TACTILE NAVIGATION

TACTILE NAVIGATION: AN ADDITIONAL PROCESSING CHANNEL FOR ENVIRONMENTS OF HIGH SENSORY LOAD

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Abstract

Persons with visual impairments often rely on navigational electronic aids, which typically employ speech commands for guidance through novel routes. However, navigational speech commands may interfere with the perception of acoustically rich environmental information, resulting in potentially detrimental effects. We investigated the sense of touch as a means to convey navigational commands instead. The somatotopic representation of the body surface within the central nervous system makes spatial information intuitive to our skin, suggesting that the tactile channel should be equivalent to, if not better than, the auditory channel at processing directional commands. Additionally, based on Wickens' Multiple resource theory, the tactile channel should mitigate the sensory load in the auditory channel in travelers with visual impairments. We tested the ability of blind users to process directional commands conveyed via a tactile navigational belt. 14 blind participants were tested with the tactile belt under conditions of either low or high acoustic sensory load, simulating different outdoor environments. For comparison, the same participants were tested also with a conventional auditory device. Consistent with previous studies, we found navigation with the tactile belt to be less efficient than navigation with the auditory aid in the absence of environmental sounds. However, we found also – for the first time, to our knowledge – that tactile performance was less compromised under conditions of high acoustic sensory load. These results will help to inform the further investigation and development of tactile displays to benefit blind travelers.

Preface

The following thesis is composed of three chapters. Chapter 1 provides the reader with the required background knowledge for the subject at hand. Chapter 2 dwells deeper into the subject, through an empirical study and its analysis. Chapter 3 concludes the thesis by discussing the findings and implications of the study investigated in the previous chapter.

Chapter 2 is in the process of further refinement for the intent of publication. It was collaborated on with Saurabh Shaw, the designer of the tactile display which was used to analyze the corresponding research questions. We designed the research under the direct supervision of Dr. Daniel Goldreich, Director of Neuroscience at McMaster University.

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CHAPTER 2

Chapter 1 – Introduction

1.1 Background

What do we do in order to convince ourselves of something's actual existence outside the realms of our own mind? In most cases, we touch it (Gallace & Spence, 2014). Touch is defined as "the most general of the bodily senses, diffused through all parts of the skin, but (in man) specially developed in the tips of the fingers and the lips" (Field, 2014). It is a sense that makes the world real to us which, it is claimed, cannot be deceived or fooled (Gallace & Spence, 2014). Touch has been described as the most fundamental means of contact with the world and the simplest and most straightforward of all sensory systems – providing us the means to connect with our surroundings (Barnett, 1972; Geldard, 1960; Gallace & Spence, 2014).

Touch is the first sense to develop in all animals, giving it its name – "the mother of the senses" (Field, 2014). Our skin, the organ that houses our sense of touch, is the first and the largest sense organ to develop prenatally – precisely, when the human embryo is less than an inch long. Postnatally, touch continues to be the primary means of experiencing the world throughout infancy and well into childhood (Field, 2014). Infants and young children are heavily dependent on touch for learning about the world, especially as visual acuity is limited in the early months of infancy (Field, 2014; Hertenstein et al., 2006). Learning about the world via touch is critical for an infant's bonding, communication and ability to identify *things*. During the new-born period, most of the affections infants receive or portray are tactile; they affectionately pat the mother's breast while nursing and months later, pat the mother's face and acknowledge kisses. Remarkably, tactile bonding begins even before birth (Field, 2014). A fetus receives continuous tactile stimulation and feedback from the mother's heart rate, respiration rate, and other physiological rhythms. Field (2014) noted that if these tactile stimulants are stripped away from rat pups upon birth, the pups are not only deprived of critical bonding, but also have high risk for hyper-excitability and underdevelopment of the hippocampus due to higher cortisol levels (Field, 2014). Furthermore, orphaned infants exposed to environments with inadequate or inappropriate tactile stimulation (in eastern European institutions) exhibited developmental delay – specifically, impaired growth and delayed cognitive development – due to the interrupted maturation of regions in the prefrontal cortex (Pollak et al., 2010). Research suggests that such developmental issues may not be due to maternal deprivation, per se; rather, they result from sensory deprivation, and more specifically, a deprivation of touch stimulation (Ardiel, 2010). The importance of touch in infant development is supported by a large body of studies, including studies demonstrating that early tactile stimulation via bonding is essential to social, cognitive, and physical development (Field, 2014; Jones & Yarbrough, 1985). A child's first emotional bonds are built from physical contact, laying the foundation for further emotional and intellectual development.

Touch has been deemed to be our most social sense; all cultures share a common understanding of basic meanings of touch in fundamental human exchanges such as aggression, comfort, and attachment (Field, 2014; Hertenstein et al., 2006). Indeed, touch may have influenced language, and perhaps even provided a medium for cognitive activities (Katz, 1989). Specifically, touch reliably communicates different emotions the same way as facial and vocal expressions do. In several previous studies, the reliability of communication via touch was examined in both strangers and romantic couples. All participants were able to communicate universal and prosocial emotions (Field, 2014). The role of touch in present day communication dates back to the evolutionary origin of the tactile signaling system (Jones & Yarbrough, 1985). Several species of nonhuman primates developed social systems centred around social grooming, also known as allogrooming. Grooming not only protects primate conspecifics from disease; most researchers agree that the prevalence of grooming in species was – and still is – indicative of important social functioning. Grooming maintains social relationships between nonhuman primates of every sex, age, and rank (Hertenstein et al., 2006). Some researchers believe that touch, rather than primitive vocal calls in nonhuman primates, is the evolutionary precursor to language in humans (Hertenstein et al., 2006).

The most apparent function of touch is to perceive the details of objects we manipulate. The importance of this function becomes obvious as we encounter novel surfaces we must learn about. For example, as we walk, we must sometimes stop to learn about a potentially slippery street, an icy slope, or a rocky terrain; it is critical to understand how rough or smooth, cold or hot a surface is to touch or maneuver through (Field, 2014). In such situations, touch can be understood to consist of two dissociable phenomena: first, the interaction of the surface with the skin, and second, the registration of this information by the neural networks in the brain associated with the skin – formally known as tactile perception (Hertenstein et al., 2006). Katz (1989) noted that in touching, "one brings object properties to life, creating through one's own muscular activity such qualities as roughness and smoothness, hardness and softness." This description of touch emphasizes the process of active touch, where the hand is dexterously wielded, so the characteristics of an object can be discerned, rather than passively imposed (Katz, 1989).

Tactile sensations – from the pleasant sensations of a gentle breeze or the warmth of a loved one's skin, to the painful experience of touching a hot stove – are all initiated by somatosensory neurons that innervate our skin (Lumpkin & Caterina, 2007). To understand various functions of touch, it is important to understand the physical components of the skin and how touch stimulation signals are conveyed from the skin to the brain (Field, 2014). The surface of the human body, the skin, is one huge sheet of tactile receptors – making it the largest, oldest and most sensitive sense organ in the body (Field, 2014; Gallace & Spence, 2014). While the size of the skin can reach approximately 18 square feet, it's even more breathtaking at the microscopic level; a square inch of skin contains a few million cells, a few hundred sweat glands, and many nerve endings, which vary in number according to location. The skin informs us about what occurs on its surface by making sense of thermal, chemical, and mechanical stimuli (Field, 2014; Gallace & Spence, 2014). These stimuli cause changes in the skin that are translated into neural signals by means of specialized receptors.

Mechanoreceptors play a particularly important role in touch sensation. In the glabrous skin, four distinct mechanoreceptor types transduce different forms of mechanical stimulus energies into distinct patterns of response (Gallace & Spence, 2014). Pacinian Corpuscles, most commonly found deep in the epidermis of the palms of the hands and soles of feet, respond most sensitively to high frequency vibrations. Meissner Corpuscles, concentrated in the glabrous skin situated in extremities such as fingertips, are responsible for high tactile sensitivity to low frequency vibrations. Both Pacinian and Meissner corpuscles contribute to the perception of flutter and slip, although Meissner corpuscles can better localize stimuli due to their high density in the skin. By contrast, the remaining two mechanoreceptors, Merkel cell-axon complexes and Ruffini Corpuscles, respond during maintained, static stimulation. The Merkel complexes are densely located in the human fingertip and are prominent in transducing spatial structure of objects and surfaces – giving rise to the perception of form and texture. Finally, the Ruffini Corpuscles are deeply situated receptors that have been less studied but are known to transduce lateral skin stretch. It is important to note that while each mechanoreceptor responds with greatest sensitivity to a particular stimulus feature, all four receptors can be activated by a suprathreshold stimulus (Johnson, 2001; Gallace & Spence, 2014).

When the skin's receptors receive a thermal, chemical, or mechanical stimulus, neurons carry the transduced signals as action potentials to the central nervous system via the spinal cord and brainstem up to the brain (Field, 2014; Lumpkin & Caterina, 2007). These neurons, which are remarkably diverse, are broadly classified as A-beta, A-delta or C-fibres depending on their degree of myelination and the speed with which they conduct action potentials (Lumpkin & Caterina, 2007). Information travelling to the brain crosses to the opposite side through decussating axons, in order to be processed by the contralateral primary somatosensory cortex as tactile perception (Field, 2014; Gallace & Spence, 2014).

Interestingly, while many research laboratories investigate vision and audition, relatively few investigate touch (Field, 2014). Since the time of Plato, Western Philosophy has privileged the study of vision over other modalities. For instance, in René Descartes' view, "All the management of our lives depends on the senses, and since that of sight is the most comprehensive and the noblest of these, there is no doubt that the inventions which serve to augment its power are among the most useful that there can be" (Descartes, 2001: p. 65). Philosophical views such as this were likely responsible, at least in part, for denigrating nonvisual modalities, including touch. With that in mind, touch's inherent complexity did not make matters any better; it can vary in its action to encompass 457 different types of body contacts (Hertenstein et al., 2006; Morris, 1971). Nevertheless, as time progressed to the 20th century, a renewed appreciation emerged for touch. For instance, David Katz noted in his book *The world of Touch* that "[fingers] obtain information on the innards of objects, whereas the eye, remaining fixed at the outer surface of objects, plays a lesser role in developing the belief in the reality of the external world" (p. 3). The basic physics concepts such as force, impenetrability, resistance, and friction are all rooted in touch (Katz, 1989). It was noted that, unlike vision, touch through the fingers was relatively more sensitive to micromorphic or substance properties (e.g. roughness, hardness) than to macromorphic or shape properties. Klatzy, Lederman, and Reed (1987) cited texture and hardness as attributes that are more salient for haptics – encompassing all things pertaining to touch – than vision, and concluded that haptics is oriented towards the encoding of substance (Klatzky et al., 1987; Gunther & O'Modhrain 2003). Furthermore, touch dominates vision in judgements of roughness, and information on properties such as temperature, weight, and hardness is generally available only to haptics (Katz, 1989). Researchers are now actively investigating these salient features of touch in order to gain a deeper understanding of the mechanisms of touch and its potential applications.

1.2 Tactile Information Processing

In a world dominated by visual and auditory cues, our sense of touch often falls into the background of our consciousness. Although we generally do not give tactile stimulation the attention we give visual and auditory stimulation, we do in fact obtain a great deal of information about our surroundings through the sense of touch (Gunther & O'Modhrain 2003). Touch helps us avoid pain and drastic temperature changes, experience pleasurable sensations, navigate through space, perceive objects we manipulate, and sometimes helps substitute for other senses (Field, 2014). Considering the sophistication of touch, might not our skin be able to comprehend a tactile language in the way that our eyes and ears can understand visual and auditory manifestations of language?

The notion of a tactile language may at first seem implausible. However, in regard to processing information, our senses of hearing and touch have some fundamental similarities – specifically, in their ability to perceive and process vibrations. Tactile psychophysics research provides evidence that in certain respects, the perceptual ranges and discriminatory limits are roughly compatible, at least overlapping, with those of hearing, signifying the potential to use stimuli comprehensible to both modalities (Gunther & O'Modhrain 2003). Attributes that can be specified via different sensory modalities are known as *amodal attributes*. The most common amodal attributes are intensity, spatial location, rate, and rhythmic structure. While touch can detect such stimulus attributes, it is more important to consider if the human haptic system is capable of resolving and understanding the potentially complex, rapidly varying temporal and spatial patterns presented to the skin that would be needed for a tactile language (Gunther & O'Modhrain 2003). Considering the infinite number of combinations of stimulus frequency, intensity, waveform, duration, and body locus, we could assume that the potential of a tactile language on the skin would be endless. Several studies have sought to determine the skin's ability to receive and understand complex systems of symbols or tactile language. Gunther and O'Modhrain (2010) found one amodal attribute to have the greatest potential for the tactile system—spatial location. Additionally, Azadi and Jones (2014) further supported the previous claim by making use of tactile displays – arrays of vibrotactile actuators. These tactile displays have been shown to be effective in presenting spatial information that directs the user to a location when navigating in unfamiliar environments (Azadi & Jones, 2014). It was further noted that the location of stimulation on the body provides a potent spatial cue about the environment to which observers readily respond. Location might therefore be the first choice to code spatial information as it is the most intuitive to our skin (Cholewiak & Collins, 2000; Azadi & Jones, 2014). The key word here is *intuitive* – the fundamental requirement of a stimulus for communicating through the skin.

Accordingly, the purpose of the research reported in this thesis is to investigate the robustness of the tactile system in processing spatial information. The skin may have possibilities for coding information about our immediate environment even superior to those of other channels "since it combines temporal and spatial qualities, and it is rarely ever 'busy'" (Bach-y-Rita, 1967). Howell (1960) went further to note that the reaction time for touch is lower than vision, and may sometimes also be lower than audition (for review, see Teichner, 1954). This suggests that a potential superiority over the other sensory channels may exist in the skin with respect to information processing. Hence, we sought to verify this hypothesis in a practical way: we tested the efficacy of a tactile navigational device for the blind.

