

**USING THE BRAINPORT FOR INDEPENDENT TRAVEL  
AND OBSTACLE AVOIDANCE**

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Individuals with visual impairments often have difficulty acquiring environmental and spatial information critical for independent travel. Orientation and mobility (O&M) is the body of knowledge and skills used by individuals with visual impairments for safe and independent travel. To aid this independence, there are a variety of mobility tools and devices to assist individuals traveling in various environments. A review of the relevant literature indicates that individuals may improve both spatial-perception and mobility through the sensory information provided by auditory and haptic sensory substitution systems. These systems provide useful sensory information about the environment and spatial relationships. The research remains limited and the versatility of these sensory substitution systems for real-world applications is still in question. The purpose of this study was to examine the capabilities of the BrainPort sensory substitution system to assist individuals with visual impairments to travel independently and avoid obstacles in a novel outdoor naturalistic environment.

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## GLOSSARY OF TERMS

**Blindness** – Individual has no remaining vision

**BrainPort** – A sensory substitution system that translates a visual image through electro-tactile stimulation on the tongue providing feedback about the environment

**BrainPort and Cane condition** – obstacle course travel condition using both the BrainPort device and long cane

**BrainPort condition** – obstacle course travel condition using only the BrainPort device

**Cane condition** – obstacle course travel condition using only the long cane

**Cane contacts** – data recorded for each obstacle the participant's long cane touches (multiple contacts with the same obstacle count only as one)

**Course layout form** – form used to record specific data for obstacle and cane contacts, veering, time of travel, and detection of obstacles

**Course sequence** – randomized sequence of which experimental conditions are completed in which course version (Course 1 or 2, Forward or Reverse)

**Course trial** – each time the participant completes a course version in an experimental condition

**Course veers** – each time the participant partially veers off of the sidewalk or contacts the handrail

**Crosswalk time** - time from when a participant first has one foot on the truncated domes until one foot steps off the truncated domes on the opposite side of the street

**Crosswalk veers** – each time the participant partially steps outside of the crosswalk area

**Data sheet** – form used to record each of the data variables for each participant

**Experimental condition** – use of the long cane, BrainPort, or cane and BrainPort together to walk through the obstacle course (BP, C, BP-C)

**Independent travel** – walking without a human guide in a person's natural environments

**Obstacle body contacts** – data recorded for each obstacle the participant's body touches (multiple contacts with the same obstacle count only as one)

**Obstacle course time** - time on the obstacle course besides the crosswalk time

**Obstacle detection task**- course trial where the participant is asked to walk through the course untimed with just the BrainPort and point to any obstacles that he or she perceives

**Orientation and Mobility (O&M)** - navigation and wayfinding focusing on the key areas of independence, safety, and efficiency of travel

**Percentage of Preferred Walking Speed** – calculation of how fast the participant traveled in the presence of obstacles as compared to the absence of obstacles

**Preferred Walking Speed** – time it takes the participant to walk using the long cane through the obstacle course without obstacles

**Research Assistant** – completed training and provided assistance in research procedures

**Session** – first, second, third, or fourth visit when the participant completes some part of the training and may complete the obstacle course conditions (only the first and last session)

**Total contacts** – obstacles contacted with the participant's cane or body in the obstacle course trials

**Total veers** – total number of veers off the sidewalk or outside of the crosswalk

**Total time of travel (Course speed)** – time it takes the participant to walk through the course with the presence of obstacles

(Total time of travel = Crosswalk time + Obstacle course time)

**Training protocol** – skill practice and development focused on improving mobility, environmental awareness, and visual skills using the BrainPort in outdoor environments

**Visual impairment** - issues with visual acuity, visual fields or some other related problem with the visual system that is uncorrected and affects a person's independence

## **1.0 INTRODUCTION**

Sensory substitution systems provide an individual with another source of information about the surrounding environment. Individuals who are blind rely on auditory, tactual, and other types of sensory information to maintain their independence. Orientation and Mobility (O&M) is the combination of skills that an individual with a visual impairment uses for navigation and wayfinding, focusing on the key areas of independence, safety, and efficiency of travel (Wiener, Welsh, & Blasch, 2010). The desire to promote independence is balanced by the need to ensure an individual's safety while navigating in familiar or unfamiliar environments. Efficient travel for an individual with a visual impairment means that the individual knows the present location and the location of the destination point, and has the O&M skills to execute travel plans in the most direct possible route (Wiener et al., 2010). Obstacle detection is required for independent travel and is usually accomplished by direct physical contact while using the long cane or visual contact with an object. The long cane may not detect objects just beyond the width of a traveler's cane arc and provides only a small amount of information about the presence of an obstacle, not its size or shape. A sensory substitution system, when used in tandem with the long cane, is able to provide the person similar physical feedback with additional information visually obtained from the environment (Lenay, Gapenne, Hanneton, Marque, & Genouelle, 2003).

## 1.1 RELEVANCE OF THE STUDY

Individuals with visual impairments struggle with independent travel due to the lack of accessible environmental information available through senses other than vision (Ponchillia, Mackenzie et al., 2007). O&M skills are necessary for these individuals to become safe and independent travelers. These individuals travel through most areas safely and efficiently using mobility tools and devices, such as the long cane, and using auditory information and other sensory feedback. However, there are still gaps in the information known about the immediate surroundings using these tools or devices. The presence of obstacles (e.g. trees, garbage cans, telephone poles, curbs) are all potential hazards normally detected visually. Although auditory information supplements what would be obtained visually, it still does not provide the depth of detail gained from the visual system. Sensory substitution technology assists to bridge the accessibility gap by providing access to the visual information in the environment through other senses. As the individual moves through the environment, information from the sensory substitution system is constantly updated to proximal environmental features. In addition, a sensory substitution system also provides feedback to the individual about positioning and movement in space (Lenay et al., 2003).

There are numerous sensory substitution systems currently on the market or being tested for feasibility. The BrainPort sensory substitution system uses a camera to take a picture and then transmits an image of reflected light to an electrode array placed on an individual's tongue (Bach-y-rita, Tyler, & Kaczmarek, 2003). Consequently, an individual's brain can understand these sensations with practice and use the visual cortex to process this information forming a mental representation of the visual image (Bach-y-rita et al., 2003). This sensory substitution technology provides an individual with an alternative source to access visual information and a

direct connection to spatial features in the environment. The ability to understand non-visual alternatives to receive sensory information, such as reading braille or using a long cane, a person's opportunity to optimize the BrainPort requires time for practice, training, and skill acquisition. Although the BrainPort is a revolutionary system, there is little research available on using the BrainPort for navigation in naturalistic settings. In a study through the University of Pittsburgh Medical Center (UPMC), Friberg, Nau, Pintar, Fisher, & Chen (2011) found that the BrainPort provided a 58.6 degree visual field and was helpful to avoid obstacles in a high-contrast (e.g. black/white) indoor obstacle course. This optimal design for detecting contrast is comparable to visual acuity tests using black letters on a white background. Friberg et al. recommended additional research to explore the functional usefulness of the device comparable to testing contrast sensitivity for vision. Contrast sensitivity refers to the ability to distinguish an object from its background. While Friberg et al. used high-contrast objects for the indoor obstacle course, the current study used lower contrast between objects and backgrounds in a more natural environmental setting. There is no research on the use of the BrainPort for outdoor use, or for using the device outdoors in conjunction with the long cane. This study explored how the BrainPort device was useful to improve independent travel and obstacle avoidance in a novel outdoor naturalistic environment.

## 1.2 BACKGROUND

Formal O&M instruction began during World War II when veterans who had lost their vision during battle were rehabilitated in Veterans Affairs Medical Centers in the United States (Wiener et al., 2010). Accordingly, the long cane was developed as a tool to offer obstacle detection to an individual. The long cane works well to protect the width of the individual's body below the waist. However, the individual is often at risk to contact environmental objects positioned from the waist up, such as walking into traffic control boxes attached to poles located on street corners and other similar objects suspended in the air. The formal instructional sequence for O&M progresses from simple skills in indoor environments to independent travel in outdoor, complex environments. Individuals with visual impairments rely on the sensory information from the environment in order to be successful and independent travelers.

With appropriate O&M skills, most individuals with visual impairments are able to travel in familiar environments using the long cane. Familiar environments are generally defined as places where an individual has been before, feels comfortable, and can reorient with little difficulty (Hill & Ponder, 1976). Unfamiliar or novel environments are more challenging for these individuals. Hill and Rieser (1993) found that successful exploration strategies for unfamiliar environments must include a systematic search technique and continuous spatial feedback from the environment. Many individuals with visual impairments lack the confidence to travel in unfamiliar environments, often relying instead on a human guide in such situations (Ponchillia, Rak, Freeland, & LaGrow, 2007).

### **1.2.1 Independence for individuals with visual impairments**

According to the World Health Organization (2010), people who are blind make up only 13% of the total population of 285 million individuals with visual impairments. Individuals with visual impairments either have a congenital visual impairment or a visual impairment that occurs later in life (Wiener, et al., 2010). This distinction is critical for understanding how an individual with a visual impairment interprets the world and forms spatial concepts. Visual memory is based on the individual's visual recollection of objects, items, and concepts prior to full vision loss (Wiener et al., 2010). Therefore, individuals who lose their vision later in life have visual memory to reference as they encounter new experiences or similar situations. For example, visual memory allows an individual to understand the size, shape, and parts-to-whole relationship of a car without physically touching and exploring each characteristic of that car. This prior knowledge then allows individuals to generalize this experience to other cars encountered or to understand how a bus may be similar. Without visual memory, concepts such as this car example must be taught explicitly moving from a complete basic to a more complex level of understanding. For instance, an individual would need to be initially introduced to the parts of the car, understand how the parts are connected, provided the opportunity to physically explore the interior and exterior features of the car, and also have the experience of how the car moves and sounds. While this level of detail may only be necessary for children during initial instruction, most concepts must be explained in this way for individuals with congenital blindness.

Individuals with visual impairments often have delays or deficits in other areas of development as a result of the missing information typically acquired through vision (Lenay et al., 2003). These deficits may include motor functioning, body and positional concepts, or

spatial understanding of the individual's environment. Vision provides context for sensory integration, which allows other forms of sensory information to be easily understood. An example of sensory integration would be the experience of feeling cold snow on your cheek. Vision allows an individual to know the snowflake fell from the sky and that it is generally covering the ground. Spatial awareness is an understanding of objects and their relationships in the environment (Kitchen, Blades, & Golledge, 1997). As a result, individuals with visual impairments often have trouble understanding the spatial relationships of objects in space and different environmental features (Lenay et al., 2003). Therefore, when an individual has misunderstandings between one's sensory integration experiences and their knowledge of spatial relationships, concepts such as knowing near and far ground objects can be difficult and abstract for a person with a visual impairment.

