multiple OI's in the navigator's vicinity are presented.

7.3.2 Design Guidelines For Multiple Objects

The creation of haptic mappings designed to communicate a single OI, began with an analysis of the objects of interest in the environment to identify the attributes which characterize the OI as an object or obstacle. As a point of clarification for the purposes of the design guidelines, the usage of the terms object and obstacle are synonymous with each other, as they are context specific depending on the situation and navigator's intent. Moreover, an object becomes an obstacle when it obstructs the path of travel, presents a danger to the traveler, or otherwise henders the travelers ability to continue on their route due to sensory deprivation. Based on the characteristics defined above distinguishing an object from obstacle, three key attributes were derived for the representation of what an OO is, and where it is relative to the navigator: distance from the navigator's position, angular direction relative to the navigator's orientation, and height of the object (e.g. head height, chest height, waist height). Although the HaptWrap discussed in chapter 5 5.3 successfully demonstrated the ease of recognition, naturalness of the haptic mappings, and intuitive design of a single OO based on positional attributes, representing multiple actors using the same approach would very quickly overwhelm the haptic channel for receiving intelligible information, therefore, three design guidelines are presented to circumvent cognitive overload.

1. *Performance*: A single object should be conveyed to the navigator at a time to minimize cognitive overload.
2. *Prioritization*: Multiple OO's should be prioritized by a function of distance and orientation (e.g. direction facing) relative to the orientation of the navigator.
3. *Human In The Loop*: The navigator has the ability to interact with the system for controlling feedback provided.

7.3.3 Human In The Loop

Autonomous systems are the way of the future with artificial intelligence (AI), growing in popularity and applications; however, when human computer interactions are occuring, it is critical to ensure the human has an interface for controlling how the system performs. For example, a simple control interface could be incorporated to facilitate user interactions to the system. The control module could be in the form of a smart watch, input sequences could resemble common gestures for a smart watch such as: covering the screen to silence alerts, pressing a button to toggle modes, or press and holding a button to perform a look around. Most notable about this form factor is that it leaves the hands free except for when inputs are necessary, does not draw further attention to the use of the assistive technology (e.g. discreet), and does not require any additional training once the input gestures are identified (e.g. intuitive). To ensure the human is in the loop and has an interface for interacting with the system, the design guidelines present system controls to be considered in integrating an input module to the system.

1. Scan in 360 degrees to gain a complete representation of all objects in the users vicinity, upon the user's request.
2. Silence the notifications from the haptic feedback to decrease cognitive overload, upon the user's request.
3. Toggle between front and rear detection only, upon user's request.
4. Toggle between indoor and outdoor mode, upon user's request.
5. Repeat a notification, upon the user's request.

The design and implementation of the input device is beyond the scope of this work: however, it is mentioned to provide a full understanding of how the proposed system could integrate an interface for user interaction, thus accounting for the human in the loop principle.

7.3.4 Haptic Speed, Fast Moving Objects

Along with describing the method for mapping multiple objects to haptic sensations and patterns, this section proposes design guidelines for addressing a novel topic to the field of haptics, how to map fast moving objects through haptic stimulation. Although the previous topic of how to handle multiple objects in the user's vicinity required additional hardware, algorithms, and input sources, this topic only requires an expert knowledge and understanding of the capabilities and limitations of vibrotactile stimulation to design intuitive haptic patterns.

In addition to representing multiple objects through haptics, another problem area remains largely unsolved which is how to communicate fast moving objects through haptic stimulation? After an extensive examination of the literature in regard to how speed has been conveyed through haptics in previous works we propose design guidelines for effectively communicating fast moving objects. Burtt (1917), developed an algorithm capable of producing a seamless representation of motion on a two dimensional vibrotactile display by varying the frequency, intensity, velocity and direction. The algorithm is based on apparent tactile motion which states that if two vibrotactile actuators are spaced in close proximity to each other and have an activation time that overlaps the user will not feel two separate sensations but rather a single sensation moving between the two actuators. The tactile brush has successfully simulated attributes such as fuel level of a vehicle, damage to a robot, or the traction produced by a vehicle's tires on the road, Israr and Poupyrev (2011b). In previous work by Israr and Poupyrev (2011a), they investigated how apparent tactile motion varied when applied to the forearm and the back. Across three different experiments they revealed impressive recognition of the apparent motion when applied to the back in a horizontal and vertical direction with varying intensities and directions of motion. Lastly Israr and Poupyrev (2010), present a novel concept they refer to as haptic blur which functions similarly to visual blur where the sensation the user feels appears to move across the skin in a smooth and seamless apparent motion. It is through a combination of these works from which a design guideline is derived for representing fast moving objects. More pointedly, it is hypothesized: a dynamic haptic pattern strategically applied to a location on the body with a high spatiotemporal capability, the speed of an object in motion can be conveyed with regard to the user's apparent motion. For instance the speed of an object could be represented by producing apparent motion on the back by simulating the spinning of a wheel similar to Israr and Poupyrev (2010)'s approach with the circles produced by the haptic blur algorithm. In this way the circle would represent the object and the speed of the circle rotating in apparent motion would indicate the relative speed of said object. However, further research would have to be done to explore the approximate threshold for which speed can be effectively and safely communicated. Furthermore if the speed of an object is an attribute associated with an object, further research should be conducted to investigate the type of objects the speed attribute is attached to. For example, if a person is walking and a vehicle drives past , is there a significant need for this information to be conveyed to the traveler? More pointedly, does this information positively affect the traveler's experience? Without these answers it is the position of these guidelines that speed of an object should be associated with objects in the user's vicinity but only to those which are traveling in the user's direction, and are within a specified speed range, also requiring further investigation to determine that threshold.