1.3 Navigational Systems for the Blind

Like our sense of touch, our ability to navigate from place to place is often overlooked. However, in the case of navigation, vision plays the crucial role; it provides us a rich and complex set of information about the surrounding environment, and informs us about the position and properties of objects in the world (Johnson & Higgins, 2006). Furthermore, it is vital in processing spatial information including depth estimation, navigation and object avoidance.

Deprivation of this information often comes with a huge cost to one's ability to independently navigate in his or her environment. Nevertheless, navigation is an integral part of daily life; thus, even if deprived of vision, a person may learn to compensate by relying on input from other sensory modalities (Guidice & Legge, 2008).

Very few people have experienced navigating large-scale, unfamiliar environments nonvisually. Imagine yourself to be blindfolded in the streets of downtown Toronto – having little to no spatial awareness – in an attempt to find the *Toronto Transit Commission (TTC)*. It is hard; yet blind individuals travel independently on a daily basis even when faced with the challenge of finding their way through environments that can be difficult to interpret, disorienting, and even intimidating (Guidice & Legge, 2008, Schinazi et al., 2016). To undertake safe and efficient navigation, blind individuals must acquire alternative travelling skills and use sources of nonvisual environmental information that are rarely considered by their sighted peers (Schinazi et al., 2016). Much research on visual impairment and blindness has approached this navigational challenge, attempting to gain an understanding of the cognitive processes underlying blind navigation. The knowledge acquired through highly focused research questions serves to develop technologies that assist in obstacle avoidance and waypoint route selection (Guidice & Legge, 2008).

The goal of navigating with or without vision is the same – locomoting from an origin to a destination – but the environmental information available to sighted and blind individuals is drastically different. To understand the challenges of blind navigation requires an appreciation of the amount of spatial information available from vision (Guidice & Legge, 2008). With vision, it is trivial to see the spatial configuration of objects in the environment and how the relation between oneself and these objects changes as one moves – also known as *piloting*. Piloting involves the use of external information to specify the navigator's position and orientation in the environment (Loomis et al., 1993).

The use of external spatial information is not limited to vision; a navigator can also use tactile, auditory, or olfactory information, as well as signals from electronic aids, such as GPS-based devices for piloting (Loomis et al., 1994). Tools such as GPS-based devices are often called mobility aids or electronic travel aids. Yet, even to this day, the most fundamental tools for mobility and travel are the cane and guide dog (Guidice & Legge, 2008). The cane is a simple mechanical device that is traditionally used for detecting and identifying obstacles, or finding steps or drop-offs in the path of travel. While the guide dog performs many of the same functions as the cane, navigation is often more efficient because the dog can help direct routes between objects, instead of the blind individual following edges, or *shorelining*. However, the cane and guide dog have similarly large limitations: they are effective for detecting proximal cues but do not provide much information regarding the orientation of the user's position and direction in the environment. The development of most electronic travel aids serve to reduce these limitations by working in synergy with the long cane or guide dog (Guidice & Legge, 2008).

1.3.1 Traditional GPS-Based Devices

Many commonly used electronic travelling aids depend on Global Positioning Systems (GPS), which provide information about the user's location almost anywhere in the world when navigating outdoors. The satellites feeding information to the GPS provide constantly updated position information whether or not the user is moving. When the user with the GPS device is in motion, the software uses sequences of GPS signals to provide heading information on the order of one to 10 meters accuracy – hence, the synergistic requirement for a blind individual to use a cane or a guide dog in conjunction with the GPS device (Guidice & Legge, 2008). Many of the commercially available GPS-based devices for the blind incorporate auditory displays of visual information, converting GPS information on the device screen into speech (Guidice & Legge, 2008; Ertan et al., 1998; Gaunet, 2006; Loomis et al., 2005). The design of such a system requires carefully selected speech events to minimize interference with a blind individual's sense of environmental sounds (Ertan et al., 1998). Nevertheless, speech from the device often taxes the user's auditory modality, which during navigation is typically already being used for localization and/or communication purposes (Johnson & Higgins, 2006). Additionally, the navigational speech conveyed to the user requires a level of semantic processing – demanding a complex network of interactions between different brain regions – before an individual can act upon it (Price at al., 1996). In light of these considerations, we propose that the sense of touch be considered as an alternative channel for navigational information to ease the demand on auditory attention.

It seems plausible that the use of the tactile modality to process navigational instructions should mitigate sensory overload, especially, when high volumes of environmental information are delivered to the auditory channel (Cholewiak & Collins, 2000; Barber et al., 2015; Jimenez & Jimenez, 2017). However, this prediction depends upon the effects of divided attention across different modalities (Martens et al., 2010; Martens & Wyble, 2010). The main research question concerns whether there is an *attentional blink* – "a deficit in reporting the second of two targets when presented in close temporal succession" (Martens & Wyble, 2010), when both target stimuli are presented within the same modality versus presented across two different modalities (Martens et al., 2010). Martens et al. (2010) showed when two target stimuli, one auditory and the other visual, were presented in quick successions there was no interference in perceiving the second target, reflecting the absence of a cross-modal attentional-blink effect. The commonly observed decrease in perceiving the second target was only found when both target stimuli were presented within the same modality, strongly suggesting the existence of modality-specific limitations rather than an amodal, higher-order "bottleneck" effect (Martens et al., 2010). Although the evidence was derived from auditory/visual tasks, this lends support to the prediction that blind travellers would benefit from a tactile navigation system under conditions of high auditory load.

1.3.2 Tactile Navigational Devices

It may be true that the attentional mechanism involved in processing concurrent stimuli prefer the use of different sensory modalities; however, it is important that the alternative modality be relatively free from information processing. An efficient use of the available sensory modalities then would be to employ the skin for the accurate perception of alerts, position, mobility, or navigation – as its surface area is very large and the great majority of it is minimally used during navigation (Cholewiak & Collins, 2000; Johnson & Higgins, 2006).

While visual-to-tactile sensory substitution devices (SSD) have been developed since the 1960s, vibrotactile belts for blind waypoint navigation has been an emerging technology only since the late 1990s (Bach-y-Rita, 1967; Ertan et al., 1998). Ertan et al (1998) were one of the pioneers to develop such a device – a haptic aid system which consisted of a wearable vest composed of vibrotactile actuators. This vest was designed to use an infrared guiding system that successfully guided participants to navigate through test paths. Following the vest, another publicized device was developed by Tsukada and Yasumura

(2004), the "ActiveBelt", that provided vibrotactile navigational information through a GPS (Jimenez & Jimenez, 2017). These devices, and several more, use vibrotactile motors to implement tactile communication for spatial information. Such vibrotactile devices can have a very practical use in enhancing Human Computer Interactions (HCI) for the blind and visually impaired traveller (Jimenez & Jimenez, 2017). Modern vibrotactile displays are effective in conveying tactile information because of their flexibility and intensity range, which allow the device to exploit the skin's mechanoreceptors for communication purposes (Cholewiak & Collins, 2000; Barber et al., 2015). Moreover, Barber et al. (2015) have shown directional vibrotactile stimulation to be the most intuitive to the sense of touch as its spatial-temporal pattern meaning may be most readily encoded in memory.

Consequently, we set out to verify how robust the human tactile system is at processing tactile communication consisting of spatial navigational information. This was carried out through a practical focus; we studied the efficacy of a vibrotactile navigational belt that communicates directional commands to a blind user via vibratory stimulation.

1.4 The Tactile Belt

In today's day and age, auditory navigational instructions are often difficult for a blind pedestrian to use when the immediate environment is rich in auditory stimuli. In such cases, an auditory device may distract the user from environmental sounds crucial for spatial orientation (Jimenez & Jimenez, 2017). There is also a potential for auditory instructions to be masked by the sounds of an acoustically rich environment. In an effort to solve these problems, Biomedical engineers at McMaster University have developed a tactile navigational display for blind people, with the intent of making independent travel more practical and less tedious for everyday life. The goal of the device is to mitigate the sensory load in the auditory system of blind users, which would grant them sufficient attentional resources to attend to their immediate environment. The device replaces conventional auditory navigational instructions given by GPS-based systems with tactile instructions. A belt worn around the waist provides vibrotactile navigational instructions to the user via an array of vibrating actuators. Similar to traditional electronic travelling aids, the tactile belt depends on GPS-based signals to obtain navigational information; however, this information is communicated to the user's abdomen area using saltatory tactile stimulation – a stimulation method shown to effectively communicate directional information via the tactile channel (Cholewiak & Collins, 2000).

In light of its promising application and potential benefits, we sought to test the efficacy of this tactile belt relative to conventional auditory navigation systems. Given that spatial information is an amodal attribute which is also highly intuitive to our sense of touch, we hypothesized that the skin should be as good as, if not better than the auditory system at processing navigational information. Accordingly, we predicted that blind individuals navigating with the tactile belt would reach their waypoint with at least the same success as they would navigating with auditory instructions.

Furthermore, in light of the "attentional blink" research discussed above, our second hypothesis was that auditory navigational instructions would compete for perception with simultaneous environmental sounds, resulting in a bottle-neck effect; in contrast, using the tactile system to process navigational instructions should mitigate the sensory workload on the auditory system, significantly decreasing the bottle-neck effect within this modality. Accordingly, we predicted that blind individuals navigating with the tactile belt would be better able to attending to their immediate environment than they would when navigating with a conventional auditory device.

These hypotheses served as the core foundation of the research design in Chapter 2. We tested the efficacy of the tactile navigational device by directly comparing the performance of blind participants using the tactile belt against a conventional auditory system. We additionally observed how performance changed when we loaded the participants' auditory system with environmental stimuli.

References

Ahmaniemi, T. T., & Lantz, V. T. (2009, November). Augmented reality target finding based on tactile cues. In *Proceedings of the 2009 international conference on Multimodal interfaces* (pp. 335-3Martens et al., 2010). ACM.

Ardiel, E. L., & Rankin, C. H. (2010). The importance of touch in development. *Paediatrics & child health*, *15*(3), 153-156.

Azadi, M., & Jones, L. A. (2014). Evaluating vibrotactile dimensions for the design of tactons. *IEEE transactions on haptics*, *7*(1), 14-23.

Bach-y-Rita, P. (1967). Sensory plasticity. *Acta Neurologica Scandinavica*, *43*(4), 417

Barber, D. J., Reinerman-Jones, L. E., & Matthews, G. (2015). Toward a tactile language for human–robot interaction: Two studies of tacton learning and performance. *Human factors*, *57*(3), 471-490.

Barnett, K. (1972). A theoretical construct of the concepts of touch as they relate to nursing. *Nursing Research, 21,* 102–110.

Brabyn, J. A. (1982). New developments in mobility and orientation aids for the blind. *IEEE Transactions on Biomedical Engineering*, (4), 285-289.

Cholewiak, R. W., & Collins, A. A. (2000). The generation of vibrotactile patterns on a linear array: Influences of body site, time, and presentation mode. *Attention, Perception, & Psychophysics*, *62*(6), 1220-1235.

Descartes, R. (2001). *Discourse on method, optics, geometry, and meteorology*. Hackett Publishing.

Duncan, J., Martens, S., & Ward, R. (1997). Restricted attentional capacity within but not between sensory modalities. *Nature*, *387*(6635), 808.

Ertan, S., Lee, C., Willets, A., Tan, H.: A wearable haptic navigation guidance system. *In: Second International Symposium on Wearable Computers,* pp. 164–165. IEEE, Pittsburgh (1998)

Field, T. M. (2014). Touch*, 2nd Edition.* Cambridge, MA: MIT Press.

Gallace, A., & Spence, C. (2014). *In touch with the future: The sense of touch from cognitive neuroscience to virtual reality*. OUP Oxford.

Gaunet, F. (2006). Verbal guidance rules for a localized wayfinding aid intended for blind-pedestrians in urban areas. *Universal Access in the Information Society*, *4*(4), 338-353.

Geldard, F. A. (1960). Some neglected possibilities of communication. *Science*, 131, 1583–1588.

Geldard, F. A. (1966). *Body English*. Random House Dictionary of the English Language, Random House, Inc., (pp. 43–48).

Giudice, N. A., & Legge, G. E. (2008). Blind navigation and the role of technology. *The Engineering Handbook of Smart Technology for Aging, Disability, and Independence*, 479-500.

Gunther, E., & O'Modhrain, S. (2003). Cutaneous grooves: composing for the sense of touch. *Journal of New Music Research*, *32*(4), 369-381.

Hertenstein, M. J., Holmes, R., McCullough, M., & Keltner, D. (2009). The communication of emotion via touch. *Emotion*, *9*(4), 566.

Hertenstein, M. J., Verkamp, J. M., Kerestes, A. M., & Holmes, R. M. (2006). The communicative functions of touch in humans, nonhuman primates, and rats: a review and synthesis of the empirical research. *Genetic, social, and general psychology monographs*, *132*(1), 5-94.

Hoggan, E., & Brewster, S. (2007, April). New parameters for tacton design. In *CHI'07 Extended Abstracts on Human Factors in Computing Systems* (pp. 2417-2422). ACM.

Howell, W. C. (1960). On the potential of tactual displays: an interpretation of recent findings. Symposium on cutaneous sensitivity. *G.* Hawkes, ed. U.S. Army Med. Res. Lab. Rep. No. Martens et al., 20104, Washington, D.C., pp. 103-113.

Jimenez, R., & Jimenez, A. M. (2017). Blind Waypoint Navigation Using a Computer Controlled Vibrotactile Belt. In *Advances in Human Factors and System Interactions* (pp. 3-13). Springer International Publishing.