### **1.2.2 History of sensory substitution systems**

Individuals with visual impairments have used sensory substitution systems for years. The process of braille reading is one of the most common forms of sensory substitution providing access to printed materials in a tactile format (Williams, Ray, Griffith, & De l'Aune, 2011). The long cane is a mobility tool/device, which provides alternative sensory feedback through tactile, auditory, and proprioceptive means (Wiener et al., 2010). This low-tech device provides similar information through an alternative sense from what is typically acquired through vision. The Optacon is one of the first technology devices to use sensory substitution by scanning letters and producing a raised line image (Williams et al., 2011). In the 1980s, Electronic Travel Aids (ETAs) began to use more advanced technology for interacting with the environment (Wiener et al., 2010). These systems produce a signal that is reflected to detect the presence, range,

direction, or dimensions of objects or other environmental features (Wiener et al., 2010). Specifically, these signals are usually in the form of light or sound in which the reflected waves represent the characteristics of the environment. Reflected waves are transmitted into another sensory format, such as auditory or tactile/haptic information, to be interpreted by the user (Strumillo, 2010). An ETA can either be used as a primary device, as the sole mobility system, or as a secondary device, used in conjunction with another mobility device for effectiveness.

There have been many ETAs developed over the years including: K-Sonar, HandGuide, Sonic Guide, Pathsounder, Binaural Sensory Aid, Laser Cane, Ultracane, Miniguide, Mowat Sensor, Polaron, Sensor 6, Walkmate, and a number of other devices (Wiener et al., 2010). Although ETAs are not commonly used by individuals who have visual impairments, research conducted with these devices had encouraging results with some limitations. The global limitations of most ETA devices include a small distance range, the need to point the device directly towards objects and thus require consistent scanning, and poor feedback quality for independent travel. The complexity of the feedback can also provide difficulties if the data becomes too overwhelming for an individual to interpret. A consistent dilemma faced in developing O&M technology is deciding what amount of information should be provided to be most useful to the traveler.

Russell (1966) and Kay (1974) presented opposing viewpoints of the advantages and disadvantages of ETAs, which are still being considered for devices today. The device Russell used kept the feedback simple by only showing the presence or absence of an obstacle. Kay, conversely, had a device provide as much information about the environment as could be detected and transmitted effectively. Each of these devices has merit. It is critical for an individual to focus on travel skills without having to sort through a plethora of information to

make judgments about what is important. However, given the lack of environmental information available to an individual with a visual impairment, it can also be useful to have the most information possible and decide for oneself what is important. Most likely this preference for the level and amount of feedback provided will vary depending on the traveler and so mobility tools or devices should allow enough flexibility for information sources to be selected. More advanced ETAs have begun to use ultrasound, electromagnetic, and LED waves to produce useful and consistent feedback (Wiener et al., 2010). Unfortunately, many of these tools or devices do not address the explicit travel issues of individuals with visual impairments.

The National Research Council (1986) identified specific needs of individuals with visual impairments that technology devices ideally should address. According to the Council, device capabilities need to include: detection of obstacles for the full size of an individual's body, walking surface information (e.g texture and missing areas), features along the path of travel, distant objects, cardinal directions, landmark information, and information for self-familiarization. None of the current ETAs address all of these issues or meet the criteria for a primary ETA/mobility device. The Laser Cane and Ultracane, are ETAs that each use were each considered primary ETAs, but neither is being produced due to the lack of use and high expense (Wiener et al., 2010). Additional considerations for travel devices include being small, lightweight, inconspicuous, affordable, and should not interfere with other sensory information. Individuals with visual impairments reported benefits of ETAs including use as early warning systems, obstacle detection for horizontal and vertical objects, drop-off and overhang detection, identifying landmarks, increased confidence in environmental awareness, and correcting veers (Penrod, Bauder, Simmons, Brostek, & Matheson, 2010).

### **1.2.3 Present and future of sensory substitution systems.**

Sensory substitution systems attempt to provide an alternative source of information to what would be acquired visually. This sensory information cannot be duplicated fully through tactile or auditory means given the complexity and depth of visual stimuli. Current and future research should focus on the quality and quantity of information that can be provided and how it affects performance for the individual (Zelek, Bromley, Asmar, & Thompson, 2003). Synesthesia is the perception of joined sensations or sharing of multiple senses, such as tasting colors, hearing shapes, and other sensory fusions. Synesthesia could allow an individual who is blind to perceive environmental features and this is the desired effect for most sensory substitution systems (Lenay et al., 2003). There are on-going debates as to whether or not the sensory substitution systems equate to actual ‘seeing’ abilities or just provide alternative access to environmental information. While this question is intriguing, it is much more practical to know how sensory substitution affects the individual’s navigation and wayfinding in the naturalistic setting.

Sensory substitution systems are consistently being refined to improve the capabilities available to users (Baldwin, 2003). Currently, the sensory substitution systems being used by the population of individuals with visual impairments primarily use either auditory or tactile feedback. Ward and Meijer (2010) found that the voICe sensory substitution system represents bright pixels as louder and pixels higher in view as higher in pitch. Using the voICe, Ward and Meijer found that participants’ performance and reported environmental awareness increased significantly over time showing potential for improvement with additional practice. In case studies using the voICe, the participants reported having “eureka” moments in which depth perception and color attributes went from being unclear “smears” to detailed images.

Eventually, there were no longer breaks in perception, just continuous sensory feedback. Participants had much clearer perceptions of those objects which they had visual memories and less vivid for objects with no visual memories (Ward & Meijer, 2010). As there are several sensory substitution systems available or in development, there are also systems that encode a visual image into electrical or tactual stimulation on the individual's body or on the tongue.

#### **1.2.4 BrainPort sensory substitution system.**

The BrainPort device was developed by Bach-y-rita beginning in the 1970s. While the device had undergone many updates and modifications, the BrainPort V100 device currently being used has a 20 x 20 electrode array placed on the tongue connected to a miniature camera mounted on the bridge of a pair of sunglasses (Wicab, 2013). The Tongue Display Unit (TDU) and Tactile-Vision Sensory Substitution unit (TVSS) were variations of the BrainPort device using a similar camera-electrode system with the tongue (Lenay et al., 2003). The tongue is an ideal surface because of its thin cutaneous layer, sensitivity from mechanoreceptor innervations for interpreting finer details, and saliva providing good conduction. Distal attribution is an awareness that movements associated with the camera correlate to stimulation on the tongue for sensory substitution systems (Siegle & Warren, 2010). The BrainPort has settings for the user to control the voltage intensity, which does not exceed 17V, a zoom magnification capability, and inverted brightness, which reverses how black and white colors are interpreted (Wicab, 2013). Moreover, the BrainPort provides auditory feedback about each of these settings.

Sensory substitution can address some of the specific issues preventing many individuals with visual impairments from traveling independently or from exploring novel environments (LaGrow et al., 2009). As an individual's quality of life can be limited by restricted access to

new social and community experiences, Havik, Steyvers, Velde, Pinkster, & Kooijman (2010) found that indoor and outdoor navigation and wayfinding technology can provide assistance for allowing an individual to be independent in each aspect of life. O&M instruction is necessary to provide the skills necessary for the individual to be independent even with these devices.

## **2.0 REVIEW OF LITERATURE**

The salient themes, which emerge from a review of the literature on sensory substitution used for independent navigation, are described in the following sections. Correspondingly, the findings are grouped according to the type of sensory information provided, the dependent variables measured, and the characteristics of the participants. In the first place, the results indicate that technology provided individuals with visual impairments access to environmental information, which increases their opportunities for independence. Also, for all of the sensory substitution technology examined in this literature review, participants from these studies were able to improve mobility performance and increase their awareness of obstacles and environmental features in almost all experimental conditions (Chebat, Schneider, Kupers, & Ptito, 2011; Zelek et al., 2003; Siegle & Warren, 2010; Bologna, Deville, Gomez, & Pun, 2011). The users developed a more complete and in-depth understanding of the environment with nearly all of the sensory substitution systems. Users' experience with these devices translated into improved travel and independence, although some participants did not benefit from using the technology devices. Lastly, although each type of device had positive effects on independent mobility and other tasks, none of them seemed to be significantly better. The voICe and BrainPort were the most common devices and seemed to offer the most potential for the future in auditory and tactual sensory substitution.

## 2.1 HAPTIC FEEDBACK SYSTEMS

There are many types of sensory substitution systems, which provide haptic feedback of the visual environment. The devices examined in this review are tactile feedback systems, such as the haptic glove and photo diode, or feedback through electrical stimulation on the tongue as with the TDU, TVSS, and BrainPort tongue devices (Zelek et al., 2003; Chebat et al., 2011; Siegle & Warren, 2010; Lozano, Kaczmarek, & Santello, 2009; Williams et al., 2011). Comparatively, the tactual/haptic systems work in similar ways by having a camera transmit an image into stimulation directly onto the individual's skin. While there is limited research available on the use of the devices for independent mobility, the BrainPort was examined in a study testing the reliability of an indoor obstacle course. While the course was found to be reliable, Friberg et al. (2011) also found that the rate of travel and obstacle avoidance both improved over time from training with the device. A photo diode uses a light-producing, finger-mounted device, which causes tactile vibrations on the individual's back (Siegle & Warren, 2010). For the other sensory substitution systems examined, the tactile glove provides feedback through vibrations on the individual's hand (Zelek et al., 2003) and the TDU device provides environmental feedback through the tactual senses of the tongue (Chebat et al., 2011). Essentially, most participants were able to improve travel performance in each instance using sensory substitution systems.

For systems providing stimulation on the tongue, individuals' accuracy judgments were found to be better at a higher stimulus intensity. Similarly, Lozano et al. (2009) also found that

judgments made about stimulus intensity were more consistent for the same sensory modality than across different modalities. Williams et al. (2011) found that using the TVSS device for object identification with shorter viewing distances was associated with higher levels of accuracy. Additionally, individuals with visual impairments were generally able to travel better using the environmental feedback provided by the devices than traveling without the devices (Zelek et al., 2003; Chebat et al., 2011). Zelek et al. found that when using the Haptic Glove, participants chose the easiest path of travel at a rate of 75% compared to a rate of 65% using their current ETA devices. However, the results were inconsistent for some of the participants and appear to be inconclusive given the small sample sizes. The participants were able to consistently identify the distance, size, and type of objects using the TDU device. Siegle and Warren (2010) found that participants were able to successfully judge distal attribution using the photo diode with training focused on this skill of interpreting the movement of the camera.