From the beginning of this work it has been the focus to utilize a single modality for conveying spatial knowledge, that being the sense of touch. The reason for this decision was two fold: the first was to avoid obstructing the primary modality used by non-visual travelers, sense of hearing, and the second was to minimize the cognitive load placed on the traveler when interacting with their environment. Although there are significant benefits to integrating audio or speech to a system for more detailed descriptions, these benefits are negated when it hinders rather than enhances the user's experience. Nevertheless, to provide a complete consideration of how a complete system could be utilized, the integration of verbal or non-verbal audio was investigated to explore the effects positive or negative, it would contribute to the overall aim of this work. For clarification, it is understood that this section directly conflicts with a requirement of not being intrusive by blocking a remaining sensory modality; on the other hand, if verbal or non-verbal audio is incorporated based on the guidelines for the human in the loop as suggested, it could significantly increase the amount of information communicated to the navigator. For instance, Jay *et al.* (2008), explored the benefits of using a crossmodal approach for representing graphical models. In their study the focus was on how haptics and audio could be combined to represent, retain, and recall graphical models. Results from their experiments demonstrate that when haptics and audio are used together there is a significant increase in retaining and recalling but when audio is used alone there is a noticeable decrease. Similarly De Felice *et al.* (2007), incorporated synthesized speech and haptic feedback to depict geographical maps. Based on their findings the redundancy of touching a geographical region while simultaneously hearing details spoken increases the user's cognitive processing of the information. Furthermore, Lahav and Mioduser (2003), developed a multimodal virtual simulator which combined audio, speech, and haptic feedback to provide a fully immersive experience for learning new locations such as school buildings, work places, or public buildings. For example the user would move through the virtual environment by manipulating a joystick while hearing footsteps, feeling a haptic sensation similar to footsteps, and receiving verbal feedback indicating things like a room name. The participant in their study demonstrated an impressive ability to navigate through the virtual rooms while retaining significant details about each room when the individual had never been in the physical room prior to the virtual experience. In summary, incorporating verbal or non-verbal audio with haptic feedback has been shown to increase the recognition, retention, and recall of an experience when integrated effectively. On the other hand the point remains, by introducing audio be it verbal or non-verbal obstructs a critical sense relied on when navigating for a non-visual traveler. For the purposes of the proposed guidelines it is understood that speech feedback offers the ability to communicate a greater level of detail otherwise not achievable through haptics alone: therefore, it should be considered. However, speech feedback should never be integrated when the user is in motion unless it is upon user request. Therefore, speech feedback should be included as a stand alone feature which can be triggered by the user similar to the previously mentioned user input options including repeating a notification, silencing a notification, or scanning the environment.

7.4 Conclusion

The information presented here is intended to be used as design guidelines for those conducting research and development in the field of haptics, sensory substitution, or human computer interaction as it applies to augmenting non-visual travel by increasing spatial knowledge through the use of dynamic haptic interactions. The secondary purpose of these guidelines are to revolutionize technology designed to augment non-visual travel, as well as to change the course of research in this field by presenting novel concepts, haptic mappings, and dynamic interactions as it applies to the use of haptics. Lastly, these guidelines were derived from several iterations of systems built to augment, not substitute current non-visual mobility aids. At each iteration qualitative and quantitative results were analyzed, weak points in the system were identified, and those weak points became the main focus of subsequent iterations; thus, these synthesized design guidelines were compiled, documented, and presented here.

At the present time, HaptWrap 3.0 is in the development phase. The wearable portion has been developed, though the machine learning convolutional neural-network models are still in the development phase.

Chapter 8

FUTURE WORK

8.1 Assistive Technology In The Future

Technology is advancing at an incredible rate. Mobile devices are increasing in speed, decreasing in size, while providing access to a variety of real-time sensor data including high resolution cameras, accelerometer, gyroscope, compass, and radios such as bluetooth LE, and wifi. On January 9, 2007, just over one decade ago Apple released the first generation of the iPhone, which completely revolutionized what we thought was possible with a mobile device. Six months later, Apple raised the bar again when it introduced the App store where developers would be able to create applications leveraging the iPhones hardware and distribute it to every user across the world from one central repository, [1]. Currently, there are approximately 2.7 billion Smartphone users across the world, 2.2 million applications in the Apple App Store and 2.8 million applications in the Google Play Store, [2]. With statistics like these, there should be no doubt about the impact Apple had on the Twentieth Century as far as interconnectedness, access to real-time sensor data, and most of all the interactions which take place between mobile devices and their users. The last decade ushered in impressive technological advancements, but the twenty-first century will bring forth advancements in the Internet Of Things (IOT), Wortmann and Flüchter (2015), Zanella *et al.* (2014), autonomous vehicles, Schwarting *et al.* (2018), Shah *et al.* (2018), and a completely new paradigm referred to as the Smart City, Su *et al.* (2011). Moreover, Zanella *et al.* (2014), identifies several examples of how the Internet Of Things will be-

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[1] https://www.history.com/this-day-in-history/steve-jobs-debuts-the-iphone

[2] https://buildfire.com/app-statistics/

come the foundation of what is to become the Smart City paradigm. In particular they describe how local businesses will provide useful data by transmitting from the building, leveraging interconnected street lights equipped with sensors to provide timely and efficient light depending on time of day, weather conditions, and the number of pedestrians traveling that particular roadway, as well as creating public wifi points transmitted from street lights, traffic lights, and/or local structures. Although Smart Cities will have to overcome many privacy concerns with the types of data it gathers, there can be no doubt it will create the optimal platform for augmenting the lives of patrons from all walks of life. In summary, the point of this section was to outline devices, highlight up and coming paradigms, and describe modalities which set the stage for the ideal navigation system for non-visual travelers.

To augment non-visual travel in the future it will be necessary to exploit the systems, sensors, and interconnectedness of the Smart City framework to develop the solution. Perhaps the most challenging component of an optimal navigational aid for non-visual travelers is the source of the input to the system. By taking advantage of publicly available input sources, a solution could be designed to provide an increased spatial awareness, and developed to interact with the user without the constraints set forth by bulky or inaccurate body worn sensors. For example, a non-visual traveler in the year 2030 would don a fully connected haptic suit including a variety of haptic actuators all receiving high resolution, dynamic, and real-time data from interconnected sensors positioned throughout the city. Allowing the Smart City framework to provide the input data so the focus of the developers can be placed on the interactions between the user and the technology. It is essential for the system to be designed in such a way to be non-intrusive, discreet, real-time, and most of all intuitive for the user to understand. Specifically the haptic mappings should be designed in such a way as to leverage the entire haptic system in addition to creating intuitive representations of objects and their characteristics such as size, position, and motion about the user. Historically haptic devices have only targeted a single haptic modality rather than deploying a solution across the entire haptic sensory system, thus rendering the quality of information able to be represented low resolution and static in nature. The haptic system of the human body offers a multi-modal interface for interactions including temperature, pressure, the stretch or displacement of skin, or the movement of limbs resulting from the kinesthetic system. An optimal navigational system will leverage the diverse capabilities of the haptic system by interfacing with each to communicate dynamic information to the user through the sense of touch. For instance, temperature would be employed to simulate the familiar feeling of chills running up the back by applying cold along the spine. Furthermore, pressure would serve a critical function in a navigation aid by applying force feedback to strategic body sites to simulate complex yet intuitive body movements. Finally, vibrotactile or electrotactile stimulation of highly receptive sites on the body are capable of achieving an impressive spatial and temporal acuity; making it an optimal modality for representing high resolution and dynamic attributes of objects across the body. Individually each of these methods of interacting with the haptic system are low bandwidth, low resolution, and primarily only support static information to be conveyed. On the other hand if these input modalities are combined the sense of touch has the ability to receive, process, and respond to high bandwidth, high resolution, and dynamic information.