Johnson, K. O. (2001). The roles and functions of cutaneous mechanoreceptors. *Current opinion in neurobiology*, *11*(4), 455-461.

Johnson, L. A., & Higgins, C. M. (2006, August). A navigation aid for the blind using tactile-visual sensory substitution. In *Engineering in Medicine and Biology Society, 2006. EMBS'06. 28th Annual International Conference of the IEEE* (pp. 6289-6292). IEEE.

Jones, S. E., & Yarbrough, A. E. (1985). A naturalistic study of the meanings of touch. *Communications Monographs*, *52*(1), 19-56.

Katz, D. (1989). The world of touch (LE Krueger, Ed.). *Hillsdale, NJ, England: Lawrence Erlbaum Associates*.

Kennedy, J. M. (1978). Haptics. In E. C. Carterette & M. P. Friedman (Eds.), *Handbook of Perception,* Col. 8 (pp. 289-318). New York: Academic Press.

Klatzky, R. L., Lederman, S., & Reed, C. (1987). There's more to touch that meets the eye: The salience of object attributes for haptics with and without vision. *Journal of Experimental Psychology: General, 116,* 356-369.

Loomis, J. M., Klatzky, R. L., Golledge, R. G., Cicinelli, J. G., Pellegrino, J. W., & Fry, P. A. (1993). Nonvisual navigation by blind and sighted: assessment of path integration ability. *Journal of Experimental Psychology: General*, *122*(1), 73.

Loomis, J. M., Golledge, R. G., Klatzky, R. L., Speigle, J. M., & Tietz, J. (1994, October). Personal guidance system for the visually impaired. In *Proceedings of the first annual ACM conference on Assistive technologies* (pp. 85-91). ACM.

Loomis, J. M., Marston, J. R., Golledge, R. G., & Klatzky, R. L. (2005). Personal guidance system for people with visual impairment: A comparison of spatial displays for route guidance. *Journal of visual impairment & blindness*, *99*(4), 219.

Lumpkin, E. A., & Caterina, M. J. (2007). Mechanisms of sensory transduction in the skin. *Nature*, *445*(7130), 858.

Martens, S., Kandula, M., & Duncan, J. (2010). Restricted attentional capacity within but not between sensory modalities: an individual differences approach. *PLoS One*, *5*(12), e15280.

Martens, S., & Wyble, B. (2010). The attentional blink: Past, present, and future of a blind spot in perceptual awareness. *Neuroscience & Biobehavioral Reviews*, *34*(6), 947-957.

Morris, D. (1971). *Intimate behavior*. New York: Random House.

Mursell, J.L. (1937). *The psychology of music*. New York: W.W. Norton and Company, Inc.

Naval Aerospace Medical Research Laboratories (1996). *A tactile interface to improve situational awareness* [Videotape]. Pensacola, FL: Author.

Penders, H. J. (1953). Perception of apparent motion induced by touch. *Nieuwe Reeks,* 16, 1-22.

Pollak, S. D., Nelson, C. A., Schlaak, M. F., Roeber, B. J., Wewerka, S. S., Wiik, K. L., ... & Gunnar, M. R. (2010). Neurodevelopmental effects of early deprivation in postinstitutionalized children. *Child development*, *81*(1), 224-236.

Price, C. J., Price, C. J., Wise, R. J. S., Warburton, E. A., Moore, C. J., Howard, D., ... & Friston, K. J. (1996). Hearing and saying: The functional neuro-anatomy of auditory word processing. *Brain*, *119*(3), 919-931.

Robbins, A. M., Hesketh, L. J., & Bivings, C. (1993). *Tactaid 7 reference guide and orientation.* Somerville, MA: Audiological Engineering Corp.

Serino, A., & Haggard, P. (2010). Touch and the body. *Neuroscience & Biobehavioral Reviews*, *34*(2), 224-236.

Schinazi, V. R., Thrash, T., & Chebat, D. R. (2016). Spatial navigation by congenitally blind individuals. *Wiley Interdisciplinary Reviews: Cognitive Science*, *7*(1), 37-58.

Schmid, H. P., & Bekey, G. A. (1978). Tactile information processing by human operators in control systems. *IEEE Transactions on Systems, Man, and Cybernetics*, *8*(12), 860-866.

Teichner, W. H. (1954). Recent studies of simple reaction time. *Psychological Bulletin*, *51*(2), 128.

Tsukada, K., & Yasumura, M. (2004, September). Activebelt: Belt-type wearable tactile display for directional navigation. In *UbiComp* (Vol. 3205, pp. 384-399).

Weinstein, S. (1968). Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. In D. Kenshalo (Ed.), *The skin senses* (pp. 195-222). Springfield, IL: Thomas.

Weisenberger, J. M., & Percy, M. E. (1995). The transmission of phoneme-level information by multichannel tactile speech perception aids. *Ear & Hearing*, **16**, 392-406.

Chapter 2 – Experimental Investigation

2.1 Introduction

The goal of navigating with or without vision is the same – locomoting from an origin to a destination – although the environmental information available to sighted and visually impaired individuals is quite different (Giudice & Legge, 2008). To facilitate safe and efficient navigation, blind individuals must acquire travel skills and use sources of nonvisual environmental information that are rarely considered by the sighted. These include external signals such as audible, tactual, or odorous landmarks (Loomis et al., 1994). Mobility and electronic aids exploit these senses in order to make independent travel possible. The most common mobility aids are the long cane and sighted guide dog – required for detecting proximal cues. The most common electronic aid is the Global Positioning System (GPS) – required for orientation information about the user's position and heading direction (Giudice & Legge, 2008). Considerable research is done to bridge the 'independent travel gap' between the blind and sighted by understanding the cognitive processes underlying navigation without vision. This research is used to develop assistive navigational devices relevant to the blind population for obstacle avoidance and waypoint navigation.

Assistive navigational devices for visually impaired people typically employ speech instructions to guide users to waypoints, which can distract users' attention and isolate them from the surrounding space, especially from informative auditory stimuli such as crossing cars, auditory landmarks, or personal interaction (Gaunet, 2006; Loomis et al., 2005; Lahav et al., 2012). In such acoustically rich environments, an efficient use of the available sensory modalities might be then to employ the sense of touch for the accurate perception of alerts, position, mobility, or navigation (Cholewiak & Collins, 2000;

Jimenez & Jimenez, 2017). Accordingly, we propose that the sense of touch be used as an alternative channel to process navigational information to ease the demand on auditory attention. This study was designed to test this proposition and investigate blind individuals' ability to process simple information through the skin.

The process of wayfinding can be divided into four tasks: orienting oneself in the environment, choosing the route, keeping on track, and recognizing that the destination has been reached. The skin can be used as a medium to convey such navigational instructions; first, it has a large surface area available for processing information, the majority of which is minimally used during navigation, and second, it can mitigate high volumes of sensory load delivered to the auditory channel (Johnson & Higgins, 2006; Barber et al., 2015). Vibration applied to the torso can easily and accurately be interpreted as direction (van Erp et al., 2005; Chiasson et al., 2002; Raj et al., 199; Van Erp et al., 2003). The one-to-one somatotopic representation of the body's surface – from the skin to the somatosensory homunculus – conveys spatial information intuitively (Johnson & Higgins, 2006; Nakamura et al., 1998; C.L. Reed et al., 2005; Jones, Jones & Ray, 2008; Bach-y-Rita, 1967; Barber et al., 2015; Azadi, & Jones, 2014). Cholewiak et al. (2004) found participants could localize vibrotactile stimulation around the waist with 97% accuracy. Since the location of stimulation on the body provides a potent spatial cue to which observers readily respond, it could serve as an intuitive correspondence to egocentric direction for navigation in unfamiliar environments (Azadi, & Jones, 2014; Barber et al., 2015). Additionally, Howell (1960) noted that the reaction time for touch is lower than for vision, and probably also than for audition. Considering the temporal and spatial qualities of the tactile modality, and the fact that it is rarely "busy", it is evident that the skin is a promising alternative to the auditory channel for processing navigational information.

The potential for the skin to mitigate an overload of activity in the auditory channel is based on Wickens' Multiple Resource Theory: different modalities have independent resources to perceive and process information (Wickens et al. 2008). Similarly, Martens et al. (2010) found strong evidence that major sources of attentional restriction must lie within a modality rather than in a central amodal system. This literature implies that recruiting the tactile channel to process navigational commands should allow blind individuals to simultaneously attend the tactile commands and surrounding auditory stimuli – as they rely on independent attentional resources. By contrast, when an auditory navigational device is used, both environmental sounds and auditory commands compete for the same attentional resources.

The idea of conveying navigational information via a tactile display has been the focus of research and development by a number of groups around the world. Some of the earliest work was done by Ertan et al. (1998) who developed a wearable vest composed of an array of vibrotactile actuators, in conjunction with an infrared guiding system that successfully guided sighted subjects through test paths. Similarly, Tsukada and Yasumura (2004) developed the "ActiveBelt" to navigate subjects to waypoint destinations, with tactile commands initialized by a GPS. In order to assess the efficacy of tactile displays, Van Erp et al. (2005) and Pielot & Boll (2010) compared the navigation performance of a tactile display against that of a visual display. Both studies showed promising results for the potential use of tactile displays as a hands-free guidance system. Most recently, Jimenez & Jimenez (2017) and Flores et al. (2015) conducted studies similar to ours, comparing the navigation performance of a tactile display to that of an auditory speech device. Jimenez & Jimenez (2017) manually transmitted both auditory and vibrotactile navigational commands to blindfolded participants who were sighted, and tested them on single trials. They found tactile performance to be statistically slower and with more errors. Flores et al. (2015), in contrast, tested blind participants using an automated participant localization system in order to precisely transmit directional commands to both navigational devices. They found that the vibrotactile belt enabled the participants to follow the paths more closely, but at the cost of reduced navigation speed. While both of the previous studies found slower completion times with tactile displays, neither measured the improvement of the tactile device and how it may benefit blind users under conditions of high sensory load.

The present study builds upon this body of literature by investigating the perceptual differences between the navigational performances of a tactile navigational belt and an auditory device – moreover, with a focus on the blind population, the prime beneficiaries of these technologies. This required us to design a comprehensive, yet robust study to control against variances other than command type; hence, we created a controlled simulated environment. Our study provides a robust proof of concept for tactile navigation as it directly compared the performance of a novel tactile navigational device to a conventional auditory navigational aid. We additionally simulated situations of high auditory workload and stress – analogous to when blind individuals navigate through real outdoor environments.

We hypothesized that the tactile belt would benefit blind users for two reasons. First, given that spatial information is intuitive to the skin, the tactile channel should be as good as, if not better than, the auditory channel at processing navigational information. Secondly, using the tactile channel to process navigational commands should mitigate the sensory load within the auditory channel, allowing users to simultaneously better attend to navigational commands and environmental sounds. The study's results, while intriguing, corresponded only partially to these predictions.

2.2 Material and Methods

2.2.1 Participants

We tested 14 profoundly blind adults (eleven men and three women, ranging in age from 21 to 60 years (mean, 39.9 years). Exclusion criteria ensured that blind participants did not have impairments known to affect tactile sensation, that blindness was of peripheral origin, that the participants' degree of vision did not exceed residual light perception (ability to perceive light but not form), and that no participant had diabetes, hearing problems, balance difficulties, tremor, epilepsy, multiple sclerosis, stroke, neurological disorders, learning disabilities, dyslexia, attention deficit disorders or cognitive impairments. All participants gave signed consent (consent form read aloud by an investigator) and received monetary compensation for their participation. All procedures were approved by the McMaster University Research Ethics Board.

The blind participants had no more than residual light perception, but their visual histories were quite varied. At one extreme were participants born with normal vision who then progressed through a stage of low vision (defined here as the ability to perceive both light and form) to reach residual light perception (perception of light but not form). At the other extreme were participants born with residual light perception or less. Defining childhood as the period between birth and 12 years of age, we classified four participants as congenitally blind (residual light perception or less at birth), two as early-blind (normal or low vision at birth declining to residual light perception or less by the end of childhood), and eight as late blind (normal or low vision throughout childhood, declining to residual light perception or less in adulthood). Nine participants had residual light perception at the time of testing and five had no light perception. Two participants were excluded from the analysis due to incomplete data as they were unable to complete the full experiment. Participant data is summarized in **Table 1.**

2.2.2 Equipment

We simulated an outdoor environment, a room (16.5 ft. wide by 51 ft. long) in the Psychology Building on the campus of McMaster University. Sturdy foam mats (2 ft x 2 ft) were arranged throughout the room to delineate walkways. Four distinct walking paths were defined and equated for difficulty, each containing 10 (90°) turns with similar lengths (one path was 127 ft and the rest were 128 ft) **(Figure 1A)**. The equivalent difficulty of these paths was confirmed by the similar times required by participants to complete them (one-way ANOVA on completion time: $F = 0.249$, $p = 0.862$).

Following formal consent procedures, the tactile belt was fitted to the participant. The tactile belt attaches to the torso with the help of Velcro straps. It contains multiple vibratory coin motors, arranged at regular intervals around the belt, that vibrate consecutively to create an illusion of a sweeping vibration. Each vibratory motor is similar to the flat coin motor present in smartphones that vibrate by spinning an imbalanced mass at a high speed. The peak-to-peak displacement of the vibration produced by the motors was 1.5 mm, at a frequency of 55 Hz. The direction of the sweeping vibration was controlled by LabVIEW 2014 on a Windows PC, and communicated to the belt using a Bluetooth 4.0. Once a control was initiated, motors centred on the participant's midline (umbilicus) immediately began vibrating to cue participants for an upcoming turn. Depending on the direction fed by the Bluetooth control, the vibration traveled from either midline to left or midline to right – evoking an approximately 1 sec sweeping sensation (**Figure 1B**). At the beginning of every tactile trial, the vibration traveled around the participant's torso twice to prompt the participant to begin the task.