## **2.2 AUDITORY FEEDBACK SYSTEMS**

According to the literature, the Prosthesis for Substitution of Vision with Audition (PSVA) (Renier & DeVolder, 2010), and the See Color Mobility device (Bologna et al., 2011) each provide auditory feedback to the user about the environment. Although these devices each provide feedback through sound, the quality and complexity of the feedback varies for each device, which also affects how useful it is for the individual. There may be multiple layers to the auditory stimuli, such as pitch and volume representing color or distance. Renier and DeVolder used the PSVA, which provides feedback from an artificial retinal image transmitted into sound perceived by the individual. Bologna et al. examined the See Color Mobility project with

audition, which provides more complex feedback with simultaneous representation of color and depth through musical instruments. Different musical instruments were used to represent different colors and pitch decreased accordingly with brightness in color.

With each of the sensory substitution auditory devices, individuals improved in the ability to complete tasks, such as picking up and setting down an object and estimating distance and space (Zepek et al., 2003; Chebat et al., 2011; Siegle & Warren, 2010; Bologna et al., 2011). With the PSVA, Reiner and DeVolder (2010) found that having prior visual experiences or knowledge about environmental factors greatly increases one's ability to make judgments about space, distance, and relative positioning.

### **2.3 DEPENDENT VARIABLES**

The O&M principles of safety, independence, and efficiency were all addressed as dependent variables in many of these studies. For instance, obstacle avoidance focuses on maintaining an individual's safety. Additionally, individuals with visual impairments must be able to travel to specific objectives and complete the desired route to maintain their independence. Lastly, efficiency consists of the rate of travel, or more specifically the relationship between distance and time. Spatial perception, which is determining distance and positioning of objects and environmental features in space, is critical for all aspects of mobility and everyday functioning (Wiener et al., 2010). Spatial skills were consistently good with each of the sensory substitution devices. Participants were able to establish distal attribution and a basic understanding for appropriate depth perception (Siegle & Warren, 2010). For example, individuals increased their rate of travel showing that technology can have a positive impact on an individual's

independence (Chebat et al., 2011; Bologna et al., 2011). The improved performance for obstacle avoidance and spatial perception demonstrated how valid and useful sensory substitution systems are for real world travel and maintaining safety.

The dependent variables were measures of mobility and spatial perception skills. These skills were picking up an object and replacing it in the same spot, perception of distance and depth, identification and awareness of environmental features, and mobility performance. Distance and time traveled, performance accuracy, and distance judgments were each examined as critical variables for understanding the validity of these devices for real-world functioning. Individuals with visual impairments were able to improve their O&M related tasks of overall time traveled, determining the most efficient path to travel, locating objectives, and performance for obstacle detection with the use of sensory substitution systems. Obstacle avoidance and locating an objective are also necessary and important aspects of successful independent travel. In one of the studies, obstacles were classified for how they were avoided: step-around (SA) or step-over (SO). Chebat et al. (2011) found that it was more difficult for individuals who are blind to step over objects than to step around them, but this improved significantly the second time through the course. With the additional tactile feedback from the systems, users successfully completed the obstacle courses (Zepek et al., 2003; Chebat et al.), traveled specific routes, and located objectives more successfully.

As sensory substitution is designed to accommodate for missing visual information, several of the performance measures focused on the perceptual tasks of distance judgment, distal attribution, and depth perception (Siegle & Warren, 2010; Renier & DeVolder, 2010). While cognition had previously been considered the major factor, perceptual focus on distal objectives was found to be more critical for appropriate distance judgments. In addition, it was also found

that visual cues and previous visual knowledge were critical for making distance judgments and understanding spatial relationships even with sensory substitution devices (Siegle & Warren, 2010). While the lack of visual experiences was a deficit for users with congenital blindness, teaching them how visual cues relate to objects in space significantly improved performance (Renier & DeVolder, 2010). Participants were able to perform general mobility tasks accurately with the See Color Mobility aid, but there were still limitations on the accuracy for color and depth details (Bologna et al., 2011).

## **2.4 PARTICIPANTS' DEMOGRAPHICS**

The research studies included participants with total blindness, low vision, and normal sight. In some of the research, sighted individuals wearing blindfolds simulated participants with visual impairments although they lack the experience of living with a disability. Individuals with normal vision who are blindfolded for research purposes are referred to as sighted individuals in this paper. There was not a consistent trend differentiating between how sighted and individuals who are blind performed with the use of sensory substitution systems on independent and spatial perception tasks (Williams et al., 2011; Renier & DeVolder, 2010). Individuals with congenital blindness performed better than sighted individuals for detection and avoidance of obstacles. Sighted individuals were able to perform better without training in depth perception tasks due to previous visual knowledge and understanding of spatial relationships. (Renier & DeVolder, 2010). The individuals who were blind were able to improve performance significantly with some training for understanding depth cues and spatial relationships. Summarily, these studies show that an individual without a visual frame of reference can develop an understanding of

these relationships when the concepts are explicitly taught. This distinction highlights the importance of visual memory to develop spatial concepts within an environment. For someone with congenital blindness, who has no visual experiences, to understand and interpret the spatial concept around them, sensory substitution systems may be able to provide additional environmental feedback to help develop these concepts.

In the sensory substitution research, the experimental focus was on adults with visual impairments. The research participants were all between the ages 19 and 72. There were 143 subjects, 71 of those having normal sight, while the additional 72 had varying degrees of low vision to total blindness. The sighted individuals wearing blindfolds navigated well on the obstacle course (Chebat et al., 2011), through open doorways (Bologna et al., 2011) and with other mobility objectives. Most of the research used participants with total blindness and some with low vision. Individuals with normal vision, who were blindfolded, performed almost as well or better in several studies compared to participants with visual impairments using sensory substitution devices (Chebat et al.). Nearly all of the experiments were conducted with novice users of the specific technology being tested. Overall performance improved for those who had a device for extended periods to use at home. Providing this additional time to practice significantly increased the user's capabilities, performance, and confidence to meaningfully interpret the sensory information.

The participants selected for each research project represented some part of the blindness or visual impairment community. Long cane users each performed well using the devices with no apparent differences. The sensory substitution studies demonstrated technology could improve navigation in large-scale spatial environments (Zelek et al., 2003; Chebat et al., 2011). Researchers used single-subject, multiple baseline and probe, and group designs all with positive

results for independent travel and spatial perception skills. Nearly all of the devices required some training to develop a minimal level of proficiency. Several of the studies contained some system development phase to help improve the usefulness of each device (Zelek et al.; Chebat et al.). Of those studies, research spanned from 2003 to 2012 with task difficulty increasing with each new version of the devices being tested. Interestingly, as the tasks became more difficult, the participants with visual impairments were able to continuously exhibit increased levels of independence and travel skills.

## **2.5 SENSORY SUBSTITUTION CAPABILITIES**

Sensory substitution systems provide several different aspects of environmental information as well as varying qualities of this information. The aim for several of the systems was to provide a range of sensory input to represent particular environmental characteristics, such as pitch representing colors or shades. Certain systems also attempted to use pitch, volume, or intensity to represent distance (Bologna et al., 2011). While some of the devices did provide useful feedback for these characteristics, the related task performance was inconsistent. Generally, users were able to determine shades as light or dark and approximate distance attributions (Bologna et al., 2011). The electro-tactile stimulation on the tongue and some of the auditory feedback devices were able to accurately portray the size and shape of objects and features. While sensory substitution systems improved most individuals' travel performance, the devices still could not be used as the primary mobility device replacing a long cane. Specifically, a primary mobility aid would need to be used independently without a long cane, which is not

possible for most individuals with severe visual impairments given the current limitations of the devices.

Sensory substitution systems had a positive impact on several aspects of travel and spatial performance (Lenay et al., 2003). While sensory substitution systems are still in developmental phases, these devices have progressed to where independent travel can be increased with practice and use. Consequently, sensory substitution should increase an individual's travel in unfamiliar environments given the increased independence, efficiency, and safety (Chebat et al., 2011). Systems, such as the Tactile Glove, TVSS, BrainPort, the voICe, PSVA, photo diode, and TDU, provide significant research opportunities for the future. There is still little known about the possible impact on travel in outdoor environments since these initial studies have been conducted in controlled indoor environments. Outdoor travel presents a multitude of challenges that need to be explored and sensory substitution systems can add to this knowledge base.

### **3.0 SIGNIFICANCE OF THE PROBLEM**

The rapid rate at which technology progresses ensures there are un-researched applications for sensory substitution systems to be utilized in more practical and real-world situations. The recent developments in the area of sensory substitution offer significant potential benefits for individuals with visual impairments to increase independence and travel in familiar and unfamiliar environments. The following study is proposed to address the gaps in the current research in sensory substitution systems.

Individuals with visual impairments often have difficulty independently navigating in unfamiliar settings because of the lack of useful information about the environment available through other senses besides vision. Permanent obstructions, such as trees, telephone poles, and mailboxes are all possible threats to an individual's safety. While permanent obstructions are more problematic in unfamiliar environments, temporary obstructions can be a problem anywhere. Temporary obstructions are obstacles such as a homeowner's garbage can, construction equipment, or broken sidewalks. This category of obstructions is especially problematic because they can make a familiar route of travel unpredictable. Obstacles, such as buildings, poles, mailboxes, and curbs, all present potential threats to an individual's safety. Many individuals with visual impairments use a mobility tool or device, such as a long cane to detect obstacles and avoid injury. While beneficial for detecting obstacles, these mobility devices still have limitations in the amount and quality of the feedback that they provide about

the environment. The devices also have limitations in how much they can ensure an individual's safety.

In order to remain safe and independent, the traveler should have access to as much useful information about the environment as possible. An awareness of environmental features, such as crosswalks, curbs, vehicles, and general objects on the sidewalk, are vitally important for safe and independent navigation. In the real environment, veering outside of the crosswalk lines decreases visibility to oncoming vehicles, increases the chances of being struck by a vehicle, and increases the likelihood of missing the opposite corner. The BrainPort allows the user to detect horizontal and vertical lines in the environment. These lines, such as the crosswalk or sidewalk edge, may help the individual to maintain a straight line of travel and to remain safely within the crosswalk. The BrainPort provides another source of environmental information that can be used to detect, interact, and explore features of the environment to improve safety and independence. While the BrainPort is not meant to be a primary mobility device or tool, it may offer significant benefits for enhancing independent travel when combined with a long cane. Individuals with visual impairments would benefit significantly from being able to receive information about the immediate surrounding environment.