8.2 Haxels, The Haptic Pixel

Early in the development of haptic technology, efforts began to create a universal haptic actuator capable of being employed in a variety of applications. Particularly it was the aim of these haptic actuators to be as small as possible, include all of the necessary components to drive a single 3.3 V. (ERM) vibration motor safely and efficiently, and be able to be connected in series for rapid prototyping and automatic indexing. The initial design of the prototyping circuit board (PCB) was roughly two inches square and used a combination of through hole and surface mount components. Although the size of the initial boards were small and could drive a vibration motor, it was not quite the form factor envisioned, nor did it allow for rapid connecting of multiple boards. After several iterations of the haptic actuators, a final design depicted in Fig. 8.1, was identified for size, interconnectability, and scalability. This final design was affectionately referred to as a "haxel" which is derived from a combination of the terms haptic and pixel. Similar to the way a computer monitor is made up of individual pixels to create the graphical user interface, haxels are able to be connected in a haptic array of any length to create a specified haptic display. Such displays could range from embedded in a stationary object in the case of the back of a chair, embedded into a fashionable garment to be hidden in plain sight, or discreetly laced into a wearable hidden from view. Fig. 8.2, features the haxel PCB actuator near a pen to serve as a size reference. Regardless of the form factor or application, the haxel PCB actuators coupled with the circuit PI formally the NeoPixel library distributed by Adafruit, allow for rapid prototyping, easy integration, and plug and play interfacing for haptic display technology. In addition to the haxel PCB, a small component referred to as the motor bump is depicted in Fig. 8.3. The purpose of the motor bump was to hold the vibration motor in a vertical position to maximize contact with the body when embedded in a wearable apparatus. Although no formal testing was done on the effectiveness of the motor bump, participants in the research studies reported they could feel all haptic actuators positioned around the body when the motor bump was applied, whereas when the motorbump was not attached to the haxel, vibration patterns were undetected, most likely due to lack of contact to the body.

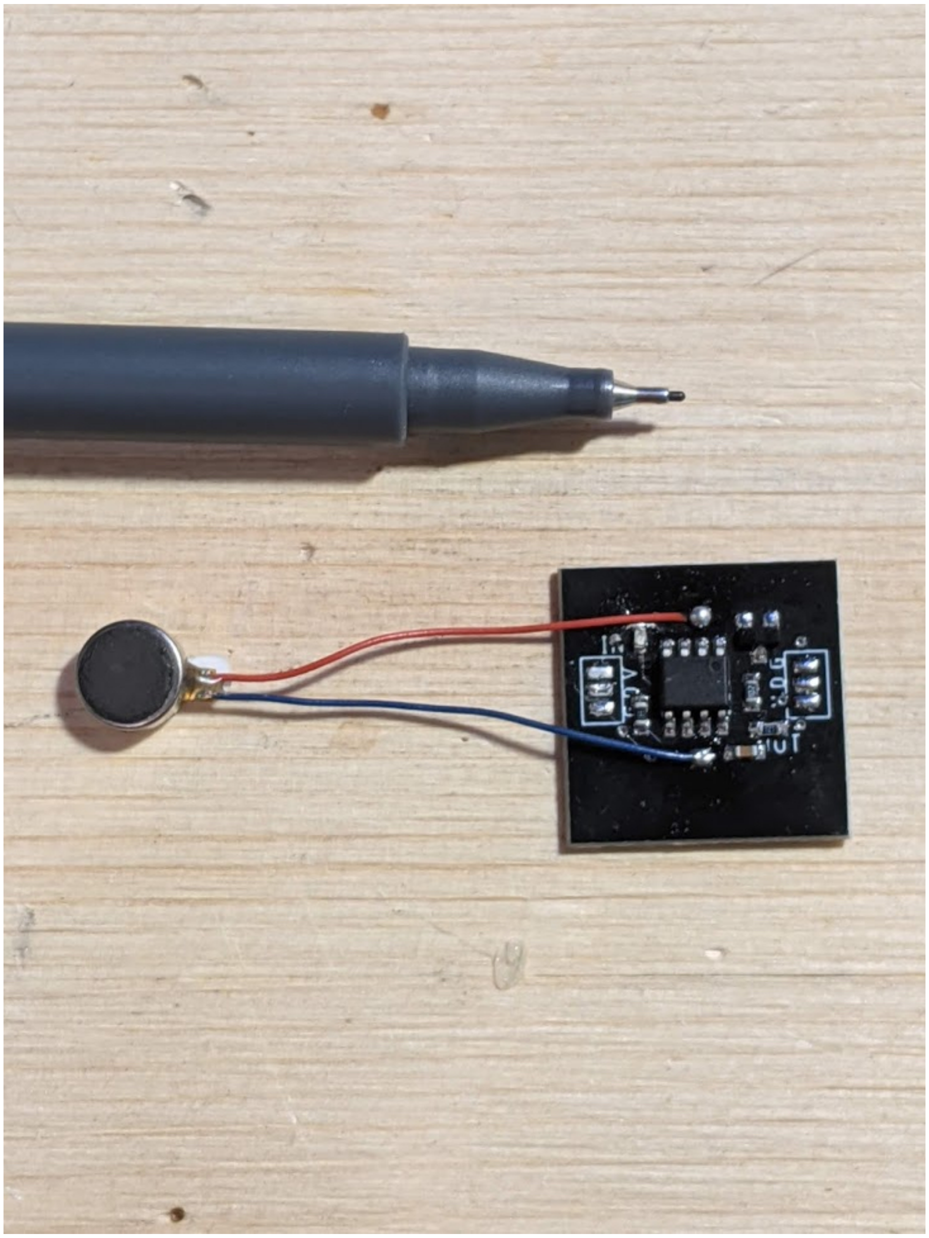

Figure 8.1: Populated haxel PCB actuator positioned next to a pen for a reference of size.

Figure 8.2: Unpopulated and populated haxel PCBs positioned together next to a pen for a reference of size.

Figure 8.3: Motor Bump, 3D printed dome designed to position the vibration motor vertically. The channel is included to feed the control leads of the motor through.