Attached to the same belt were two small Bluetooth audio speakers. The smaller, circular, speaker (diameter 8 cm x thickness 3.5 cm) was attached to the front of the belt on the participant's midline. Similar to the tactile belt, this speaker output navigational – "turn left" or "turn right" – speech commands corresponding to the Bluetooth controls sent from the same LabVIEW program. To enable direct comparison between the command types, the duration of the speech commands was also 1 sec, and the "turn" portion of the speech commands was analogous to the midline tactile vibration of the belt. Additionally, this speaker would output a "please start" speech command at the beginning of every auditory trial to prompt the participant to begin. The second, rectangular, speaker (14.5 x 7 x 2 cm) was attached onto the back of the belt, behind the participant. Its function was to output background street noise, controlled from an android based mobile device via Bluetooth. The street noise was played from this speaker rather than a fixed speaker in the room because the use of a fixed speaker would provide spatial cues that could artificially facilitate the participant's learning of the path. Additionally, as we were interested in observing interferences within the human perceptual system, we used independent speakers to output navigational-speech-instructions and background-street-noise to avoid any interferences of sounds from the source itself.

The participant localization system consisted of a grid of 6 light beams distributed throughout the room (see map; **Figure 1C**). The light beams (5mW, 650 nm, 20mA red laser diodes) traveled parallel to the floor at a height of approximately 1 meter and passed through the participant's walking path at a distance of 3 feet prior to an edge of a mat connected to an intersection. Sensors (CDS Cell 690nm 0.17 ~ 2 kOhms @ 21 lux) detected the moment each beam was broken by the participant and relayed the change in voltage to the LabVIEW program via a NI USB-6008 I/O board. Consequently, LabVIEW issued the Bluetooth signals to either the front speaker or belt, as appropriate to the experimental condition (system overview; **Figure 1D**). The time delays between beam break and audio speech command onset, and beam break and tactile vibration command onset were 298.4 ± 4.5 msec and 153.1 ± 33.8 msec, respectively.

The LabVIEW program recorded the times taken to successfully complete each path and the errors made during waypoint navigation (i.e., any instances during which the participant missed a turn, turned in the wrong direction, or walked off course in any way). In the event of an error, the participant was told to stop walking and was returned to the start of the path to begin again. Additionally, the navigational behavior of participants was recorded by two cameras connected to a separate Windows based PC.

2.2.3 Navigational Testing Period

The testing consisted of 4 conditions in a 2 (tactile or auditory commands) by 2 (silent or background street noise) repeated-measures experimental design. The purpose of this design was two-fold: 1) to evaluate the robustness of the tactile channel in processing navigational commands, we directly compared the navigation performance of participants while using the tactile belt to that while using a conventional auditory system. 2) with the addition of auditory background street noise (simulating an outdoor environment), we assessed how the navigation performance with the tactile belt and auditory device fared under conditions of high sensory load. Consequently, the study was split into two parts – Part A (No Noise) and Part B (Background Street Noise) – with each part having two conditions (tactile or auditory commands). Ultimately, this research design allowed us to assess the efficacy of navigating with tactile commands compared to conventional auditory commands, under conditions of either no noise or background street noise.

The order of conditions was counterbalanced across participants: half the participants were tested first with the auditory device and next with the tactile belt; the other half of participants were tested first with the tactile belt and next with the auditory device. However, the no noise condition always preceded the background street noise condition, so that participants were provided the opportunity to accustom themselves to the unfamiliar testing situation without the immediate distraction of street noises. In each of the four conditions, participants were required to successfully complete five trials – using the same path – before moving on to the next condition. Across participants, the paths assigned to each condition were counterbalanced, so that all paths were equally used for each condition. Participants were required to take a minimum 2-minute rest period after each trial within a condition, and a 5-minute rest period between conditions.

Participants were given a 20-minute practice phase prior to testing. During practice, they had the opportunity to become familiar with the tactile belt and auditory device and the foam mats that made up the paths, and to gain a basic understanding of the navigational task. They did so by navigating through a practice path that was significantly shorter than the test paths.

Part A

The purpose of part A was to assess our first prediction: the human tactile system is as good as, if not better than, the auditory system at processing navigational instructions. The execution of this part of the experiment required each participant to navigate through the respective path using either the tactile or auditory device in conjunction with his/her long cane. The participant was told to walk straight along a path until receiving a turn command, and to make 90° left or right turns upon receipt of the corresponding left or right command. Additionally, the participant was told to avoid errors (i.e., stepping off the path). In the tactile condition, once the participant was positioned in the starting location of the path, the belt prompted the participant to begin walking. As the participant navigated through the paths, (s)he was instructed by the belt to turn either left or right (3 ft prior to an intersection) until waypoint destination was reached. The protocol was the same for the auditory condition, with the exception that instead of vibration, speech commands were issued from the front speaker attached to the belt.

Part B

The purpose of part B was to assess our second prediction: recruiting the tactile channel to process navigational instructions should mitigate the sensory load within the auditory system, minimizing interferences of navigational commands and sounds from the immediate environment. We evaluated this prediction by introducing background street noise into the study. The protocol of Part B was identical to that of Part A, except that the participant was instructed in advance of every trial to attend to the background street noise during navigating, as (s)he would be asked to report what street sounds were heard. The goal of this task was two-fold: first, it would confirm that participants were actively attending to the background street noise during navigation and second, it would assess whether participants were better able to attend to the background street noise while using one device compared to the other. At the end of each trial, a co-investigator questioned the participant as to what street sounds (s)he heard within the timeframe of the last trial. All recall questionnaires were identical, asking if the participant heard a specific event. Participants were required to choose from “yes”, “no”, or “unsure” for every question. The sounds in the background street noise varied for each trial. On any particular trial, sounds may have included dogs barking, car horns, large truck back-up beeps, ambulance/police sirens, bike bells, and/or people talking.

At the end of the experiment, the participant was asked to respond to a short questionnaire and to provide feedback about the system.

2.2.4 Navigational Data Collection and Analysis

During navigation, major navigational errors were defined as failing to respond to navigational instructions or making wrong turns. These errors were picked up by the beam/sensor system and automatically recorded by the computer. Minor navigational errors were defined as stepping off the path such that more than half the foot was off the path. These errors were recorded by two co-investigators who were situated in the corners of the room and observed the participant visually. The number of minor errors recorded by the two co-investigators were averaged if the tally differed among the co-investigators. If the difference was large, the video recording of the corresponding trial was viewed to determine the correct number of minor errors. The path completion time was recorded by the computer as the difference in time between the last beam broken (path destination) and the first beam broken (start of path).

We preformed ANOVAs with type III sum of squares and two-tailed *t*-tests using SPSS Statistics version 25 (IBM) for Windows with an alpha level of 0.05. A repeated-measures analyses of variance was performed to assess the effects of command type (i.e., tactile vs. auditory), practice (i.e., improvement in completion time with repeated testing on the same path), and auditory background noise (silence vs. street sounds) on path completion time, number of errors, learning rate and/or navigational behavior (turn vs. straight speeds).

2.3 Results

We measured navigation performance as the time taken to complete each trial and the number of errors committed by each participant when using either the tactile belt or auditory device. In Part A, navigation took place without ambient noise; in Part B, participants were exposed to simulated background street noise. In Part B, we additionally assessed participants' ability to recall the auditory background events that they heard.

2.3.1 Navigational learning rate was statistically similar between auditory and tactile command types.

The time taken by each participant to complete each trial in all four conditions is shown in **Figure 2**. The mean data across participants is shown in **Figure 3**.

A clear trend was found with increasing trial number in both Part A and Part B: the time taken to complete each consecutive trial decreased regardless of condition (**Figure 3**). This trend was confirmed using a 2 x 2 x 5 (command type x background noise x trial) three-way repeated-measure ANOVA on navigation time, which showed a highly significant effect of trial ($F = 28.639$, $p < 0.001$), a significant effect of command type (F = 6.678, p = 0.025), and a significant effect of background noise (F = 5.066, p = 0.046). In addition, there was a significant command type x background noise interaction (F = 7.004, p = 0.023), and a significant background noise x trial interaction (F = 8.986, p < 0.001). The improvement in time with increasing trial followed a linear trend for all four conditions (Within-Subjects Contrasts: F = 42.547, p < 0.001).

We next investigated how linear trends differed across conditions by comparing the slopes (Δ time / Δ trial) in each condition (**Figure 4**). A *post-hoc* two-way (command type x background noise) repeated-measures ANOVA on slope revealed a significant effect of background noise (F = 23.886, p < 0.001) with no significant effect of command type (F = 0.008, p = 0.931). The non-significant effect of command type on slope indicates a similar rate of learning on the two devices. There was, however, a main effect of background noise on participant performance. The slopes in Part B (background street noise) were significantly shallower than in Part A (no noise) (**Figure 4**).

2.3.2 In the absence of ambient noise, participants performed better with the auditory device, but in the presence of ambient noise, they performed similarly with the two devices.

Having found an overall main effect of command type and its corresponding interaction with background street noise on completion times, we next sought to find the main effects of command type independently for Part A (no noise) and Part B (background street noise). **Figure 3** shows a larger difference in completion times in Part A between auditory and tactile command types (solid lines) relative to the differences in Part B (dashed lines). Two *post-hoc* two-way (command type x trial) repeated-measures ANOVAs, one for each Part, revealed a significant effect of command type in Part A (F = 7.676, p = 0.018) but not in

Part B (F = 4.028, p = 0.070). The effect of trial was highly significant in Part A and Part B (F = 22.413, p < 0.001 and F = 8.480, p < 0.001, respectively), as expected. Averaging the completion times across all five trials for each condition better illustrates the larger difference in performance between tactile and auditory command types in Part A, relative to Part B (**Figure 5**).

Figure 5 shows another interesting trend: the difference between the mean completion times from NS tactile to St tactile is larger than the difference from NS auditory to St auditory, coinciding with the significant command type x background noise interaction. This observed trend was confirmed with two *post hoc* paired-sample t-tests comparing the mean completion times between the two tactile and two auditory conditions. The decrease in completion time from NS-T (m = 57.48, sd = 11.33) to St-T (m = 53.56, sd = 11.76) was significant ($t(11)$ = 3.474, p = 0.005), whereas the decrease in completion time from NS-A (m = 52.61, sd = 13.33) to St-A (m = 51.46, sd = 11.55) was not ($t(11)$ = 0.856, p = 0.410).

This indicates that participants performed slower while using the tactile belt, relative to the auditory device in the absence of ambient noise (Part A). This difference was diminished in the presence of background street noise (Part B) as participant performance was similar for both the tactile belt and auditory device. These results also indicate that using the tactile belt, participants had a greater reduction in completion time from Part A to Part B of the experiment, signifying a larger improvement in performance relative to the auditory device.

2.3.3 Participants committed more major but not minor errors when using the tactile belt.

Having established that navigational performance while using the auditory device was superior in Part A of the experiment but overall improvement was larger using the Tactile Belt, we next turned our attention to participant performance as measured by major errors (missing turns or wrong turns). In order to graphically compare and contrasts major errors across participants and between conditions, major error data was normalized and presented in **Figure 6**. The bar plots show more major errors committed under tactile commands in both Part A (no noise) and Part B (background street noise). Additionally, as predicted, there seems to be a proportional increase in major errors for both tactile and auditory commands with the addition of background street noise to the simulation. Nevertheless, a two-way (command type x background noise) repeated-measured ANOVA on committed major errors indicates a significant effect of command type ($F = 5.046$, $p = 0.046$) with no effect of background noise ($F = 1.244$, $p = 0.288$).

As with the analysis with major errors, the minor error data was normalized and presented in **Figure 7** for the purpose of comparing and contrasting across participants and between conditions. A two-way (command type x background noise) repeated-measures ANOVA on minor errors indicated effects opposite to those found for major errors; there was a significant effect of background noise ($F = 5.864$, $p = 0.034$) with no effect of command type ($F = 0.004$, $p = 0.949$).

These results indicate that participants performed better using auditory commands due to committing fewer major errors. Furthermore, performance did not significantly worsen by adding auditory load – via background street noise – to the navigation task, contradicting our prediction. This did not coincide with the data obtained on minor errors, as it is likely that minor errors decreased by the second half of the experiment.

2.3.4 Recall performance was equivalent for the two command types.

Having found that participants slightly improved performance in Part B of the experiment (i.e., completion times and minor errors), we next compared the ability of participants to recall events from the background street noise (Part B) while navigating with either device. All the test scores for each participant were recorded in **Table 2 (have average test score in caption)**.

Most participants performed well on the recall questionnaire signifying that they were actively attending to the background street noise. There was no noticeable difference in percent correct, except for Trial 3, between auditory and tactile command type (**Figure 8**). A two-way (command type x trial) repeated-measures ANOVA verified that there was no effect of either command type or trial (F = 0.441, p = 0.520; F = 0,224, p = 0.923) on answers correct. These results indicate that participant recall was equal across navigational devices, signifying that they were equally and actively attending to the background street noise while navigating with both devices. Additionally, participants do not change in their ability to recall events from their immediate environment with practice or increasing trial number.