For the BrainPort to be a useful device or tool for individuals with visual impairments, the field needs to better understand the benefits of using it in an outdoor unfamiliar setting. The BrainPort has not been tested with experimental controls in naturalistic outdoor environments. The outdoor environment presents dynamic challenges to any traveler. Lighting is one example of an uncontrollable variable as it is always present in various levels in an outdoor environment. These dynamic variables may affect perception with the BrainPort and mobility performance. Sidewalks frequently have obstructions, some may be permanent and some may be temporary,

but all present unpredictable threats to an individual's safety. The outdoor environment is constantly changing. The limited amount of research in using sensory substitution systems had focused on controlled indoor environments.

### **3.1 RESEARCH QUESTIONS**

In order to determine the efficacy of the BrainPort for independent travel, the following research questions were examined in this study:

- 1) What impact does the BrainPort system have on an individual's rate of travel in a novel outdoor environment?
- 2) What impact does the BrainPort system have on an individual's ability to detect and avoid obstacles in a novel outdoor environment?
- 3) What impact does the BrainPort system have on an individual's ability to maintain an optimal straight path of travel in a novel outdoor environment?

## **4.0 METHODS**

This study focused on independent travel and avoiding obstacles using the BrainPort in a novel outdoor naturalistic setting. The O&M specialist worked with the UPMC Eye Center and directly with the Sensory Substitution Laboratory staff to develop and implement this project. The proposed study was approved through the University of Pittsburgh Institutional Review Board.

### **4.1 RESEARCH HYPOTHESIS**

- 1) The participant will improve the time traveling while using the BrainPort and cane together compared to using either device individually.
- 2) The participant will improve the ability to avoid obstacles using the BrainPort compared to the long cane.
- 3) The participant will decrease the frequency of veering using the BrainPort compared to using the long cane.

## 4.2 RESEARCH DESIGN

This study examined the effectiveness of the BrainPort sensory substitution device for improving independent travel and obstacle avoidance with environmental feedback in a novel outdoor environment. This research was designed as an exploratory pilot study to provide information necessary for more detailed research. The study used a within-subjects experimental design to compare independent travel in an obstacle course through pre-training and post-training assessments with and without the BrainPort across three travel conditions. There were eight individuals, who are totally blind, participating in this study. The novel outdoor obstacle course was in a controlled environment at the Western Pennsylvania School for Blind Children, which had an *urban trail* with a controlled streetlight crossing. While environmental variables cannot always be controlled, natural light levels were recorded using a Fisher Scientific Traceable Dual-Range Light Meter for each subject's course sequence. The light meter readings were taken for each session with a participant to determine the effect of lighting level changes and whether shadows were likely present.

### 4.2.1 Obstacle course description.

The course area had concrete sidewalks with iron handrails and mulch flowerbeds on the perimeter in some locations. The sidewalk texture was slightly rough and gritty, but remained flat and unbroken. The street was a smooth blacktop surface. The crosswalk was made from stones and painted red. The stone surface was slightly uneven, although not very noticeable just from walking on it. The white painted crosswalk lines were on each side of the stone crosswalk and were also smooth. Although the surface texture may have provided the participant feedback

about veering out of the crosswalk, these differences in the crosswalk were minimal and consistent for each obstacle course. There was a stoplight control at the street crossing, which only turns red when the Accessible Pedestrian Signal (APS) was activated. An APS activation button was located on each side of the crossing, although the researcher did not ask the participant to use this. There were two lanes of traffic with no intersecting street. A wheelchair ramp was located on each side of the street crossing with a block of yellow truncated domes located on each ramp.

The courses were each approximately 53 feet with a single turn and a controlled street crossing, which was an additional 24 feet. The obstacle course was designed to be portable to easily stage the intended routes during the research sessions. The course area was measured by the researcher and marked with black outdoor tape to ensure consistent placement of obstacle items. The obstacles were removed in order for the *urban* trail to return to its original state and to be available to the school at other times. For this study, the simulated obstacles included three different sized garbage bags: small (13 Gallon), medium (30 Gallon), and large (55 Gallon) (Table 1). Additionally, there were several 45-gallon garbage cans used as higher obstacles and black floor mats, used to simulate a lower void, possibly a texture or elevation change, on the established route to the BrainPort user. The black garbage bags and cans were filled with paper or plastic materials to give the obstacles shape and mass. Small weights were placed in the bottom of the garbage bags to keep the wind from moving them from the desired location. Obstacles were either objects on the ground to step around or over as well as objects hanging from above to be stepped around or under. The larger objects, garbage cans and garbage bags filled with paper, were to be avoided and stepped around. The floor mat may have appeared as an obstacle to the participant, but this should have been walked on or stepped over. The hanging

objects were arranged by having Irwin Quick-Grip bar clamps fixed to the handrails and 2” x 4” boards going up and over the course sidewalk from which to hang obstacles. Obstacles were hanging at a height of 4 ½ feet off the ground, although this varied depending on the height of the participant. At this height, most participants would contact the obstacle with their body but not with the cane.

**Table 1.** Obstacle database with dimensions and course placements.

<u>Object ID</u>	<u>Description</u>	<u>Dimensions (LxWxH) feet</u>	<u>Course 1 (# of obstacles)</u>	<u>Course 2 (# of obstacles)</u>
A	Small bag – 13 gallon – black Hefty Blackout bags	1 x 2 x 2	3	1
B	Medium bag – 30 gallon – black Up & Up -black	2 x 2 x 2	2	4
C	Medium- (Half full) - black - 55 gallon Husky True tie	1 x 3 x 2	2	2
D	Large bag – (full) – 55 gallon drum liner black Husky true tie -	2 x 3 x 2	1	1
E	Garbage can – 45 gallon - black Rubbermaid Roughneck	2 x 2 x 3	3	3
F	Floor mat – Black- rubber outdoor Apache Mills –	6 x 4	1	1

#### **4.2.2 Obstacle course analysis.**

To prevent memorization, the four routes were randomly chosen for each travel condition. Each course was arranged on a different section of the urban trail section with obstacles arranged in a different configuration of object size and placement. The courses were determined to be equivalent through an analysis of the horizontal and vertical walking paths available between each of the obstacles and course parameters (Table A1). Each course allowed for only one optimal walking path, a two-foot width at any point between obstacles to allow for a participant to pass through unobstructed. Furthermore, the complexity of the courses were arranged to approximate an equal number of turns, walking paths, obstacle sizes and locations, course length, street crossings, and environmental variables. There were an uneven number of small and medium obstacles between Course 1 and Course 2, although both course have 12 obstacles total. The courses were modeled after the UPMC indoor obstacle course. The indoor obstacle course used a 7 feet by 40 feet space with 280 square feet (Nau & Fu, 2011). By including 10 obstacles on the course, there was one obstacle for every 28 square feet. The outdoor obstacle courses were each 53 feet by 6 feet, not including the street crossing since there were no obstacles in that space. Therefore, the outdoor courses were 318 square feet with 12 obstacles, which was also approximately one obstacle every 28 square feet. The designs for Course 1 (Appendix A1) and Course 2 (Appendix A2) are included with obstacle placement information.

### 4.3 PARTICIPANTS

Participants were recruited from the group of UPMC research participants in other BrainPort research including an FDA study focusing on device safety, a Veterans Rehabilitation study, a clinical outcomes study, and a tele-rehabilitation study for supporting BrainPort training after leaving UPMC. A script of the information provided to the potential participants over the phone or through email is provided in Appendix B1. Participants were also asked the basic screening questions to ensure that they qualify for this study. Verbal consent was initially provided over the phone. A written consent form (Appendix B2) was provided and explained to participants, and also signed by them before beginning any of the experimental conditions with the obstacle course. Participants were already screened as part of the UPMC research protocol. Participants all met the inclusion criteria and none of the exclusion criteria for this study.

#### Inclusion Criteria

- 1) At least 18 years old
- 2) Able to speak and comprehend English
- 3) Prior experience with the BrainPort
- 4) Prior O&M training including long cane travel
- 5) Able to travel safely and independently in outdoor environments including street crossings using a long cane
- 6) Residual visual capacity limited to light perception
- 7) Able to provide feedback regarding the BrainPort
- 8) Able to use a telephone or computer to communicate with the research staff
- 9) Comprehends the informed consent form

10) Able to complete the training and four site visits

Exclusion Criteria

- 1) Other developmental, physical or sensory disabilities
- 2) Issues with oral health, tongue sensitivity or numbness
- 3) Is currently pregnant

There were eight participants recruited for this study (4 male and 4 female). For each of the participants remaining vision was no better than light perception and each were long cane users. Participants' ages ranged from 25 to 68. Three of the participants had lost their sight at birth and the others had lost their sight at various other ages (Table 2). Participating in the BrainPort outdoor training and assessment study may have coincided with other instructions and assessments as part of the overall training regimen of the larger BrainPort investigation.

**Table 2.** Participants' demographics for age, gender, and vision loss

ID	Age	Gender	When vision loss occurred (years ago)	Age at onset (years)
1	43	F	34	9
2	55	M	10	45
3	52	M	Birth	Birth
4	38	M	14	24
5	25	M	7	18
6	68	F	Birth	Birth
7	60	F	Birth	Birth
8	39	F	30	9

#### 4.4 PROCEDURES

The following protocol describes, in detail, the established steps for which each of the eight recruited participants completed during this study. Progression moved from establishing baseline long cane skills through post-training assessment with randomized route and obstacle assignment (Figure 1).