8.3 Conclusion

Indeed, many solutions have been explored to assist non-visual travelers through a variety of applications, modalities, and form factors; namely focused on orienting, guiding, or providing route planning assistance. Certainly navigational and orientation aids serve a purpose; however, the focus of the research presented here took an alternative approach to the implementation of an electronic travel aid. Contrary to the approach which designs technology excluding the end user from the equation, the implementation documented here, began with, and was continually guided by the end user at the forefront of the design, non-visual travelers. As a result of including the end user into the equation through human centered need finding studies, the approach for addressing the topic of non-visual travel aids once again defied the status quo by focusing on empowering the navigator to make navigational decisions for him or herself. The concept of gathering real-time data pertaining to a navigator's environment, mapping it to dynamic haptic interactions, then communicating it to the user to increase spatial knowledge is in direct contrast to the vast majority of related works in the field which primarily focus on directing the navigator rather than allowing them to make informed navigational decisions. The novelty in this approach is in the real-time gathering and transferring of environmental information; thus, increasing the traveler's spatial awareness resulting in safe, efficient, and independent transit. It is a subtle notion, but surprisingly, historically, it is one that is often overlooked pertaining to the design and development of electronic travel aids.

To address the aforementioned limitations that exist in current non-visual travel aids, several iterations of a wearable device capable of providing 360° of spatial knowledge in three-dimensions: distance, angular direction, and elevation through the use of intuitive vibrotactile haptic mappings have been proposed.

According to a survey we conducted with 80 individuals who identified as blind or low vision, revealed that auditory queues were the primary method of obtaining situational awareness about the environment during travel. Some examples of this were: listening to traffic to know when to cross a street safely, listening for familiar sounds like bus stops, automotive shops, or music from nearby restaurants, and echolocation created from the tapping of the long white cane. To ensure we did not impair the traveler's primary mode of receiving information, we opted to leverage the sense of touch by applying vibrotactile haptic feedback directly to the torso of the user. Consequently, this approach reduced the cognitive capacity by not occupying an essential sensory modality crucial for safe and effective travel. Moreover, the attention of the navigator was not split between the critical auditory information relied on to make important navigational decisions based on ambient sounds emitted from the environment, and audio feedback from an ETA. Further still, the haptic and auditory sensory input modalities can operate independent of one another; thus, the proposed approach of directing spatial information to the sense of touch, while freeing the auditory system for receiving information in parallel, allows it to be non-intrusive. Next, focus was placed on ensuring the haptic patterns were intuitive, which led to an examination of the natural or instinctive patterns, habits, or reflexes humans have in terms of a cause and effect analysis. For example, from the time a baby is born its natural instinct is to eat; therefore, if something touches its lips the baby will reflexally respond by opening its mouth and attempting to eat from the object. Additionally, the human body has a fundamental ability to orient and position objects relative to itself known as egocentric reference. By leveraging the instinctive response of the human body, the creation of haptic mappings representing the position of a static object (e.g. not in motion) described in terms of dimensions (e.g. distance, angular direction, and elevation) was possible. Subsequently, the static patterns gave rise to the further creation of a novel haptic mapping hereby referred to as dynamic interactions, represented by situational metaphors. For instance, through dynamic interactions it was possible to depict an object in motion based on a situational metaphor representing a scenario commonly encountered during travel on public streets such as: a person walking up from behind, passes to the right, and continues on past, or a vehicle approaching from the left and stopping in front. Each of these dynamic mappings were composed of a series of static patterns strung together similar to how a sequence of single frames make up a video.

To assess the effectiveness of the haptic patterns it was necessary to ensure that each metaphorical depiction of a real life situation could be easily recognized. Initially the design was implemented in a two-dimensional matrix of vibrotactile motors embedded in the back of an ergonomic chair. The primary focus of this work was to determine if individuals who self identify as blind or low vision could interpret three-dimensions of an OO's position conveyed through a two-dimensional array of vibration actuators applied to the lower back. The preliminary study yielded an impressive aptitude for recognizing static vibrotactile representations of an object positioned in a 180° angular direction along the frontal plane. Consequently the next iteration was focused on covering a 360° angular direction with respect to the users position and orientation. In addition to the static representations depicted in the first study, the second study introduced the aforementioned dynamic haptic interactions. To accurately assess the effectiveness of the apparatus and the naturalness and ease of recognition of the haptic patterns, an experiment was designed to evaluate recognition accuracies of static patterns first, then dynamic interactions thereafter. Results from the study demonstrate a surprising ability to recognize individual dimensions presented in the static patterns, as well as an impressive aptitude for identifying and describing dynamic patterns depicting objects in motion around them in 360°. That said, it became clear that the heartbeat rhythm used to communicate the dimension of distance placed a high demand on the mental capacity due to the spatiotemporal recognition of varying tempos used to represent distances. Furthermore, the time necessary to execute the heartbeat rhythm was inadequate for being used in a real-time solution. This led to the design of an apparatus capable of communicating distance effectively, efficiently, and in near real-time referred to as the HapBack. This design not only decreased the mental effort associated with identifying a distance but also increased the overall performance and accuracy in recognizing the mapping of distance. Once again it should be noted that the point of this work is not to guide, stear, or provide navigational information, rather it is to gather positional details of objects in the navigator's environment, then produce an intuitive haptic mapping that describes where said object is relative to the navigator. Simply put, providing an increased spatial awareness will allow a non-visual travel to obtain an understanding of his or her environment never before achievable with current assistive travel aids.