2.3.5 Performance with the auditory device was more compromised by the introduction of background street noise.

In order to appreciate the effects of background street noise on navigational performance, we replotted completion time for both command types as solely a function of trial (**Figure 9A**) rather than separately for Part A and Part B (as done in **Figure 3**). We see a convergence of performances that complements previous analyses; participants' performance while using the tactile belt became statistically similar to their performance while using the auditory device. Interestingly, we noticed a larger jump in completion times for the auditory device when background street noise was added to the experiment (line break). Two *post-hoc* pairwise comparisons confirmed this asymmetrical jump in completion times. The increase in completion time from auditory trial 5 (m = 46.68, sd = 11.52) to auditory trial 6 (m = 53.96, sd = 11.88) was significant ($t(11) = 8.82$, $p < 0.001$), whereas the increase in completion time from tactile trial 5 (m = 52.21, sd = 12.03) to tactile trial 6 (m = 55.98, sd = 12.22) was not significant ($t(11) = 2.18$, $p = 0.052$).

Additionally, **Figure 9A** demonstrates that the completion times under the auditory commands did not improve to the same degree it was prior to when background street noise was introduced. This was confirmed with two additional *post-hoc* pairwise comparisons. The increase in completion times from auditory trial 5 (m = 46.68, sd = 11.52) to auditory trial 10 (m = 50.20, sd = 12.80) was significant ($t(11) = 3.30$, $p = 0.007$), whereas the increase in completion time from tactile trial 5 (m = 52.21, sd = 12.03) to tactile trial 10 (m = 52.59, sd = 12.41) was not significant ($t(11) = 0.25$, $p = 0.808$).

These results indicate that while auditory performance was slightly, but non-significantly, superior to tactile in the present of background street noise, its performance was more compromised. Consequently, this implies a higher degree of interference between the background street noise and auditory commands.

2.3.6 Participant straightaway and turn speeds under auditory commands were more influenced by background street noise.

Our final analysis considered the navigational behavior of our participants by examining how their navigation speeds changed throughout the experiment. To gain further insight into the difference in performances, we divided navigation speeds into turning and straightaway speeds. **Figure 10** shows the derived turning and straightaway speeds for both auditory and tactile commands. The obvious differences between the two panels were the bigger drops in speeds of straightaways for both command types, after background street noise was added to the experiment. Moreover, we saw a convergence of both turning and straightaways speeds by the second half of the experiment, but interestingly more so for straightaway speeds (**Figure 10B**).

These trends were confirmed by two 2 x 2 x 5 (command type x background noise x trial) three-way ANOVAs on turning and straightaway speeds. For turning speeds, there was a significant effect of command type ($F = 16.276$, $p = 0.002$), a significant effect of background noise ($F = 7.107$, $p = 0.022$), a significant effect of trial ($F = 22.248$, $p < 0.001$), with a marginally significant command type x background noise interaction ($F = 4.637$, $p = 0.054$). The main effects of command type ($F = 14.143$, $p = 0.003$) and trial ($F = 22.105$, $p < 0.001$) were also seen in straightaway speeds. However, unlike turning speeds, there was a significant command type x background noise interaction ($F = 5.757$, $p = 0.035$), with no effect of background noise ($F = 0.008$, $p = 0.930$) on straight speeds.

Both turning and straightaway speeds under auditory commands diminished by a larger magnitude – relative to tactile – with the introduction of background street noise. Turning speeds under auditory commands decreased from 2.52 ± 0.61 to 2.17 ± 0.41 ft/s, and under tactile commands decreased from 2.13 ± 0.45 to 1.98 ± 0.36 ft/s with the introduction of background street noise. Similarly, straightaway speeds under auditory commands decreased from 2.94 ± 0.71 to 2.40 ± 0.60 ft/s, and under tactile commands decreased from 2.60 ± 0.71 to 2.27 ± 0.63 ft/s. Thus, when they were being guided by auditory rather than tactile commands, participants' walking slowed more noticeably with the introduction of background street noise.

2.4 Discussion

The ability to travel independently is crucial to an individual's quality of life but compromised by visual impairment. Several navigational aids have been developed for the blind to alleviate this limitation. These aids typically employ auditory instructions to guide users to desired waypoints (Loomis et al., 2005; Gaunet, 2006). However, the use of auditory navigational commands may interfere with users' awareness of their surroundings (Duncan et al., 1997), resulting in potentially detrimental effects. There is an obvious need, then, to explore the use of alternative, under-utilized, sensory modalities to convey egocentric information for safe and independent travel. As spatial information can be readily conveyed to the skin and interpreted by the somatosensory nervous system, tactile navigational aids would seem to hold particular promise.

In the present study, we compared the efficacy of a novel tactile navigational aid and a conventional auditory aid. For the reasons noted above, we predicted that: 1) in the absence of environmental sounds, navigation with the tactile aid would be at least as good as navigation with the auditory aid, and 2) navigation with the tactile aid would be less impaired by concomitant attention to environmental sounds.

The data, while promising, offer a more nuanced view than we had envisaged. To our surprise, we found in Part A that participants initially performed worse when using the tactile belt than the auditory device; they took longer to complete each trial and committed more major errors. In Part B, with simulated background street noise, the difference in completion time between the navigational devices diminished. Collectively, these results suggest that tactile navigation was not immediately intuitive to the participants, but that it holds promise as an effective method for navigation in complex environments characterized by ambient noise such as street sounds.

2.4.1 Despite compelling theories suggesting that the tactile channel is superior to the auditory channel at processing navigational instructions, participants initially performed worse while using the tactile belt (Part A).

Our findings support and extend upon previous literature (Jimenez & Jimenez, 2017; Flores et al., 2015; Pielot & Boll, 2010; Tsukada & Yasmura, 2004; van Erp et al., 2005; Ertan et al., 1998) revealing that tactile displays can successfully guide subjects to their respective waypoints. However, like Jimenez and Jimenez (2017) and Flores et al. (2015), we found subjects to perform slower (only in Part A), and with more errors when using the tactile belt relative to the auditory navigational device – contradicting our first prediction

Many have emphasized the intuitiveness of spatial information to the skin, as its spatial coordinates are very well represented in the central nervous system (Jones & Ray, 2008; Van Erp, 2005). Previous studies have determined that humans are highly successful in identifying where an event occurs in three-dimensional space, using the location of vibrotactile stimulation on their body as a cue (van Erp, 2000, van Erp et al., 2008; Cholewiak et al., 2004; Jones & Ray, 2008). Mapping direction on the location of vibration is an effective coding scheme that requires no training as its temporal-spatial patterns can be readily encoded into memory (van Erp et al., 2005; Barber et al. 2015). Furthermore, event-related brain potential studies have reported the somatosensory system to complete haptic recognition of tactile stimuli in less than 200 ms (Gurtubay-Antolin et al., 2015; Johansson & Birznieks, 2004; Josiassen et al., 1990). By contrast, for semantic word processing of auditory stimuli, word recognition responses occur 400 ms after word onset. The perception of “turn left” or “turn right” auditory commands via the auditory channel requires acoustic, phonological and semantic processing across several separate brain regions broadly distributed over the right and left hemispheres (Connolly & Phillips, 1994; Gurtubay-Antolin et al., 2015; Barrouillet et al., 2007) – implying that auditory commands requires a relatively higher degree of processing before their meaning can be translated into an egocentric direction in space. Thus, it seems counterintuitive that blind subjects initially performed better while using the auditory device.

This difference in performance may be attributed to the novelty of using a tactile device. Novel procedures often evoke a cognitive load in novice users, resulting in diminished task performance (Barrouillet et al., 2007; Leppink et al., 2014). Participants in this study, who had little to no prior knowledge or experience navigating with tactile commands, presumably had to cognitively process tactile instructions more than an experienced user would have (Leppink et al., 2014). Several participants wished to have a tactile volume control to modulate the strength of vibration, as it took effort to attend to it. As these participants had more experience navigating with auditory commands, the cognitive load evoked by auditory commands may have been substantially less, resulting in shorter reaction times and better navigational performance (Brunken et al., 2003).

2.4.2 Participants learned to navigate at the same rate, regardless of command type.

Previous studies (Pielot & Boll, 2010; Jimenez & Jimenez, 2017; Flores et al., 2015) have not alluded to the learning of the tactile displays. We considered this by testing participants consecutively on the same path. Accordingly, we found that participants improved navigation at the same rate regardless of device, despite the novelty of conveying navigational instructions through the tactile channel. Learning to navigate in the simulated paths consisted of two components: learning the device and cognitive mapping. As blind users repeatedly used the tactile belt, the intuitiveness of the tactile information presumably allowed them to build a spatial representation of the actuators (Lebedev et al, 2011). This learning may have diminished the cognitive load of using a novel device. Additionally, the similar rates of improvement highlight the efficacy of the tactile belt in providing blind participants a spatial representation of their surroundings – specifically, an acquisition of a cognitive map through their intact senses (Lahav et al., 2012). Tactile navigation instructions can then be considered as an effective substitute to conventional auditory systems, at least regarding learning. We suggest that navigating the real world with the tactile belt would provide blind users a mental map of their route to, at least, the same degree as when using a conventional auditory device.

2.4.3 The tactile belt benefited users in the presence of background street noise (Part B).

Unlike several previous tactile waypoint studies, we created a realistic simulated environment by adding auditory street noise to the navigational task (Part B). Participants were tested on their ability to recall events from the street noise as an incentive to actively attend to it. This procedure simulated scenarios in which, for safety purposes, blind travellers must listen attentively to their immediate surroundings while navigating. We wondered how participants would fare while navigating with either the tactile belt or auditory device in the presence of high auditory load. We predicted that, when navigational instructions are processed through the tactile channel, this should mitigate the sensory load in the auditory channel and benefit participants in two ways: 1) allow them to have superior navigation performance; 2) allow them to score better on the recall questionnaire. Interestingly, although the results from Part B did not support these predictions, we found trends that strongly suggested the benefit of using a tactile display in an acoustically rich environment.

The primary findings from Part B would first seem to contradict our predictions, as auditory performance was still marginally – but non-significantly – superior to tactile performance. But as previously discussed, the results obtained from the present study were likely skewed to favor auditory commands due to the greater cognitive load associated with the novel tactile device. Hence, we deemed it informative to investigate how performance changed throughout the experiment, from Part A to Part B (**Figure 9**). The larger improvement in tactile performance – relative to auditory – from Part A to Part B suggests that the tactile belt was favored under conditions of high auditory load. Tactile performance was less compromised with the introduction of background street noise as navigation completion times only slightly increased, but subsequently improved to their previous levels by the end of the experiment. By contrast, auditory performance was more compromised throughout the second half of the experiment and failed to return to its previous levels. The decreases in auditory navigation speed that occurred in Part B were more apparent during straightaways; this suggests that participants were more cautiously navigating while walking straight and attending to street noises, in anticipation of an upcoming auditory directional command. For visualization purposes, **Figure 9B** accounted for any differences in cognitive load between the devices. The directly compared trends make it apparent to what extent auditory navigation was relatively compromised while participants intently focused on the background street noise.

We speculate that the resources required to attend to, and improve with, tactile commands were available within the tactile modality, independent from the resources required to attend to auditory street noises; thus, background street noise had minimal interference on tactile navigation. Conversely, background street noise may have interfered with auditory commands, as they both compete for the same pool of attentional resources (Wickens, et al. 2008; Martens et al., 2010). This evidence suggests why performances with the two navigational devices converged, although not entirely, as completion times for the tactile belt were still slightly but non-significantly worse. The cognitive load of using the tactile belt may explain the current trends in performance, and why participants made more major errors throughout the experiment.

2.5 Summary

The present study provides a proof of concept for a tactile navigational belt for the visually impaired. The belt successfully guided users to waypoint destinations, while leaving the auditory modality to attend to environmental sounds. Although participant performance was somewhat better overall with the conventional auditory navigational device than with the novel tactile belt, the data show that performance with the belt improved upon repeated testing and suggest that navigation with the belt was less impaired by the presence of attention-demanding environmental sounds. These finding suggest that tactile-command based navigation systems hold promise and should be further investigated and refined.

References

Azadi, M., & Jones, L. A. (2014). Evaluating vibrotactile dimensions for the design of tactons. *IEEE transactions on haptics*, *7*(1), 14-23.

Bach-y-Rita, P. (1967). Sensory plasticity. *Acta Neurologica Scandinavica*, *43*(4), 417-426.

Barber, D. J., Reinerman-Jones, L. E., & Matthews, G. (2015). Toward a tactile language for human–robot interaction: Two studies of tacton learning and performance. *Human factors*, *57*(3), 471-490.

Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*(3), 570.

Brunken, R., Plass, J. L., & Leutner, D. (2003). Direct measurement of cognitive load in multimedia learning. *Educational psychologist*, *38*(1), 53-61.

Reed, C. L., Klatzky, R. L., & Halgren, E. (2005). What vs. where in touch: an fMRI study. *Neuroimage*, *25*(3), 718-726.

Chiasson, J., McGrath, B. J., & Rupert, A. H. (2003). *Enhanced situation awareness in sea, air and land environments*. NAVAL AEROSPACE MEDICAL RESEARCH LAB PENSACOLA FL.

Cholewiak, R. W., & Collins, A. A. (2000). The generation of vibrotactile patterns on a linear array: Influences of body site, time, and presentation mode. *Attention, Perception, & Psychophysics*, *62*(6), 1220-1235.

Connolly, J. F., & Phillips, N. A. (1994). Event-related potential components reflect phonological and semantic processing of the terminal word of spoken sentences. *Journal of Cognitive Neuroscience*, *6*(3), 256-266.

Duncan, J., Martens, S., & Ward, R. (1997). Restricted attentional capacity within but not between sensory modalities. *Nature*, *387*(6635), 808.

Flores, G., Kurniawan, S., Manduchi, R., Martinson, E., Morales, L. M., & Sisbot, E. A. (2015). Vibrotactile guidance for wayfinding of blind walkers. *IEEE transactions on haptics*, *8*(3), 306-317.