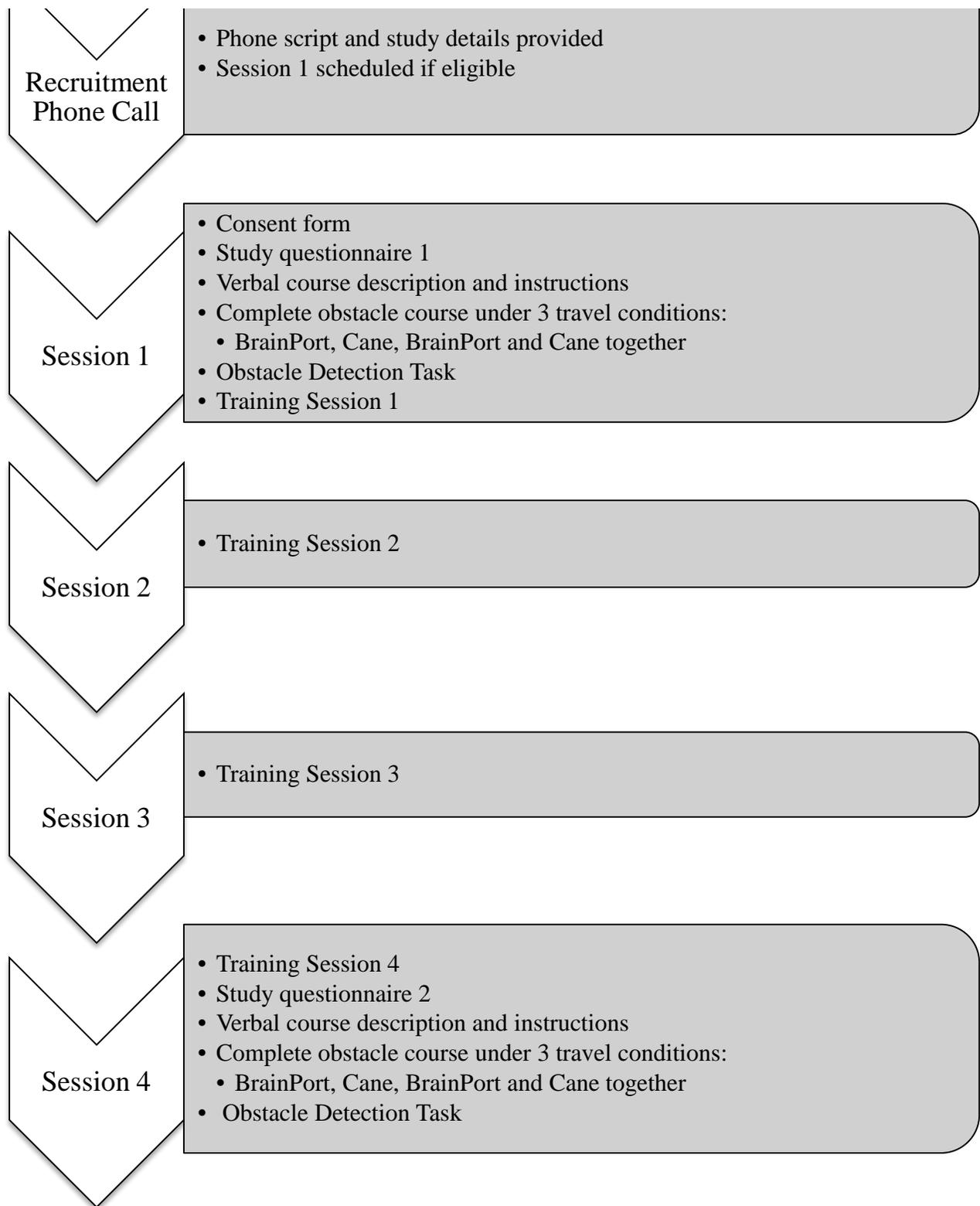
#### **4.4.1 Baseline.**

The researcher reviewed or read aloud each part of the consent form with each participant (Appendix B2). The participant then signed the consent form as well as one of the research assistants acting as a witness. The researcher went through study questionnaire one with the participant (Appendix C1). Using the established verbal script for each travel condition (Appendix D1), the researcher provided directions at the beginning of the session and provided additional information before each experimental condition. First, the researcher walked with the participant using human guide to the beginning of the obstacle course. The participant was asked to walk the unfamiliar course using a long cane in order to obtain their preferred walking speed (PWS) similar to the information collected for the indoor obstacle course (Nau & Fu, 2011). This initial travel condition was free of all simulated obstacles. Participants were told to ask their questions before starting and were informed that the instructor would not answer or respond to questions asked during each course trial. The version of the course used for each travel condition was randomized and the remaining course version was reserved for the obstacle detection task.

Following the verbal script (Appendix D1), the researcher told the participants what was expected, including the description of the obstacle course, and other pertinent details regarding each travel condition; specifically that each course includes a turn. Participants were consistently prompted by the researcher as to when they needed to turn. The participants were also told to prepare to cross at the controlled street crossing as they would normally, although traffic was very infrequent. The participants walked through the course, using one or both of the devices, while the O&M specialist walked within arm's reach to ensure safety. Each course

route was expected to take from 30 to 600 seconds based on mock condition trials. Most course trials were completed in the range of 60 and 300 seconds.

Each participant completed a version of the obstacle course three times traveling independently in random order: 1) with the BrainPort, 2) with a long cane, 3) with the BrainPort and long cane. These three conditions were followed by an obstacle detection task where the participant walked through a section of the course to point out the obstacles detected with the BrainPort. The participant's detection of obstacles, specifically which obstacles were detected, was the only item recorded and this was not timed. Course sequencing was randomized for each condition for the sessions. For each of the four sessions, the obstacle course trials lasted one to two hours including obstacle course set-up. All of the participants scheduled two sessions in the same day with one session held in the morning and then one session in the afternoon. Each of the course trials were videotaped for data collection purposes.



**Figure 1.** Flow chart for the BrainPort study procedures.

#### **4.4.2 Training program.**

After baseline data was established, participants came back one to two weeks later for three additional sessions. Participants went through the obstacle course at Session One and Four. Training occurred at all four of the sessions. The training program focused on detecting and identifying shadows, sidewalks, curbs, crosswalks, intersections, and interpreting sensory information from the BrainPort as a participant typically would along a route. The UPMC laboratory staff used training protocols as part of the training and intervention to support success and skill development for the participants in their studies (Nau, Pintar, Fisher, Jeong, & Jeong, 2014). For an individual to develop proficiency with a device, training and practice were required. The training protocol for this study focused on building skills needed for detecting and interpreting environmental features with the BrainPort. The participant was asked to review the options for adjusting settings and preferences. For practice and training, obstacles were arranged randomly on the course. The BrainPort Training Program document (Appendix E1) was completed as the participant went through each task described below. The following is a description of the procedures for the training program:

- 1) The participant was asked to look in front, left, and right to determine presence of any obstacles. If the individual located an obstacle, the participant was asked to focus on it and determine its approximate distance away. Then the participant was asked to walk up to the obstacle without touching it. The participant then located the obstacle and explored it with a hand or the long cane. This process was repeated for other obstacles.
- 2) Again, the participant was asked to look around for obstacles. After locating two obstacles, the participant attempted to safely walk around/between them and avoid contacting them.

- 3) As the participant approached the crosswalk, the participant stopped on the truncated domes before reaching the street. The participant turned off the invert setting on the BrainPort. The participant was then instructed to scan to the left and right of their visual fields to determine the location of each crosswalk line. The participant then crossed the street remaining between the crosswalk lines and keeping one of the lines in view while crossing. The participant followed this line by shorelining visually similar to how a participant uses this technique with the long cane.
- 4) The participant approached where the floor mat was located. The participant was instructed to scan up and down and determine where the mat starts and stops and then look for horizontal lines at the top and bottom of the floor mat.
- 5) After approaching the gazebo, the participant was asked to scan left and right to find the opening. The participant became familiar with how vertical and horizontal lines appeared with the BrainPort.
- 6) The participant walked along the sidewalk and determined left and right edges through contrast changes. The participant was asked to determine if there were surface changes through the light and dark colors detected with BrainPort. The participant followed a visual shoreline by keeping the sidewalk edge in view. The participant repeatedly practiced finding these changes in the surface through contrast changes.
- 7) The participant was asked to walk with the BrainPort and cane to get used to maintaining attention to multiple sources of sensory information simultaneously. They did this by traveling specific routes around the area by the WPSBC.

- 8) The participant was asked to adjust settings on the BrainPort to explore what works best for various environmental conditions. The participant examined shaded and sunny areas (if possible) to determine the appearance of these characteristics with the BrainPort.
- 9) The participant repeated these procedures in each of the four training sessions increasing the complexity and exploring different environments in the area (Urban trail, sidewalk along the street, approaching intersections and crosswalks).

#### **4.4.3 Post-training assessment.**

After the training sessions, each participant returned for the fourth session to complete the second set of obstacle course conditions. All procedures were replicated based on the protocol for the first obstacle course session. A final questionnaire (Appendix C2) was given and some questions were repeated from the previous questionnaire (Appendix C1) to evaluate the participant's use of the BrainPort and travel behaviors. Each participant again traveled through the obstacle three times: using the cane, using the BrainPort, and using the BrainPort and cane together. Following these three conditions, the participant once again completed the obstacle detection task by pointing at obstacles while walking through the obstacle course. Although participants were not instructed to use a particular cane technique, all eight participants used two-point touch when traveling independently. Participants were paid \$25 at the end of each of the four visits with an additional \$50 at the completion of four visits for a total of \$150. The participants completed the obstacle detection task at this session as well. All of the eight participants returned to complete the rest of the sessions after participating in the first session.

## 4.5 DATA ANALYSIS

### 4.5.1 Data collection.

Procedures for collecting data about participant performance were the same for each individual. A course layout data sheet (Appendix E2) was created to record which obstacles were contacted related to the position on each obstacle course. An additional data sheet (Appendix E3) was used to record the participant's time of travel, obstacle contacts, veering, environmental luminescence, and obstacle identification. Obstacle contacts were recorded separately for instances where the long cane contacts the obstacle instead of just the body. The long cane is typically considered an extension of the body when walking through an environment. When an individual contacts an obstacle with the long cane, the rate of travel would likely decrease. Therefore, reducing obstacle contacts even with a long cane is desirable for travel efficiency.

Each session with a participant was video recorded for later review and scoring. Additionally, the majority of the participant training sessions were video recorded as well. The researcher watched each video multiple times looking for the specific information regarding performance. Data were recorded from the videos regarding time of travel, obstacle contacts with the body and the cane, the size of the obstacles contacted, and veering out of the course or crosswalk. Time of travel was segmented between the time on the obstacle course and time in the crosswalk. The Preferred Walking Speed (PWS) was computed by dividing the course length (77 feet) by the time traveled without obstacles. The course speed (CS) was computed by dividing the course length (77 feet) by the time traveled in the cane condition. The Percentage of Preferred Walking Speed, often used in gait research as a measure of travel, was a comparison of traveling in two different conditions. In this case, the comparison is for traveling with a

natural mobility device (long cane) with and without obstacles present:  $(CS/PWS) \times 100 = PPWS$  (Friberg et al., 2011). Duration of travel (time) and obstacle contacts were recorded. The duration of travel was recorded using a stopwatch, which was started as the participant stepped past the initial marking indicating the beginning of the course, and then stopped once the participant stepped past the end marker. Individual differences between participants, such as the amount of prior O&M training, between participants were controlled for by having each participant act as their own control from pre-training to post-training. A questionnaire was completed by each participant at Session One (Appendix C1) and Session Four (Appendix C2) to provide information on O&M training, BrainPort training, onset of a visual impairment, and confidence with the BrainPort and for independent travel.