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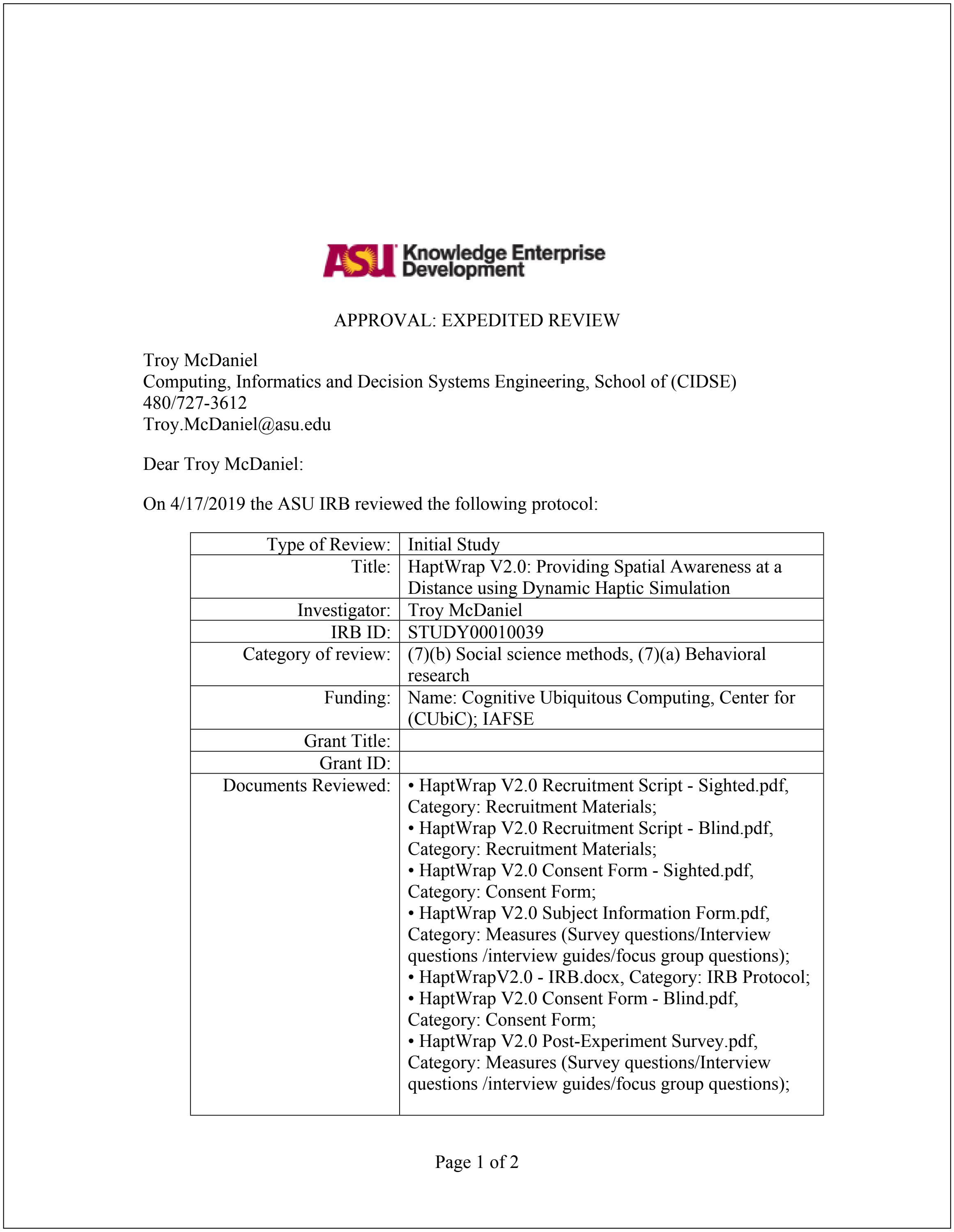
APPENDIX A

UNIVERSITY APPROVAL FOR HUMAN TESTING



ASU Knowledge Enterprise Development

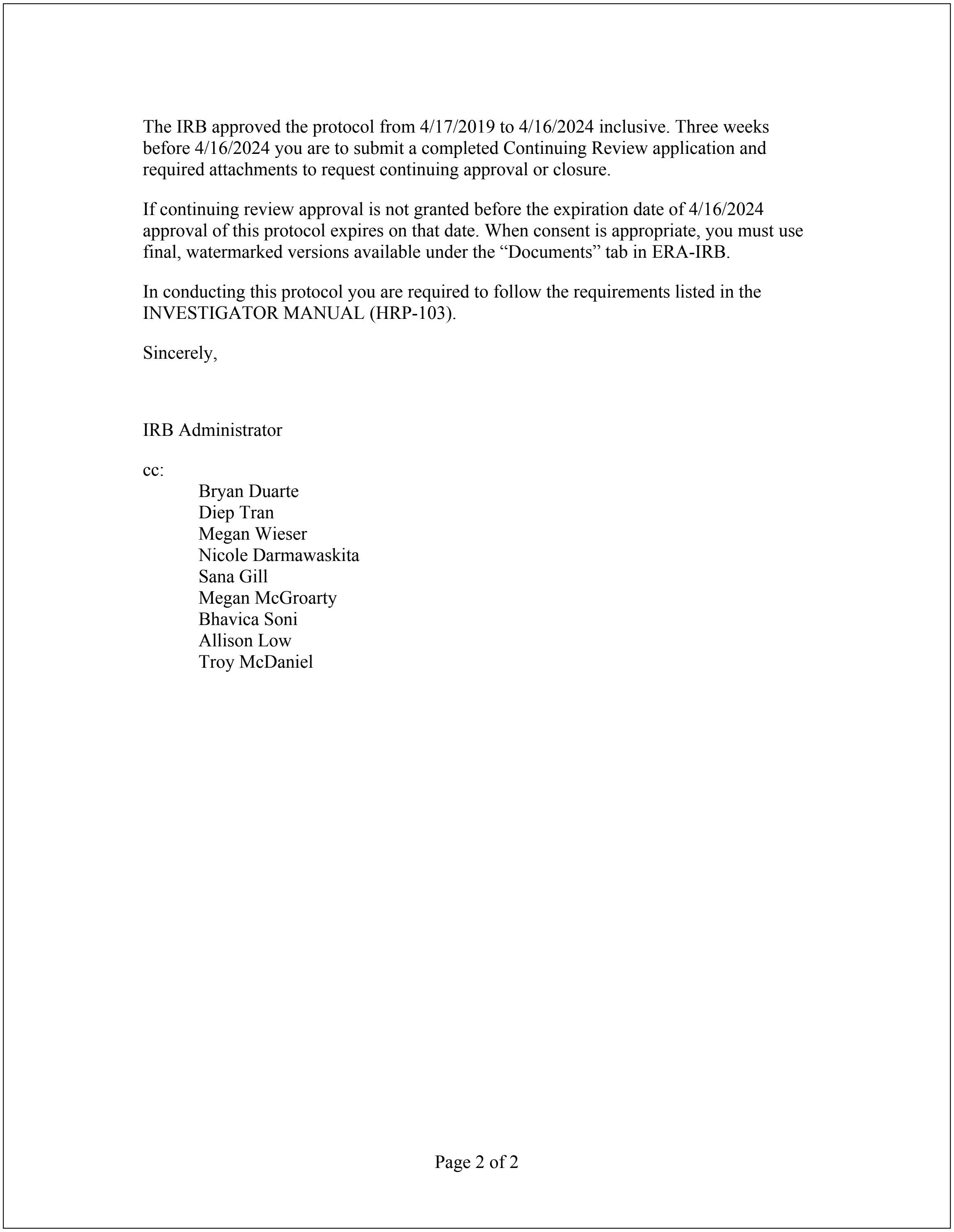
APPROVAL: EXPEDITED REVIEW

Troy McDaniel
Computing, Informatics and Decision Systems Engineering, School of (CIDSE)
480/727-3612
Troy.McDaniel@asu.edu

Dear Troy McDaniel:

On 4/17/2019 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	HaptWrap V2.0: Providing Spatial Awareness at a Distance using Dynamic Haptic Simulation
Investigator:	Troy McDaniel
IRB ID:	STUDY00010039
Category of review:	(7)(b) Social science methods, (7)(a) Behavioral research
Funding:	Name: Cognitive Ubiquitous Computing, Center for (CUbiC); IAFSE
Grant Title:	
Grant ID:	
Documents Reviewed:	• HaptWrap V2.0 Recruitment Script - Sighted.pdf, Category: Recruitment Materials; • HaptWrap V2.0 Recruitment Script - Blind.pdf, Category: Recruitment Materials; • HaptWrap V2.0 Consent Form - Sighted.pdf, Category: Consent Form; • HaptWrap V2.0 Subject Information Form.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • HaptWrapV2.0 - IRB.docx, Category: IRB Protocol; • HaptWrap V2.0 Consent Form - Blind.pdf, Category: Consent Form; • HaptWrap V2.0 Post-Experiment Survey.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions);



The IRB approved the protocol from 4/17/2019 to 4/16/2024 inclusive. Three weeks before 4/16/2024 you are to submit a completed Continuing Review application and required attachments to request continuing approval or closure.