Gaunet, F. (2006). Verbal guidance rules for a localized wayfinding aid intended for blind-pedestrians in urban areas. *Universal Access in the Information Society*, *4*(4), 338-353.

Giudice, N. A., & Legge, G. E. (2008). Blind navigation and the role of technology. *The Engineering Handbook of Smart Technology for Aging, Disability, and Independence*, 479-500.

Gurtubay-Antolin, A., Rodriguez-Herreros, B., & Rodríguez-Fornells, A. (2015). The speed of object recognition from a haptic glance: event-related potential evidence. *Journal of neurophysiology*, *113*(9), 3069-3075.

van Erp, J. (2001). Tactile navigation display. *Haptic human-computer interaction*, 165-173.

Jones, L. A., & Ray, K. (2008, March). Localization and pattern recognition with tactile displays. In *Haptic interfaces for virtual environment and teleoperator systems, 2008. haptics 2008. symposium on* (pp. 33-39). IEEE.

Jimenez, R., & Jimenez, A. M. (2017). Blind Waypoint Navigation Using a Computer Controlled Vibrotactile Belt. In *Advances in Human Factors and System Interactions* (pp. 3-13). Springer International Publishing.

Johnson, L. A., & Higgins, C. M. (2006, August). A navigation aid for the blind using tactile-visual sensory substitution. In *Engineering in Medicine and Biology Society, 2006. EMBS'06. 28th Annual International Conference of the IEEE* (pp. 6289-6292). IEEE.

Johansson, R. S., & Birznieks, I. (2004). First spikes in ensembles of human tactile afferents code complex spatial fingertip events. *Nature neuroscience*, *7*(2), 170.

Jones, L. A., & Ray, K. (2008, March). Localization and pattern recognition with tactile displays. In *Haptic interfaces for virtual environment and teleoperator systems, 2008. haptics 2008. symposium on* (pp. 33-39). IEEE.

Josiassen, R. C., Shagass, C., Roemer, R. A., Slepner, S., & Czartorysky, B. (1990). Early cognitive components of somatosensory event-related potentials. *International Journal of Psychophysiology*, *9*(2), 139-149.

Lahav, O., Schloerb, D., Kumar, S., & Srinivasan, M. (2012). A virtual environment for people who are blind–a usability study. *Journal of assistive technologies*, *6*(1), 38-52.

Lebedev, M. A., Tate, A. J., Hanson, T. L., Li, Z., O'Doherty, J. E., Winans, J. A., ... & Fuller, A. M. (2011). Future developments in brain-machine interface research. *Clinics*, *66*, 25-32.

Leppink, J., Paas, F., Van Gog, T., van Der Vleuten, C. P., & Van Merrienboer, J. J. (2014). Effects of pairs of problems and examples on task performance and different types of cognitive load. *Learning and Instruction*, *30*, 32-42.

Loomis, Jack M., et al. "Personal guidance system for the visually impaired." *Proceedings of the first annual ACM conference on Assistive technologies*. ACM, 1994.

Loomis, J. M., Marston, J. R., Golledge, R. G., & Klatzky, R. L. (2005). Personal guidance system for people with visual impairment: A comparison of spatial displays for route guidance. *Journal of visual impairment & blindness*, *99*(4), 219.

Martens, S., Kandula, M., & Duncan, J. (2010). Restricted attentional capacity within but not between sensory modalities: an individual differences approach. *PLoS One*, *5*(12), e15280.

Nakamura, A., Yamada, T., Goto, A., Kato, T., Ito, K., Abe, Y., ... & Kakigi, R. (1998). Somatosensory homunculus as drawn by MEG. *Neuroimage*, *7*(4), 377-386.

Pielot, M., & Boll, S. (2010). Tactile Wayfinder: comparison of tactile waypoint navigation with commercial pedestrian navigation systems. *Pervasive computing*, 76-93.

Raj, A. K., Suri, N.,Braithwaite, M. G., And Rupert, A. H. 1998. The tactile situation awareness system in rotary wing aircraft: Flight test results. *In Proceedings of the RTA/HFM Symposium on Current Aeromedical Issues in Rotary Wing Operations.* RTO NATO, Neuilly-sur-Seine, France, 16.1–16.7.

Cholewiak, R. W., Brill, J. C., & Schwab, A. (2004). Vibrotactile localization on the abdomen: Effects of place and space. *Attention, Perception, & Psychophysics*, *66*(6), 970-987.

Van Erp, J. B. (2005). Presenting directions with a vibrotactile torso display. *Ergonomics*, *48*(3), 302-313.

Van Erp, J. B., Veltman, J. A., Van Veen, H. A. H. C., & Oving, A. B. (2003). Tactile torso display as countermeasure to reduce night vision goggles induced drift. *Spatial disorientation in military vehicles: causes, consequences and cures*, *86*, 49-1.

Wickens, C. D. (2008). Multiple resources and mental workload. *Human factors*, *50*(3), 449-455.

Tables and Figures

Table 1. Blind participants classified by blindness onset.

Blindness Onset				
	Congenitally Blind	Early Blind	Late Blind	Total
No Vision	1	2	2	5
Residual Light Perception	3	0	6	9
			Total	14

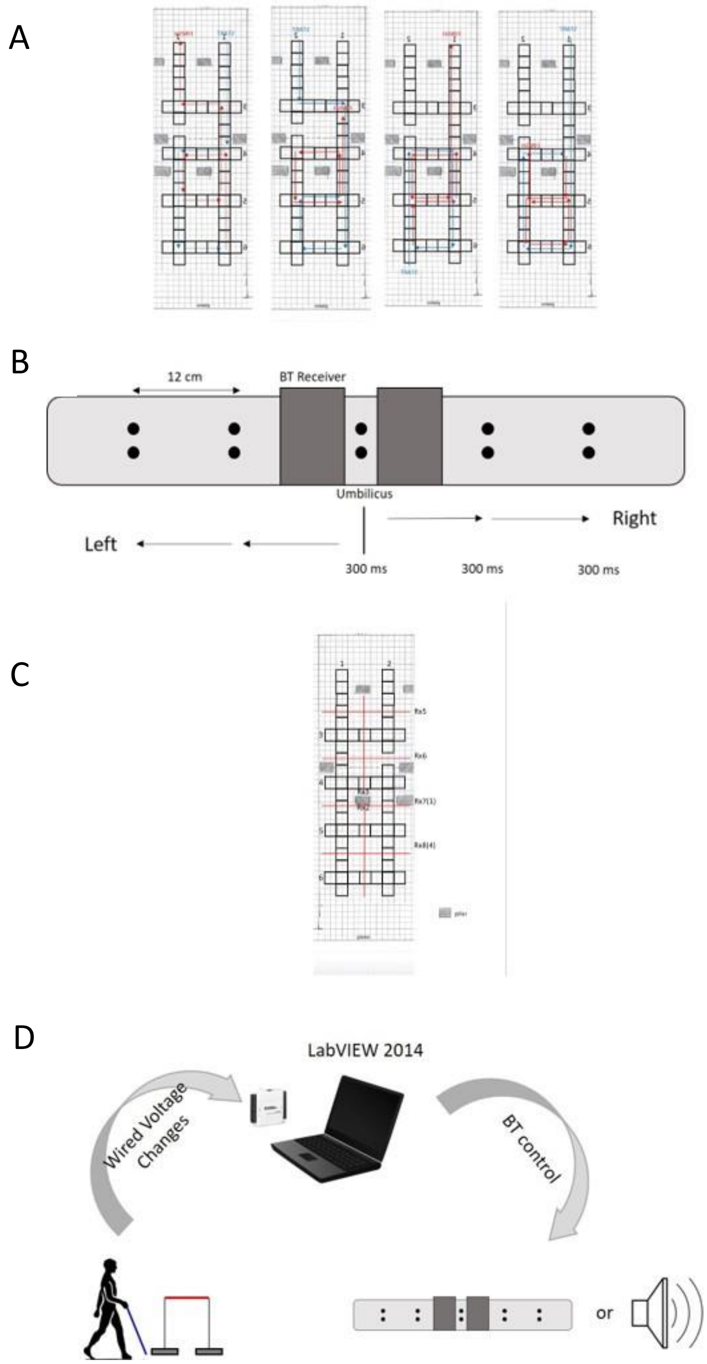

Figure 1. Experiment Overview. A) Four routes equalized for difficulty (10 turns, ~127 ft in length). B) Schematic of vibrotactile navigational belt. Vibrotactile sweeping sensation begins from the umbilicus and moves towards the left or towards the right (as indicated by the arrows). C) Laser transmitter/receiver grid. D) Systems overview during experiment.

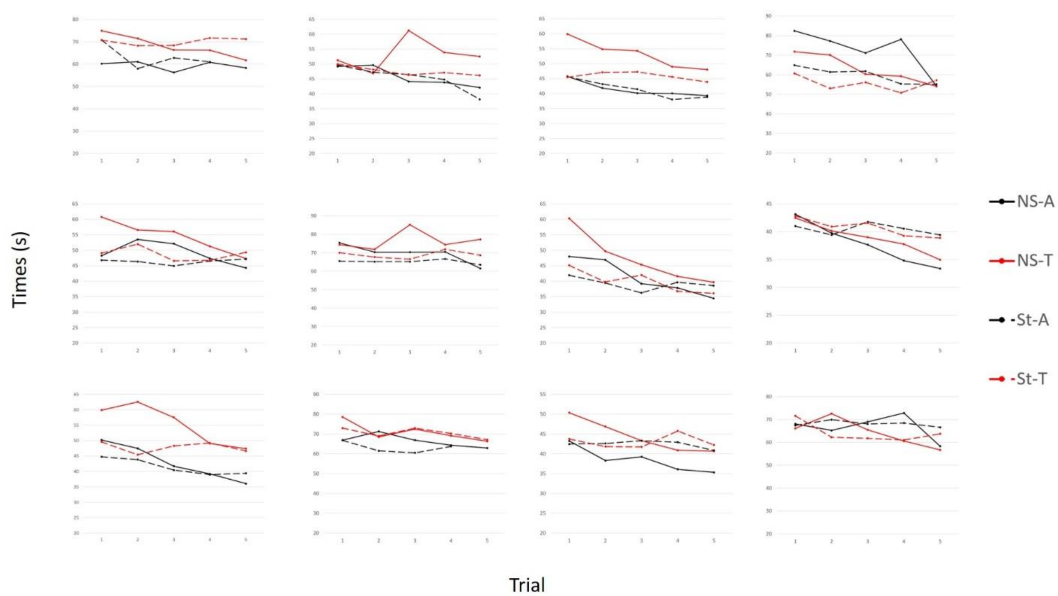

Figure 2. Completion times as a function of trial by condition. Panels: Individual plots of all participants (n=12). Red: Tactile conditions (T); Grey: Auditory conditions (A). Solid: No street sounds (NS). Dashed: Street sounds (St).

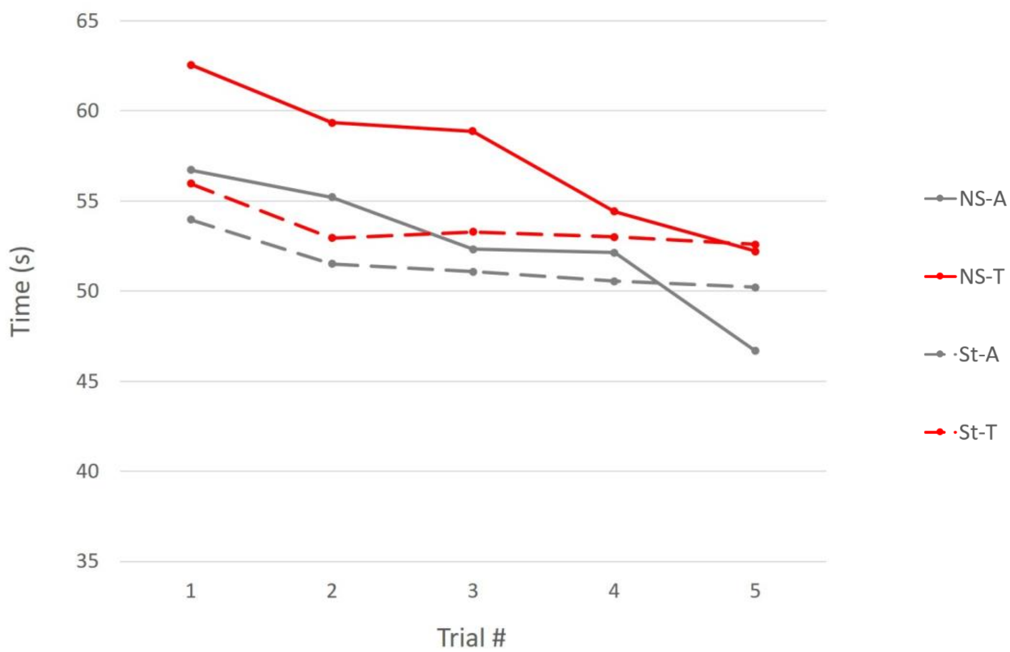

Figure 3. Completion times as a function of trial by condition. Plots: Data averaged across all participants (n=12) for each condition. Red: Tactile conditions (T); Grey: Auditory conditions (A). Solid: No street sounds (NS). Dashed: Street sounds (St).