After the research procedures were completed for the session, the results were recorded as the researcher watched the video and completed the course layout (Appendix E2) and data form (Appendix E3). For the obstacle detection task, the researcher recorded each accurate or inaccurate detection of an obstacle and the specific obstacle that was detected. For data purposes, the hanging obstacles were small or medium obstacles and were recorded separately as both hanging and the appropriate size. The researcher recorded the number of obstacles the participant contacted with any part of the body. The researcher recorded the number of obstacles the participant's cane contacted as well. Veering was defined as when the participant had one foot partially or completely off of the sidewalk or outside of the crosswalk path. The participant was prompted by the researcher to step back onto the course when veering outside of the course area. The optimal path of travel for the course was determined by how many times the participants veered off the sidewalk, crosswalk, or outside of the course area. These data items were recorded on the appropriate course layout diagram (Appendix E2).

Furthermore, the overall luminescence or light level present during each participant's walk was recorded using a digital light meter. A light meter reading was taken at three different areas of the course and then the averaged per session. Lighting conditions were recorded to investigate how lighting conditions affect performance and perception with the BrainPort. The dependent variables were duration of travel, the frequency of contacting obstacles, and the frequency of veering off the course. Identification and detection for each specific obstacle was analyzed across participants. The experimental results were analyzed across time of travel, number of obstacles detected, luminescence, number of times veering off the course or crosswalk, and type and size of obstacles detected, and participant characteristics. Mean and standard deviations for each dependent variable were calculated across travel and lighting conditions as well as the onset of the visual impairment for each of the participants.

#### **4.5.2 Training research assistants.**

Since the researcher was responsible for conducting the training with participants, providing instructions before and after each obstacle course trial, and recording data from the videos, additional support was needed to implement the research procedures and interpret the data. Three research assistants were identified to set up the obstacle courses, to video record the course trails, and collect data from the taped sessions. Training the research assistants occurred over two 2-hour sessions. They were trained to video record the course trials and training procedures. The research assistants were taught to walk a specific route while video recording, to have the best view of the research participant. Six mock training videos, using a sighted person walking through the obstacle course using a cane or just walking without using anything, were created to ensure inter-rater reliability between the researcher and the research assistants scoring of the

taped sessions. These mock videos were scored by the researcher and then scored by the research assistant. There was 85% agreement between the researcher and research assistant in all of these training sessions. The spaghetti plots for time and contacts were contributed by Jennifer Murphy from University of Pittsburgh's Statistics Consulting Center. Information recorded onto the data sheets (Appendix E2; Appendix E3) was entered into an SPSS spreadsheet for easy reference. Analysis was conducted using SPSS to tabulate and provide statistical results. Additional variables were created within SPSS for averages between Session One and Session Four, ranked scores, and difference scores between Session One and Session Four.

Information recorded for each trial included:

- Which condition was it? (BrainPort, Cane, BrainPort and Cane together)
- Lighting conditions appearance
- Note the date and time on the video
- Note the sex of the participant
- Note the version of the course being used (Course 1 or 2, Forward or Reverse)
- Note any other important information
- Watch each video multiple times tabulating different data separately to ensure nothing was missed
  - Record the approximate time to complete the course from when the participant crosses the marking at the beginning until crossing the marking at the end of the course.
  - Record the time it takes to complete the street crossing from when the participant first steps on the truncated domes (raised bumps near crosswalk) to when they step onto truncated domes on opposite side

- Record total number of obstacles a participant contacts with any part of the body
- Record the number of obstacles the cane contacts
- Record specifically on the data layout sheet (Appendix C) which obstacles the participant contacted
- Record the number of times the participant steps off of the main sidewalk on the course
- Record the number of times the participant steps outside of the crosswalk in the street crossing
- Record number of times the participant is off the course and needs to be redirected or prompted verbally or physically for time or safety issues

#### Obstacle Detection Task

- For untimed trial, record the number of obstacles the participant points out
  - Record how many appear to be accurate and how many inaccurate
  - Record specifically which obstacles the participant points out

## 5.0 RESULTS

The purpose of this study was to examine the capabilities of the BrainPort sensory substitution system to assist individuals with visual impairments to travel independently and avoid obstacles in a novel outdoor naturalistic environment. The research questions, which guided the analysis of the data, were (a) what impact does the BrainPort system have on an individual's rate of travel in a novel outdoor environment? and (b) what impact does the BrainPort system have on an individual's ability to detect and avoid obstacles in a novel outdoor environment? and (c) what impact does the BrainPort system have on an individual's ability to maintain an optimal straight path of travel in a novel outdoor environment?

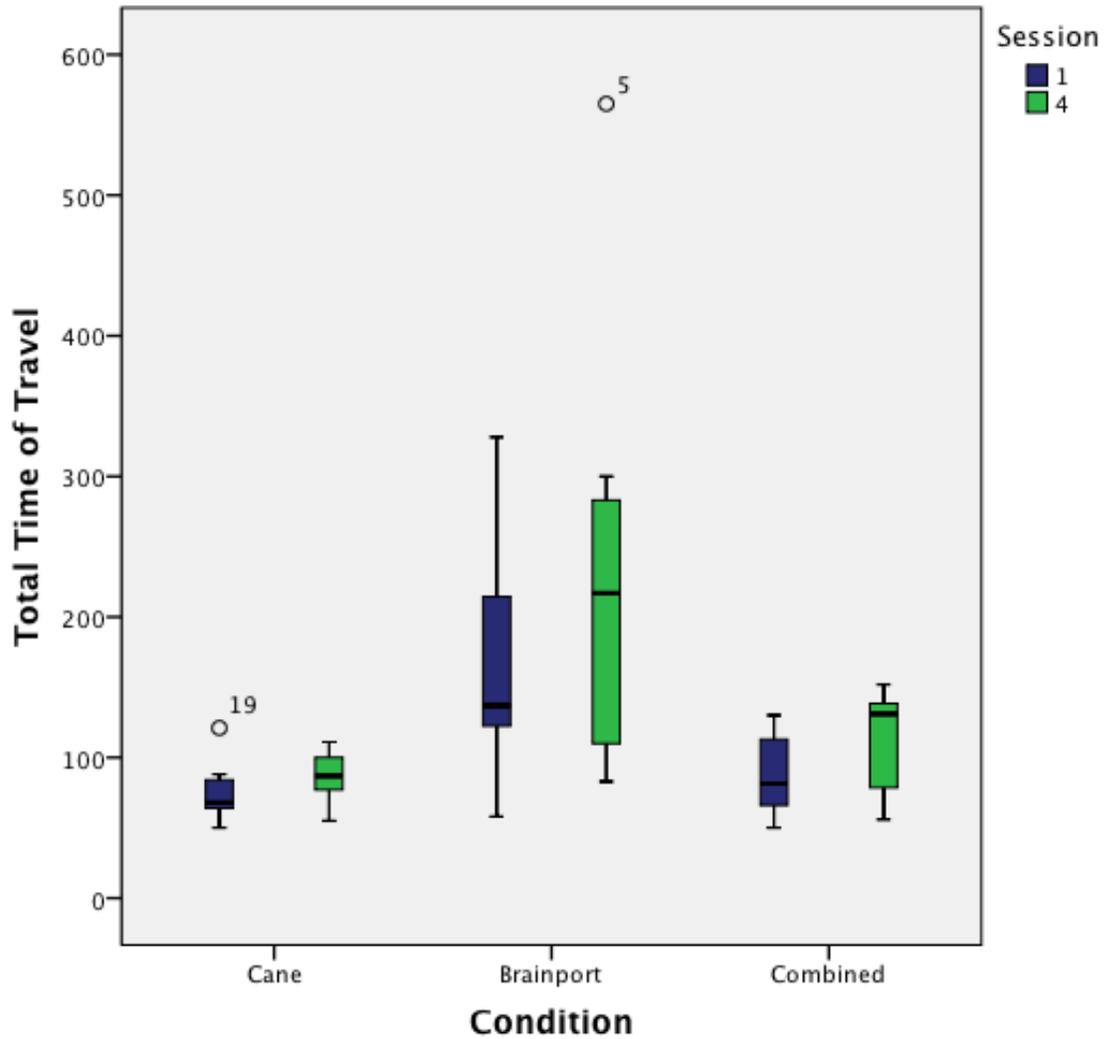
The results were not normally distributed for the different travel conditions. In the boxplot for time of travel for different travel conditions, the scores for each session display a much wider range for the BrainPort condition compared to either of the other two travel conditions (Figure 2). The boxplots for total contacts (Figure 3) and total veers (Figure 4) appeared to each have more normal distributions. A Levene's test showed that the dependent variable, total time of travel, was not normally distributed and violated the homogeneity of variance assumption (Table 3). The variables of total contacts and total veers did not violate this assumption and may have a normal distribution.