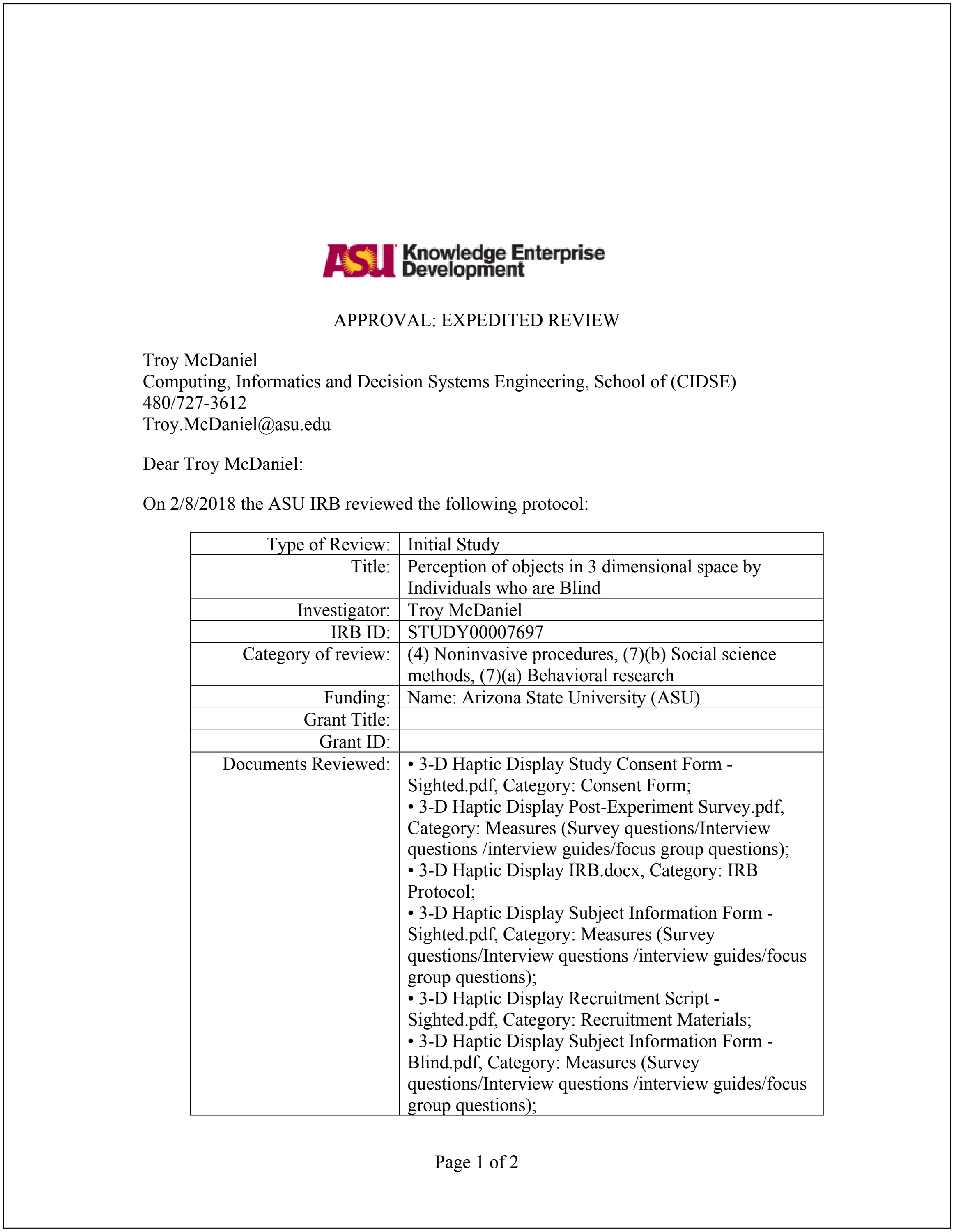
If continuing review approval is not granted before the expiration date of 4/16/2024 approval of this protocol expires on that date. When consent is appropriate, you must use final, watermarked versions available under the “Documents” tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc:
- Bryan Duarte
- Diep Tran
- Megan Wieser
- Nicole Darmawaskita
- Sana Gill
- Megan McGroarty
- Bhavica Soni
- Allison Low
- Troy McDaniel