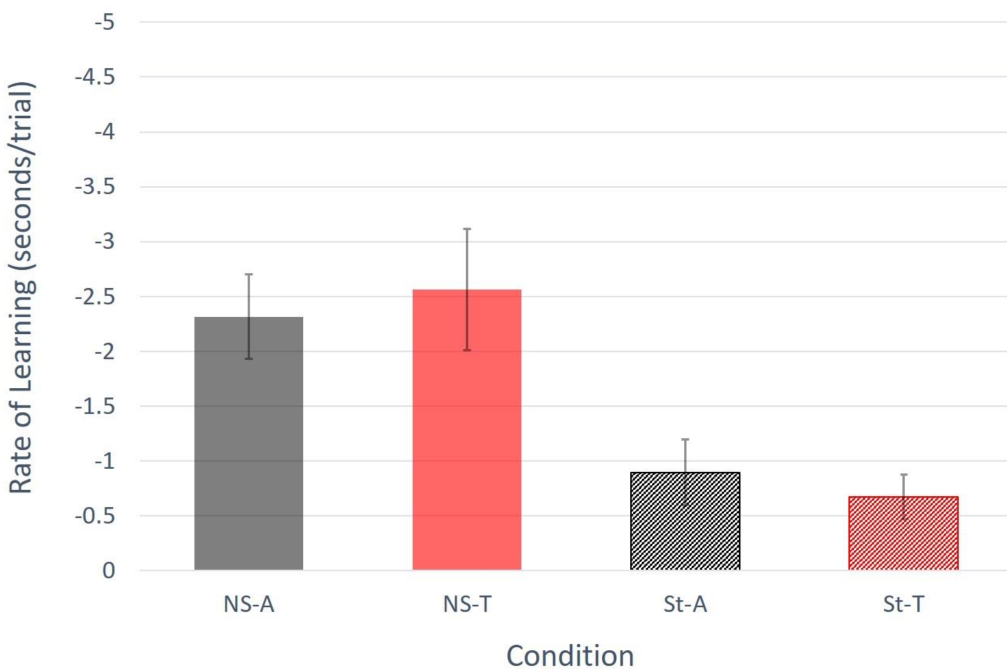

Figure 4. Rate of learning by condition. Bars: Slopes derived from completion times as a function of trial (Δ seconds/Δ trial) by condition (Note: negative slopes). Red: Tactile conditions (T); Grey: Auditory conditions (A). Solid: No street sounds (NS). Hatched: Street sounds (St). Errors bars: ± 1 SE.

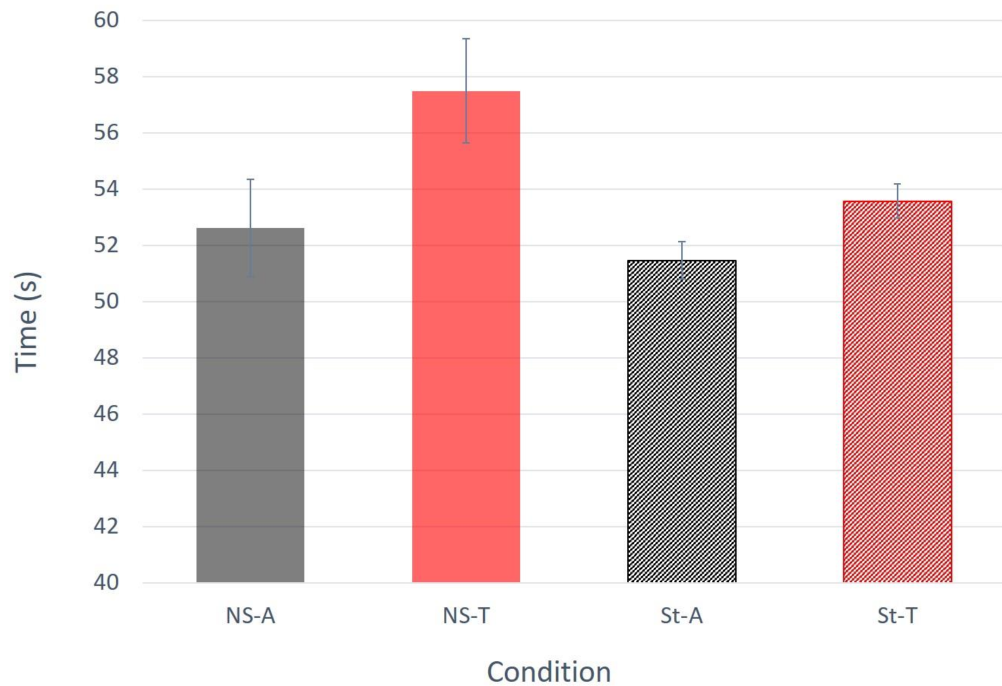

Figure 5. Mean completion times by condition. Bars: Completion times averaged across all trials within a condition. Red: Tactile conditions (T); Grey: Auditory conditions (A). Solid: No street sounds (NS). Hatched: Street sounds (St). Errors bars: ± 1 SE.

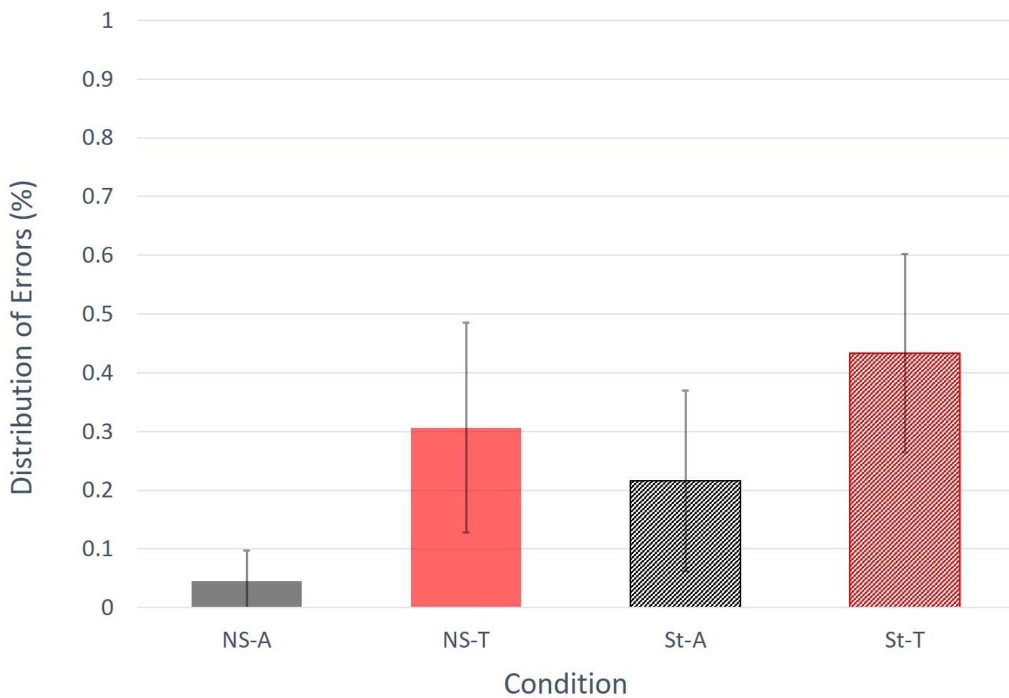

Figure 6. Distribution of major errors by condition. Bars: Mean proportion of all errors by condition (bar heights sum to 1). Red: Tactile conditions (T); Grey: Auditory conditions (A). Solid: No street sounds (NS). Hatched: Street sounds (St). Errors bars: ± 1 SE.

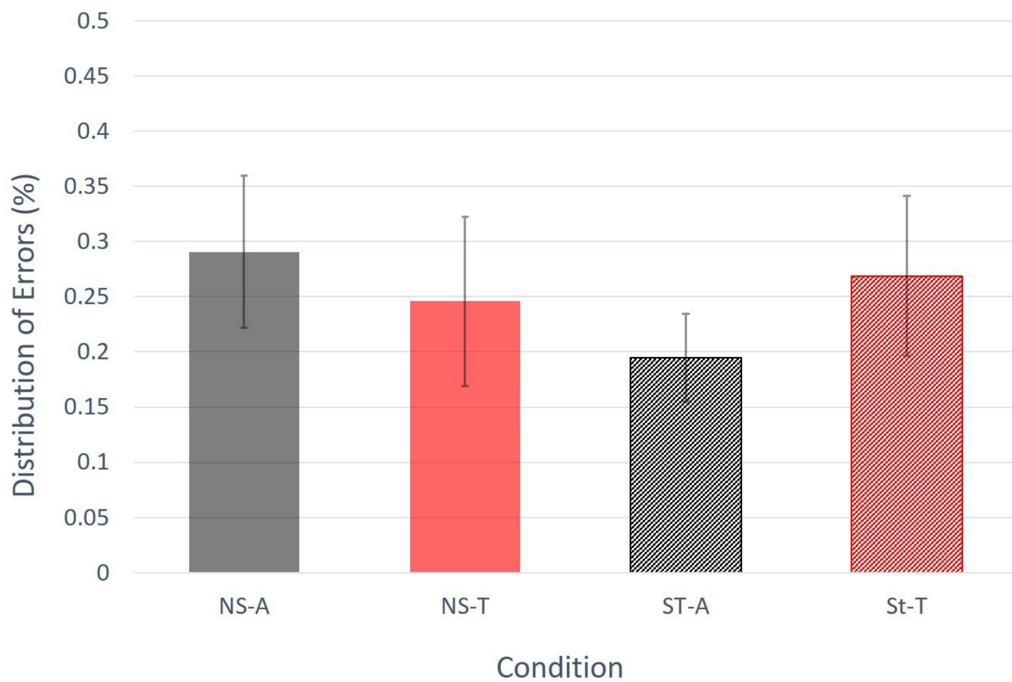

Figure 7. Distribution of minor errors by condition. Bars: Mean proportion of all errors by condition (bar heights sum to 1). Red: Tactile conditions (T); Grey: Auditory conditions (A). Solid: No street sounds (NS). Hatched: Street sounds (St). Errors bars: ± 1 SE.

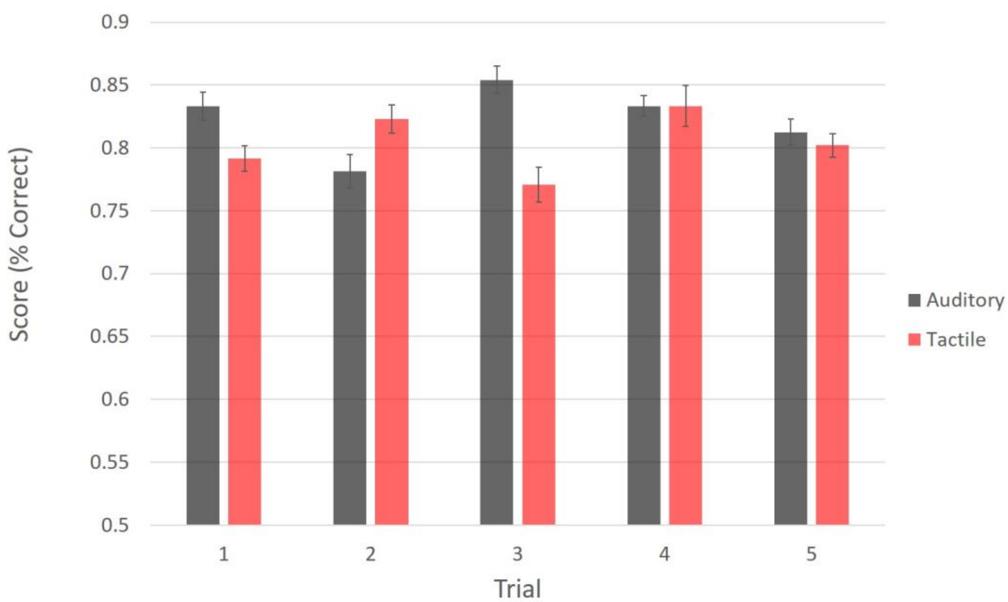

Figure 8. Recall questionnaire scores compared between command types (Part B). Bars: Mean % correct scores by trial number. Red: Tactile conditions; Grey: Auditory conditions. Error bars: ± 1 SE.

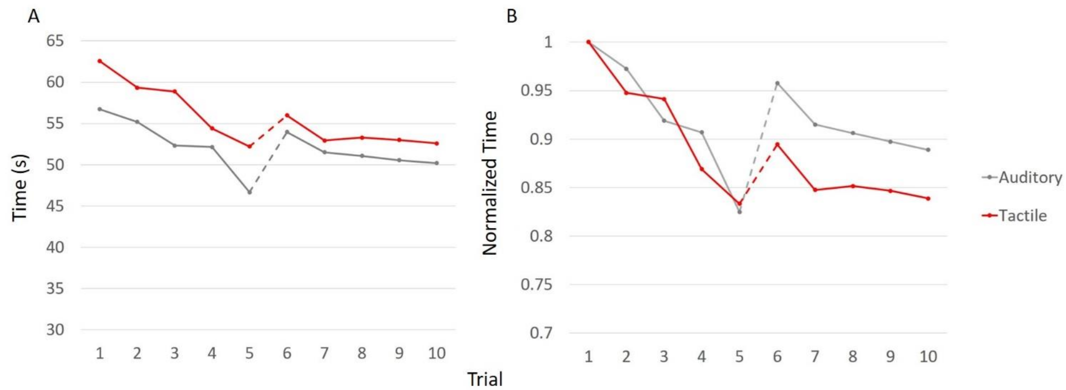

Figure 9. A) Completion time as a function of trial by command type. Figure 2 was replotted by connecting tactile trial 5 (NS) to tactile trial 1 (St) (Arrow head). Same was done for auditory. B) Completion times normalized against trial 1. Each completion time from Figure (A) was divided by the completion time from trial 1 of the corresponding command type. Dashed lines: Background street noise introduced to experiment. Red: Tactile conditions; Grey: Auditory conditions.