**Table 3.** Levene's Test for Homogeneity of Variance across conditions.

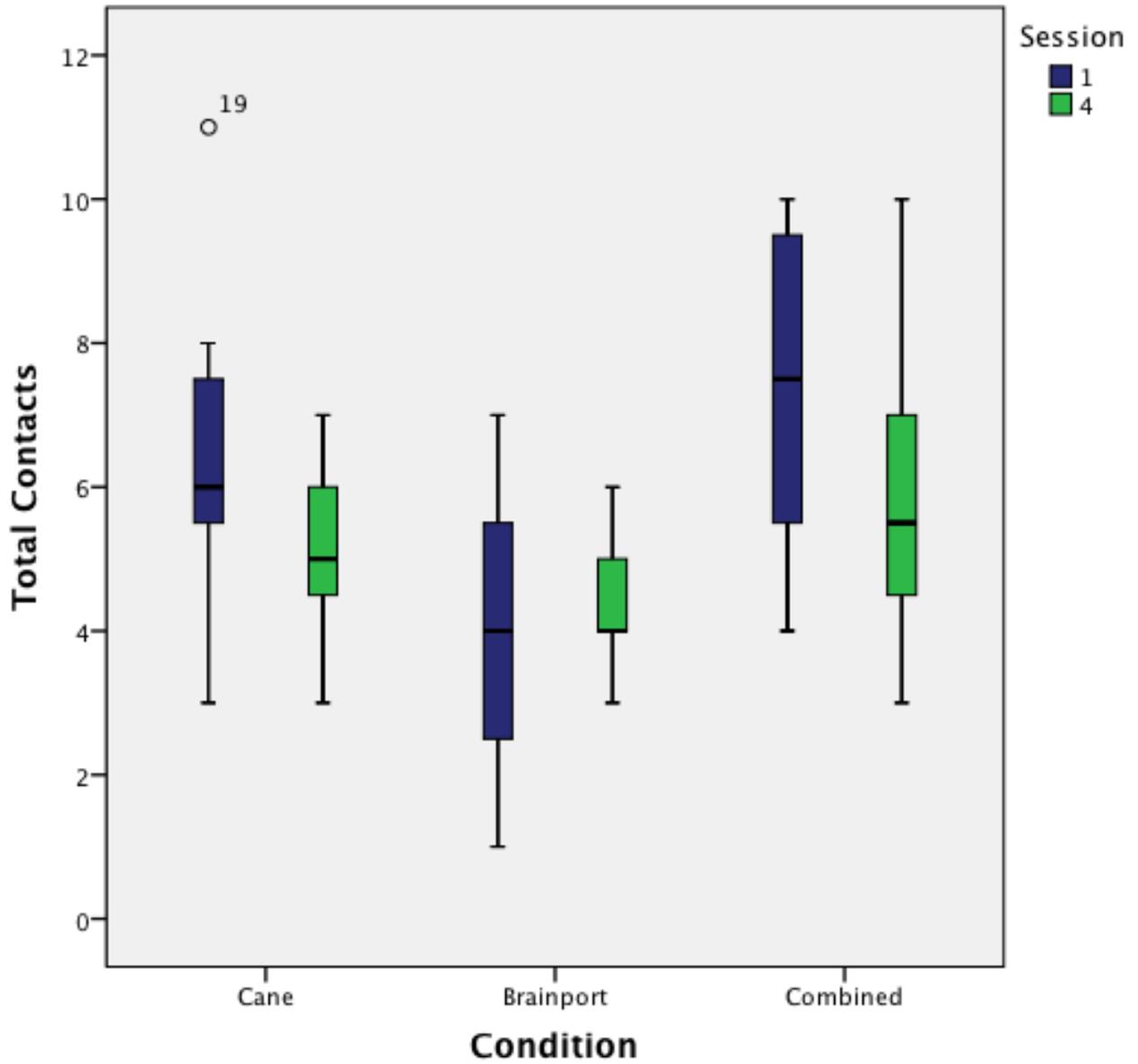
Test of Homogeneity of Variances				
	Levene Statistic	df1	df2	Sig.
Total Time of Travel	6.438	2	21	.007
Total Contacts	.159	2	21	.854
Total Veers	.184	2	21	.833

Time of travel and total contacts were the most valued variables for this research study to demonstrate an effect related to real independent travel. Due to the small sample size and abnormal distribution for total time of travel, non-parametric testing was determined to be a better fit for the experimental results. The Friedman ANOVA Test is used to evaluate differences between three treatment conditions in a repeated measures design, as a non-parametric alternative to the Repeated Measures ANOVA (Gravetter & Wallnau, 2007). The Friedman's ANOVA requires that participants are in each treatment condition and that the scores are ranked data or numerical scores converted to ranked data. A Friedman's ANOVA was conducted for each of the main dependent variables: time of travel, total number of contacts, and total number of veers. Given that the sample size was small and there was an increase in time of travel from Session One to Session Four in each travel condition, each participant's scores from Session One and Session Four were averaged to provide a more consistent performance score. This average from Session One to Session Four for each participant was ranked compared to other participants for each condition. Each participant had an average score and ranked score for the cane condition, BrainPort condition, and the BrainPort and Cane combined condition. The ranked mean scores were used to compare results across conditions for the Friedman's ANOVA. These ranked means were created for each participant and in each condition for total time of travel, total obstacle contacts, and total number of veers. Before reviewing the results for the

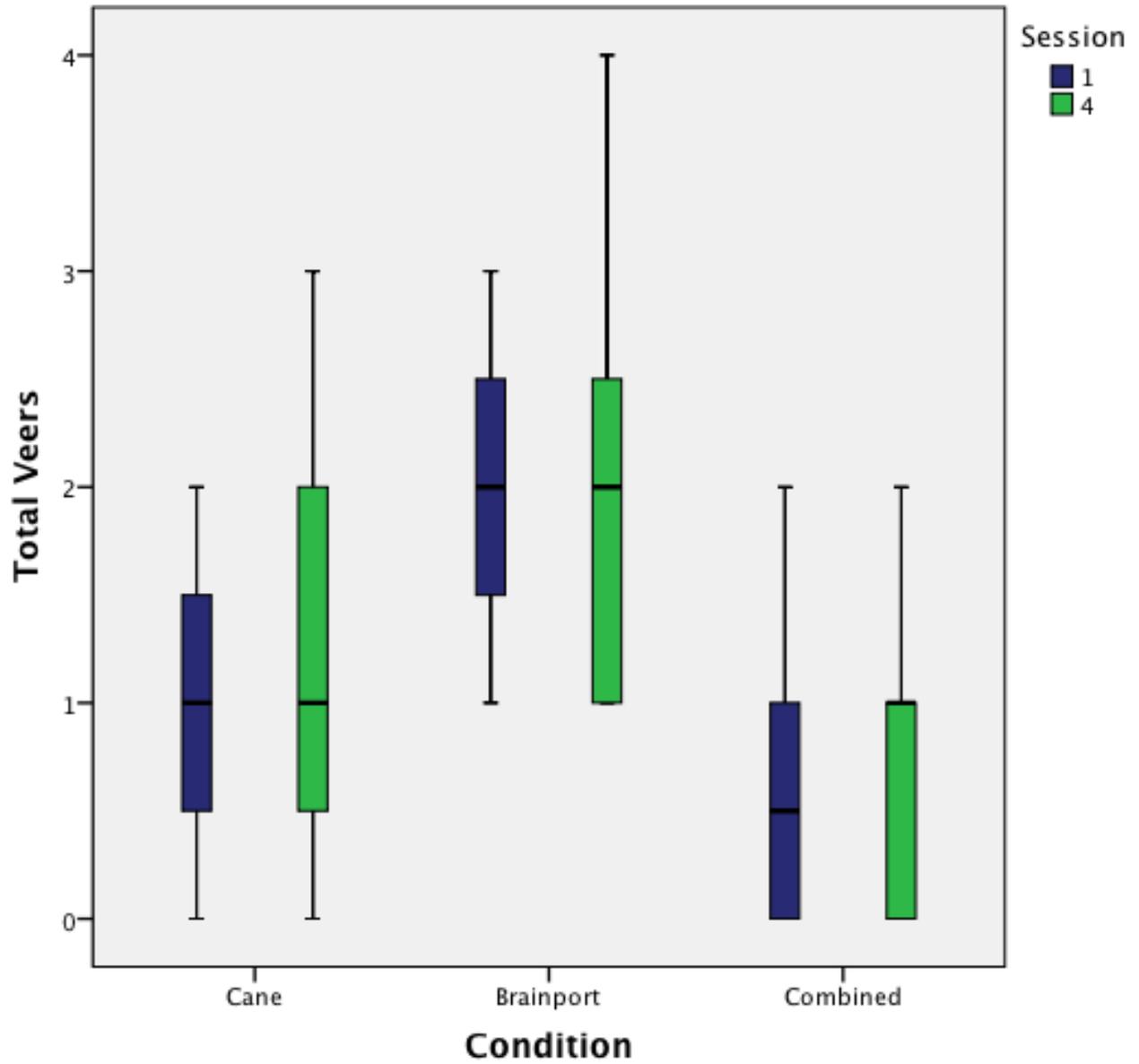
research questions, statistics are reported on reliability results and performance statistics are reported across travel conditions.



**Figure 2.** Boxplot displaying distribution of total time of travel for each session and each travel condition.



**Figure 3.** Box plots of distribution of total contacts for sessions and each travel condition.



**Figure 4.** Boxplot of distribution of total veers for each session and each travel condition.

## 5.1 RELIABILITY OF RESEARCH PROCEDURES

### 5.1.1 Reliability of training and research procedures.

Research procedures were conducted consistently throughout this study. The obstacle course assignment was randomized to prevent course versions from having an effect on performance. The randomization resulted in a complete Latin Square where each sequence of experimental conditions occurs at least once between all participants (Table 4). For Session Four, the BrainPort and Cane combined condition and the BrainPort only travel condition more frequently occurred first, compared to the Cane only condition (Table 5). This could be a “learning effect,” based on the ordering the participants received these treatments. This was explored through additional testing. Each travel condition occurred multiple times for each course version of the obstacle course (Table 6). The frequency of each condition occurring for each course was close to being equal for the four courses (Table 7). There was not any significant Spearman Correlation found between the course version and the main dependent variables: total time of travel ( $\rho = .010$ ,  $p = .944$ ), total contacts ( $\rho = -.142$ ,  $p = .335$ ), or total veers ( $\rho = -.247$ ,  $p = .090$ ) (Table F1).

Training procedures were the same for all of the participants. The training program was video recorded as well for most of the sessions to ensure reliability between participants. These videos were reviewed by the researcher to ensure consistent procedures were followed in each instance. Each course trial occurred on the same

sections of the sidewalk and outdoor “urban trail”. Obstacles were set up for training and practice purposes with the BrainPort. An outline and description of the procedures to be completed during training was followed for each participant as well. These procedures ensured the training program was the same for each research participant. Research procedures for completion of the obstacle course were recorded as well to ensure reliability between participants. The researcher followed a verbal script for consistent explanations for each participant (Appendix D1). The obstacle course was organized according to the layout forms (Appendix A1; Appendix A2) and obstacles were placed in consistent locations. The procedural sequence was randomized for each participant at the Session One and Session Four. This was done to prevent any effects between an experimental condition and any of the courses. This was also done to prevent learning effects by having certain conditions occur in the same order consistently.

**Table 4.** Random assignment of travel conditions in procedural order.

		Experimental Condition Sequencing		
		Order		
Participant ID	Session	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>
1	1	3	2	1
	4	3	1	2
2	1	2	3	1
	4	2	1	3
3	1	1	2	3
	4	2	1	3
4	1	3	2	1
	4	3	1	2
5	1	1	2	3
	4	3	2	1
6	1	1	3	2
	4	2	1	3
7	1	2	1	3
	4	1	2	3
8	1	2	1	3
	4	3	2	1
Treatment: 1=Cane 2=BrainPort 3=BrainPort & Cane				

**Table 5.** Frequency of condition by session and order.

Condition	Session	Order		
		1	2	3
Cane	1	3	2	3
	4	1	5	2
	Total	4	7	5
BrainPort	1	3	4	1
	4	3	3	2
	Total	6	7	3
Combined	1	2	2	4
	4	4	0	4
	Total	6	2	8

**Table 6.** Course version for each travel condition and participant for each session.

Participant ID	Session	Condition		
		Cane	BrainPort	BrainPort and Cane
1	1	4	3	1
	4	1	4	2
2	1	2	4	3
	4	1	2	3
3	1	2	1	4
	4	1	2	3
4	1	2	3	4
	4	3	4	1
5	1	4	3	2
	4	2	3	1
6	1	3	1	2
	4	4	2	3
7	1	1	2	4
	4	2	1	3
8	1	3	4	2
	4	4	1	2

Course version = 1, 2, 3, or 4

**Table 7.** Frequency of conditions for each course version.

Course Version	Condition		
	Cane	BrainPort	BrainPort and Cane
1	4	4	3
2	5	4	5
3	3	4	5
4	4	4	3

### **5.1.2 Reliability of questionnaire instruments.**

Two questionnaires were created to collect basic demographic information, information about the participants' visual impairments, and their comfort level with the BrainPort. The first questionnaire (Appendix C1) was completed at the first session and the final questionnaire (Appendix C2) was completed at the fourth session. These questionnaires were reviewed by three professionals in the field of blindness rehabilitation. For validity of the questionnaires, these reviewers provided feedback on any confusing terminology, unclear questions, and other suggested revisions. The questionnaires were altered to meet the requests of the reviewers and maintain the integrity of the intended information to be acquired.