ASU Knowledge Enterprise Development

APPROVAL: EXPEDITED REVIEW

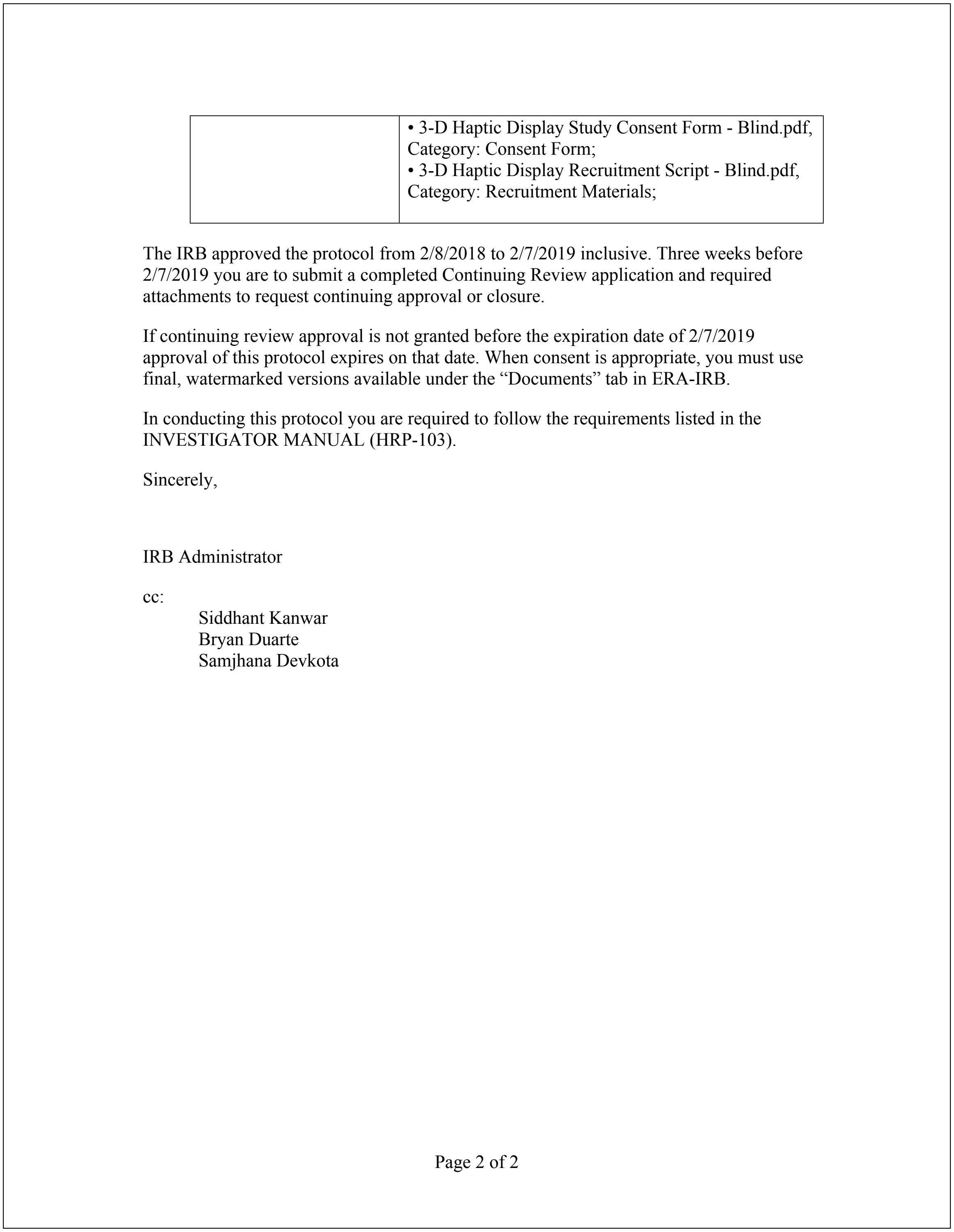
Troy McDaniel
Computing, Informatics and Decision Systems Engineering, School of (CIDSE)
480/727-3612
Troy.McDaniel@asu.edu

Dear Troy McDaniel:

On 2/8/2018 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Perception of objects in 3 dimensional space by Individuals who are Blind
Investigator:	Troy McDaniel
IRB ID:	STUDY00007697
Category of review:	(4) Noninvasive procedures, (7)(b) Social science methods, (7)(a) Behavioral research
Funding:	Name: Arizona State University (ASU)
Grant Title:	
Grant ID:	
Documents Reviewed:	• 3-D Haptic Display Study Consent Form - Sighted.pdf, Category: Consent Form; • 3-D Haptic Display Post-Experiment Survey.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • 3-D Haptic Display IRB.docx, Category: IRB Protocol; • 3-D Haptic Display Subject Information Form - Sighted.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • 3-D Haptic Display Recruitment Script - Sighted.pdf, Category: Recruitment Materials; • 3-D Haptic Display Subject Information Form - Blind.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions);

Page 1 of 2



	• 3-D Haptic Display Study Consent Form - Blind.pdf, Category: Consent Form; • 3-D Haptic Display Recruitment Script - Blind.pdf, Category: Recruitment Materials;

The IRB approved the protocol from 2/8/2018 to 2/7/2019 inclusive. Three weeks before 2/7/2019 you are to submit a completed Continuing Review application and required attachments to request continuing approval or closure.

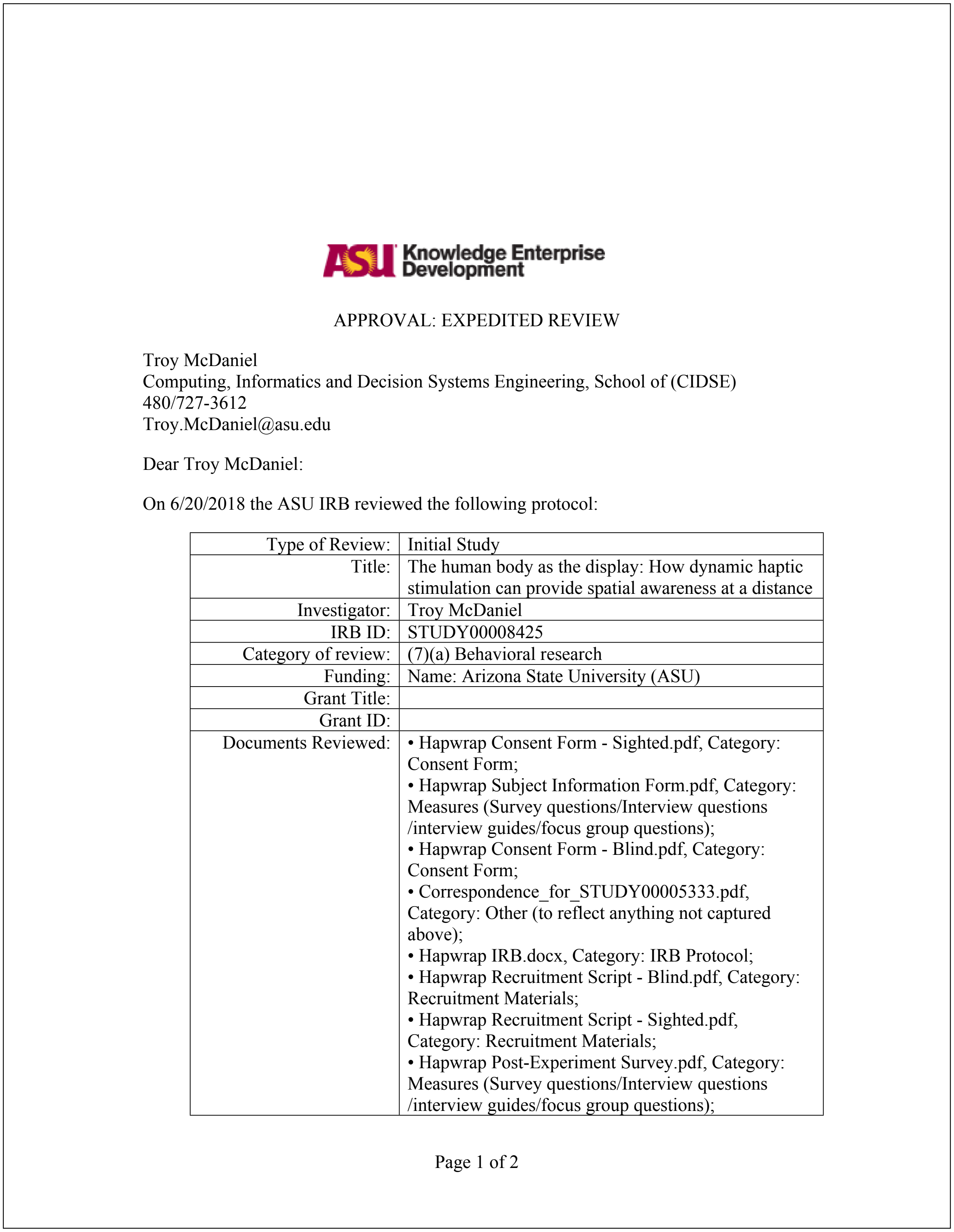
If continuing review approval is not granted before the expiration date of 2/7/2019 approval of this protocol expires on that date. When consent is appropriate, you must use final, watermarked versions available under the “Documents” tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc:
Siddhant Kanwar
Bryan Duarte
Samjhana Devkota