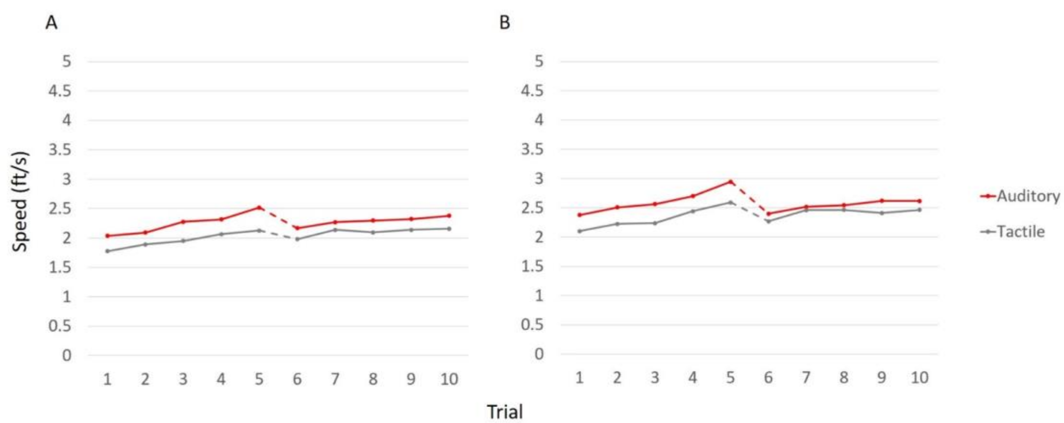

Figure 10. A) Turning speeds as a function of trial by command type. Plots: Mean turning speeds of every trial averaged across participants. B) Straightaway speeds as a function of trial by command type. Plots: Mean straightaway speeds of every trial averaged across participants. Dashed lines: Background street noise introduced to experiment. Red: Tactile conditions; Grey: Auditory conditions.

Chapter 3 – Discussion

3.1 Summary

We investigated the efficacy of a tactile display, in comparison to a conventional auditory device, in navigating blind individuals through an unfamiliar environment. Our investigation was motivated by two hypotheses that we formulated prior to the study: 1) As spatial information is intuitive to the skin, the tactile channel should be at least as good as the auditory channel at processing navigational information, and 2) The use of tactile navigational commands should mitigate the sensory load within the auditory channel, allowing users to better attend to navigational commands in a noisy environment.

We tested these hypotheses using a tactile vibrational belt. The tactile belt design was chosen with attention to two important factors: the location and the type of stimuli. The torso is the most suitable location to provide vibrotactile stimulation with an intuitive correspondence to egocentric direction (Barber et al., 2015). Additionally, of the three types of vibrotactile stimuli – directional, dynamic and static – to convey direction, the tactile belt used directional stimuli. While both dynamic and directional vibrotactile stimuli are motion-based, only directional represent specific direction within an environment while dynamic may be of random movement. Correspondingly, directional stimulation has been shown to be most effective in representing directional commands, as its wavelike motion intuitively encodes the desired movement along the stimulus direction (Barber et al., 2015).

Interestingly, we found that navigational performance with the tactile belt was initially inferior to that with the auditory device – contradicting our first hypothesis. The initial differences in performance were presumably due to the difficulties experienced by the participants in using a novel device. Nevertheless, performance with the tactile belt improved over repeated trials at a rate similar to the improvement observed with the auditory device. Crucially, upon the addition of background street noise , tactile performance was less compromised than auditory, indicating the benefit of using the tactile belt in an acoustically rich environment. This result supported our second hypothesis and provided evidence– for the first time to our knowledge – that Wickens' Multiple Resource Theory applies to navigational performance with tactile versus auditory navigational systems.

Overall, the results demonstrated the ability of the somatosensory system to process navigational instructions and will, we believe, prove useful in the future development of navigational assistance technology

3.2 Current limitations

A limitation that we encountered, which may also have affected previous tactile navigation studies, is that the cognitive load induced by using a novel device evidently impaired participants' initial performance in the tactile condition. Future studies comparing the perception of amodal instructions should find approaches to equalize the cognitive load across tested devices. One possible approach– as done by Jimenez & Jimenez (2017) – is to test blindfolded sighted participants. As sighted people navigate primarily via vision, they will presumably find both auditory and tactile instructions to be challenging. Nevertheless, many sighted people have some experience receiving auditory navigational instructions, either from devices (e.g., GPS instructions while driving) or from other people, so tactile commands would presumably still be more novel for them. An alternate and more robust approach would be to perform longitudinal studies with blind participants, comparing tactile to auditory devices to investigate how performance changes over time – effectively, training participants to such a point that neither device is novel to them.

Another limitation concerns the specific design parameters of the tactile belt that we tested. Participant feedback obtained during our end-of-experiment interview indicated that the majority of participants wished to have control over the tactile volume (i.e., vibration amplitude) in order to be able to strengthen the stimuli. The current version of the tactile belt is only a prototype, and there is ample room to optimize the characteristics of the stimuli that the belt provides. This might be achieved by further understanding and exploiting the spatial capabilities of the skin to further increase the intuitiveness of the tactile display.

3.3 Future Directions

Future research could focus on several areas. These include: optimizing tactile navigation systems, extending their range of application to scenarios other than navigation for blind individuals, and enhancing the device characteristics to provide a richer interface with the environment.

3.3.1 Optimization

Suboptimal information transfer, whether due to device limitations or user overload, poses a challenge. Under such circumstances, poor decision making, slower response times, and generally poor performance result. It is important then for an information display to maximize the amount of information transferred while minimizing cognitive workload interfering with the task at hand (Prewett et al., 2012). We predicted that the tactile belt would facilitate navigation with an efficacy equivalent or superior to that of speech commands. We found, however, that tactile navigation fell short of conventional auditory navigation, resulting in somewhat longer completion times and more major errors. These findings in fact coincide with those of previous tactile navigational studies (Pielot & Boll, 2010; Jimenez & Jimenez, 2017; Flores et al., 2015), suggesting a consistent shortcoming of tactile navigational displays. However, this does not imply that tactile displays are impractical tools for navigation. These studies showed the tactile display to be only marginally inferior to conventional navigational displays, despite it being a novel concept. Furthermore, in the present study, despite its somewhat inferior performance, the tactile belt was less compromised by the addition of environmental noise load. Therefore, with further development as well as with user practice, it seems likely that tactile displays will be able to compete favourably with auditory navigational devices, particularly in noisy environments.

It is crucial, for any navigational task, to distribute information across sensory channels, improving the time sharing of concurrent stimuli in multitask environments (Ferris & Sarter, 2010). The present study compared performance with a tactile display to performance with a conventional auditory device. If either command type was not optimized for its respective modality, performance would be skewed to favour the other command type. This is what presumably occurred with tactile commands. Accordingly, research must develop vibrotactile array patterns that are more intuitive to the somatosensory system. One way of doing so is to couple studies on tactile displays with functional magnetic resonance imagining (fMRI). Such studies would contribute towards an understanding of how spatial vibrotactile information in a certain region of skin is decoded by the primary somatosensory cortex (SI) (Zappe et al., 2004), allowing us to determine which vibrotactile characteristics optimize its activity. This would help elucidate array designs that are more meaningful to our sense of touch, and presumably, more readily encoded into memory.

3.3.2 Extending the Range of Applications

Tactile navigation systems should be applied not just to navigation for blind individuals, but to any situation where information transfer needs to take place under conditions of high auditory load or low visibility. Possible applications include to pilots, astronauts, and scuba divers; the use of tactile displays recruits an additional sensory channel – the skin – to maintain a spatial awareness of the unique environments encountered by these individuals, while minimally disturbing their performance (Gunther & O'Modhrain, 2003).

3.3.3 Device Enhancement

Tactile displays, like the belt used in the present study, are often limited to navigation and directional commands. This limits their expressive range of communication (Ferris & Sarter, 2010). Although the encoding of directional vibrotactile stimuli may be especially intuitive, the use of dynamic and static stimuli may be necessary to express messages of greater complexity (Ferris & Sarter, 2010, Barber et al., 2015). Training with these types of tactile stimuli has proved to be challenging, as they are not as readily encoded into memory as are their directional counterparts (Barber et al., 2015). However, similar to the learning of abstract visual or auditory symbols, longer training times are usually required before abstract tactile symbols can be reliably deciphered. With sufficient practice, information transmission rates can be surprisingly high (Ferris & Sarter, 2010). Furthermore, these tactile stimuli have dimensions which can be manipulated to form basic vocabulary elements of tactile communication, as originally modeled by Geldard (1966). Tactile stimulus dimensions include location, frequency, duration, and waveform. The location and relative positioning of tactile stimuli on the body serves as a first order dimension for tactile communication, considering the intuitiveness of spatial information.

Next, the frequency; there are two mechanoreceptors that code different frequency ranges in the skin – the Pacinian and Meissner corpuscles – which may be harnessed to evoke different vibration sensations. Considering intensity, tactile communication can exploit a continuum of intensities ranging from the threshold of detection up to the limits of discomfort to evoke subtle dynamic variations. The duration of a vibrotactile stimulus can provide an important means of grouping tactile events when layering different information. Finally, the waveform of a vibrotactile stimulus can be modulated to make a sine wave or a square wave, which are perceived respectively as smooth or rough (Gunther & O'Modhrain, 2003). These dimensions can holistically be manipulated to create a means of communication more complex than simple directional commands, allowing the user to maximize the acquisition of information.

The enhancement of the tactile display from a simple navigational system to a device interfaced with the environment could serve as the foundation for a tactile suit in the future, as different applications may require the use of different body sites. In waypoint navigation, for example, the suit could provide the user with cues along the torso for upcoming turns submerged by high traffic in streets or hallways. To do so, the intensity of directional vibrotactile command could vary as a function of distance; the intensity would be low at a far distance, but as the user approaches the turn, the belt would provide increasingly stronger directional cues spaced out at specific time intervals. If obstacles were to ever arise at head level, a distracted, and especially blind, individual would require the suit to provide a potent vibrotactile cue at the chest, to warn the user of a potentially hazardous contact. While driving, the suit could provide the driver a spatial representation of surrounding cars, mitigating the number of visual stimuli to attend to as the driver focuses on the road ahead. Similarly, in the dark, the suit could supplement vision of upcoming turns, winding roads, and hidden pedestrians or animals. Multimodal input has been found to be a reliable mode of communication due to its redundancy and levels of communication that are more robust than single-mode interactions (Barber et al., 2015). If the suit were to become advanced enough, objects in the distance could be transposed onto the user's hand. The high sensitivity and spatial acuity of the hand could provide users an egocentric and allocentric spatial representation of their environment by just scanning their hand through space of interest. This would be especially informative to blind individuals, as their tactile acuity is often enhanced (Wong et al., 2011). Such a tactile suit could serve far more uses than just the ones mentioned here, creating a new means of interacting with the world.

3.4 Final Thoughts

We consider touch, our largest sensory modality – rarely ever busy – as an additional channel to optimally communicate information. We often forget its importance as we become more reliant on our other sensory modalities. However, touch's central role in early life seems to establish the foundation of all other forms of communication developed later in life (Hertenstein et al., 2006). It would only make sense then to preserve its importance by incorporating it as an active interface integrated with the surrounding environment. Thus, we would get a real "feel" for the information, as touch is the sense that makes the world real to us.

"We forget that touch is not only basic to our species, but the key to it" (Schanberg, 1995).

References

Barber, D. J., Reinerman-Jones, L. E., & Matthews, G. (2015). Toward a tactile language for human–robot interaction: Two studies of tacton learning and performance. *Human factors*, *57*(3), 471-490.

Ferris, T. K., & Sarter, N. (2010). When content matters: The role of processing code in tactile display design. *IEEE Transactions on Haptics*, *3*(3), 199-210.

Flores, G., Kurniawan, S., Manduchi, R., Martinson, E., Morales, L. M., & Sisbot, E. A. (2015). Vibrotactile guidance for wayfinding of blind walkers. *IEEE transactions on haptics*, *8*(3), 306-317.

Geldard, F.A. (1966). *Body English*. Random House Dictionary of the English Language, Random House, Inc., (pp. 43–48).

Gunther, E., & O'Modhrain, S. (2003). Cutaneous grooves: composing for the sense of touch. *Journal of New Music Research*, *32*(4), 369-381.

Hertenstein, M. J., Verkamp, J. M., Kerestes, A. M., & Holmes, R. M. (2006). The communicative functions of touch in humans, nonhuman primates, and rats: a review and synthesis of the empirical research. *Genetic, social, and general psychology monographs*, *132*(1), 5-94.

Jimenez, R., & Jimenez, A. M. (2017). Blind Waypoint Navigation Using a Computer Controlled Vibrotactile Belt. In *Advances in Human Factors and System Interactions* (pp. 3-13). Springer International Publishing.

Pielot, M., & Boll, S. (2010). Tactile Wayfinder: comparison of tactile waypoint navigation with commercial pedestrian navigation systems. *Pervasive computing*, 76-93.

Prewett, M. S., Elliott, L. R., Walvoord, A. G., & Coovert, M. D. (2012). A meta-analysis of vibrotactile and visual information displays for improving task performance. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, *42*(1), 123-132.

Schanberg, S. (1995). "The Genetic Basis for Touch Effects." In *Touch in Early Development*, edited by T. Field, 67–79. Skillman, New Jersey: Johnson and Johnson.

Wong, M., Gnanakumaran, V., & Goldreich, D. (2011). Tactile spatial acuity enhancement in blindness: evidence for experience-dependent mechanisms. *Journal of Neuroscience*, *31*(19), 7028-7037.

Zappe, A. C., Maucher, T., Meier, K., & Scheiber, C. (2004). Evaluation of a pneumatically driven tactile stimulator device for vision substitution during fMRI studies. *Magnetic resonance in Medicine*, *51*(4), 828-834.