ASU Knowledge Enterprise Development

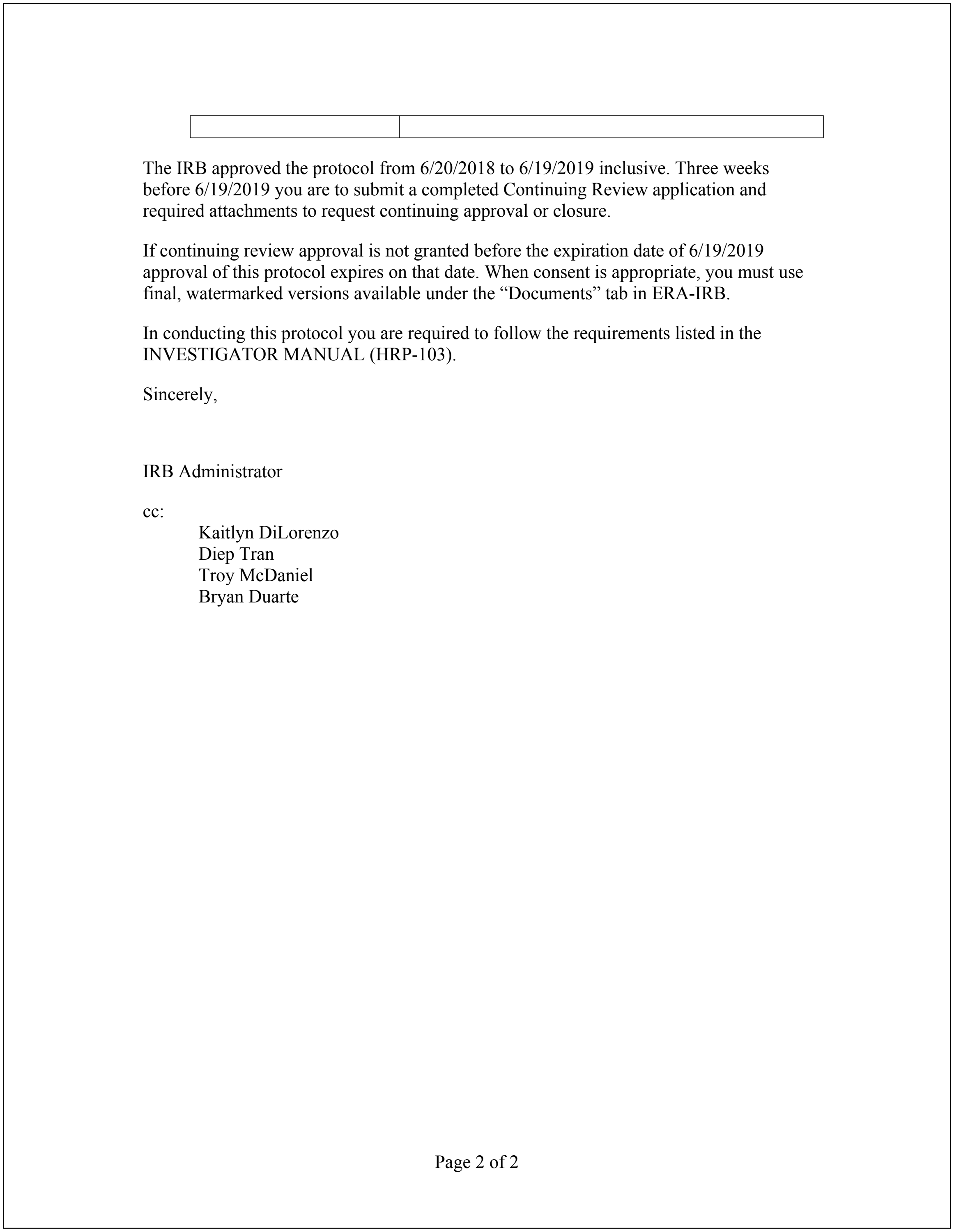
APPROVAL: EXPEDITED REVIEW

Troy McDaniel
Computing, Informatics and Decision Systems Engineering, School of (CIDSE)
480/727-3612
Troy.McDaniel@asu.edu

Dear Troy McDaniel:

On 6/20/2018 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	The human body as the display: How dynamic haptic stimulation can provide spatial awareness at a distance
Investigator:	Troy McDaniel
IRB ID:	STUDY00008425
Category of review:	(7)(a) Behavioral research
Funding:	Name: Arizona State University (ASU)
Grant Title:	
Grant ID:	
Documents Reviewed:	• Hapwrap Consent Form - Sighted.pdf, Category: Consent Form; • Hapwrap Subject Information Form.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Hapwrap Consent Form - Blind.pdf, Category: Consent Form; • Correspondence_for_STUDY00005333.pdf, Category: Other (to reflect anything not captured above); • Hapwrap IRB.docx, Category: IRB Protocol; • Hapwrap Recruitment Script - Blind.pdf, Category: Recruitment Materials; • Hapwrap Recruitment Script - Sighted.pdf, Category: Recruitment Materials; • Hapwrap Post-Experiment Survey.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions);



The IRB approved the protocol from 6/20/2018 to 6/19/2019 inclusive. Three weeks before 6/19/2019 you are to submit a completed Continuing Review application and required attachments to request continuing approval or closure.

If continuing review approval is not granted before the expiration date of 6/19/2019 approval of this protocol expires on that date. When consent is appropriate, you must use final, watermarked versions available under the “Documents” tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc:
Kaitlyn DiLorenzo
Diep Tran
Troy McDaniel
Bryan Duarte