### **5.1.3 Reliability of data collection.**

Reliability was tested for each of the data collectors across the video recorded trials. Since the collection of data involved some subjectivity, the videos were scored by more than one

researcher to ensure reliability. The researcher scored all of the videos and recorded all of the appropriate data (Table 8). Inter-rater reliability was ensured by having a research assistant rescore 22 of the 64 videos and tabulate all of the appropriate data. The level of acceptable reliability was set at 80%. The level of agreement was 89% between the researcher and the research assistant. For test-retest reliability, the researcher rescored each of the videos after a 3-week period to ensure reliability of his own data collection. There was 95% agreement between the two data collection periods.

**Table 8.** Inter-rater reliability data between researcher and research assistant, and test-retest reliability for the researcher’s observations.

Reliability Results

	Trials Scored	Number of data items recorded	Agreements with PI	Disagreements with PI	Percent Agreement
<b>Test-Retest Reliability</b>					
Principal Investigator	64	1922			
PI Rescore Reliability	64	1915	1825	97	95%
<b>Inter-rater Reliability</b>					
Principal investigator	22	653			
Research Assistant	22	649	578	75	89%

## 5.2 FINDINGS RELATED TO QUESTION 1

What impact does the BrainPort system have on an individual's rate of travel in a novel outdoor environment?

In order to determine what effect the BrainPort had on an individual's time of travel, an average score was computed from time of travel at Session One and Session Four. These averages were ranked across participants for each travel condition. The Friedman's ANOVA results of the ranked scores were significant for total time of travel. For the three travel conditions, the average means between sessions were 81.06 (Rank Avg= 1.13) for the Cane condition, 183.56 (Rank Avg= 2.88) for the BrainPort condition, and 100.31 (Rank Avg= 2.00) for the BrainPort and cane condition (Table F2; Table F3). The total time of travel changed significantly between travel conditions,  $\chi^2(2, N=8) = 12.250, p=.002$  (Table F4). The Spearman Correlations were not significant between the total time of travel and participant characteristics of age, gender, or onset of vision loss (Table F5-F10). The other correlations will be discussed in later sections.

### 5.2.1 Cane travel condition.

The mean performance time of travel for the cane condition was 75.38 (SD=21.73) (Table F11) at Session One and 86.75 (SD=18.13) at Session Four (Table F12). For the time of travel in the first session, values ranged from 50 to 121 seconds. For the fourth session, the total time of travel values ranged from 55 to 111 seconds. The total time of travel was divided into crosswalk time and course time. Participants' time of travel increased from the first session to the fourth session in the recorded times for the course and crosswalk for the cane condition. The mean performance crosswalk time for the cane condition was 23.50 (SD=7.48) at Session One and

24.63 (SD=8.05) at Session Four (Table F13). Participants' crosswalk times at Session One ranged from 16 seconds to 36 seconds. Participants' crosswalk times then at Session Four ranged from 15 seconds to 42 seconds. The participants' course time at Session One was 51.88 (SD=16.69) and 62.13 (SD=15.18) at Session Four (Table F14). For all of the participants, their course times ranged from 39 seconds to 105 seconds at Session One and then 34 seconds to 85 seconds at Session Four.

The Percentage of Preferred Walking Speed was calculated from the speed of the participant walking through the course without the presence of obstacles while using the long cane compared to the speed with the long cane in the presence of the obstacles. The PPWS ranged from 52 to 88 percent of their normal walking speed (Table 9). This showed that the obstacles slowed participants down to some extent and this decrease in speed was variable between participants.

**Table 9.** Individual participant PPWS in comparison to speed with the cane and on the obstacle course.

Participant ID	PWS (ft/sec)	Cane Travel (ft/sec)	PPWS (percent)
1	1.35	0.96	71
2	0.90	0.88	78
3	1.48	1.07	72
4	1.22	0.64	52
5	1.43	1.20	84
6	1.60	1.20	75
7	1.51	1.20	80
8	1.75	1.54	88
Mean			75

### **5.2.2 BrainPort only travel condition.**

For the BrainPort only condition, the mean performance time of travel increased from 166.75 (SD=82.97) at Session One (Table F11) to 233.50 (SD= 156.61) at Session Four (Table F12). The total time of travel was divided between the crosswalk time and the obstacle course time and this increase was consistent for each of these. For the BrainPort only condition, the mean obstacle course time increased from 124.25 (SD=75.69) at Session One to 179.63 (SD=129.41) at Session Four (Table F14). Participants' obstacle course times ranged from 40 seconds to 277 seconds at Session One. At Session Four, participant obstacle course times ranged from 57 seconds to 471 seconds. For the BrainPort only condition, the mean crosswalk time increased from 42.50 (SD=12.28) at Session One to 53.88 (SD=38.60) at Session Four (Table F13). Participants' crosswalk times ranged from 18 seconds to 53 seconds at Session One. At Session Four, participants' crosswalk times ranged from 8 seconds to 102 seconds.

### **5.2.3 BrainPort and cane combined condition.**

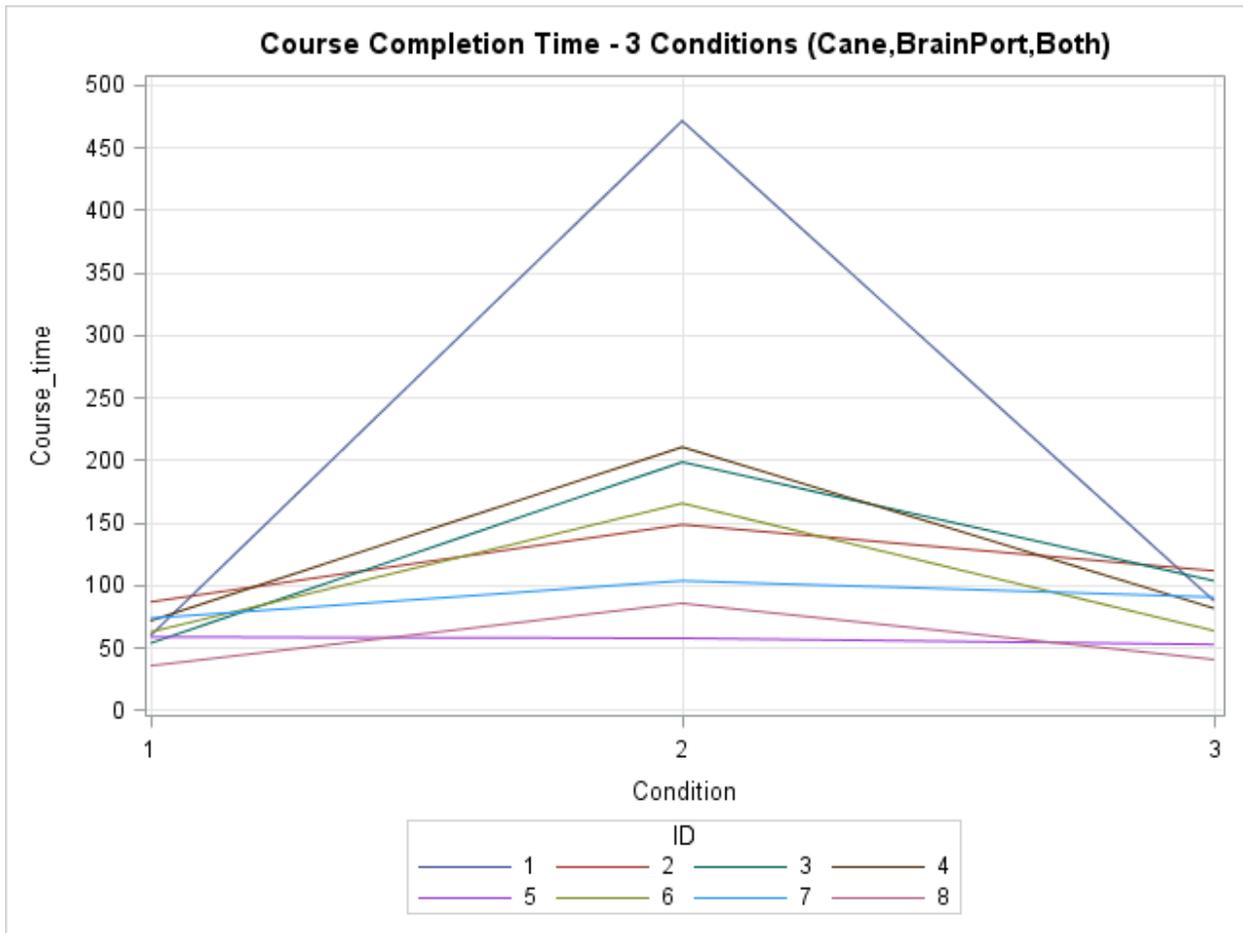
For the BrainPort and cane combined condition, the mean performance time of travel increased from 87.63 (SD=28.08) at Session One (Table F5) to 113.00 (SD=36.60) (Table F12) at Session Four. As the total time of travel was segmented, the crosswalk time and the obstacle course time each also increased for the BrainPort and long cane combined condition from Session One to Session Four. For the BrainPort and cane combined condition, the mean obstacle time increased from 65.88 (SD=24.50) at Session One to 78.38 (SD=24.76) at Session Four (Table F14).

Participants' obstacle course times ranged from 39 seconds to 105 seconds. At Session Four, participants' crosswalk times ranged from 40 seconds to 111 seconds. For the BrainPort and cane combined condition, the mean crosswalk time increased from 21.75 ( $SD=6.78$ ) at Session One to 34.63 ( $SD=17.50$ ) at Session Four (Table F13). Participants' crosswalk times ranged from 11 seconds to 33 seconds. At Session Four, participants' crosswalk times ranged from 15 seconds to 65 seconds.

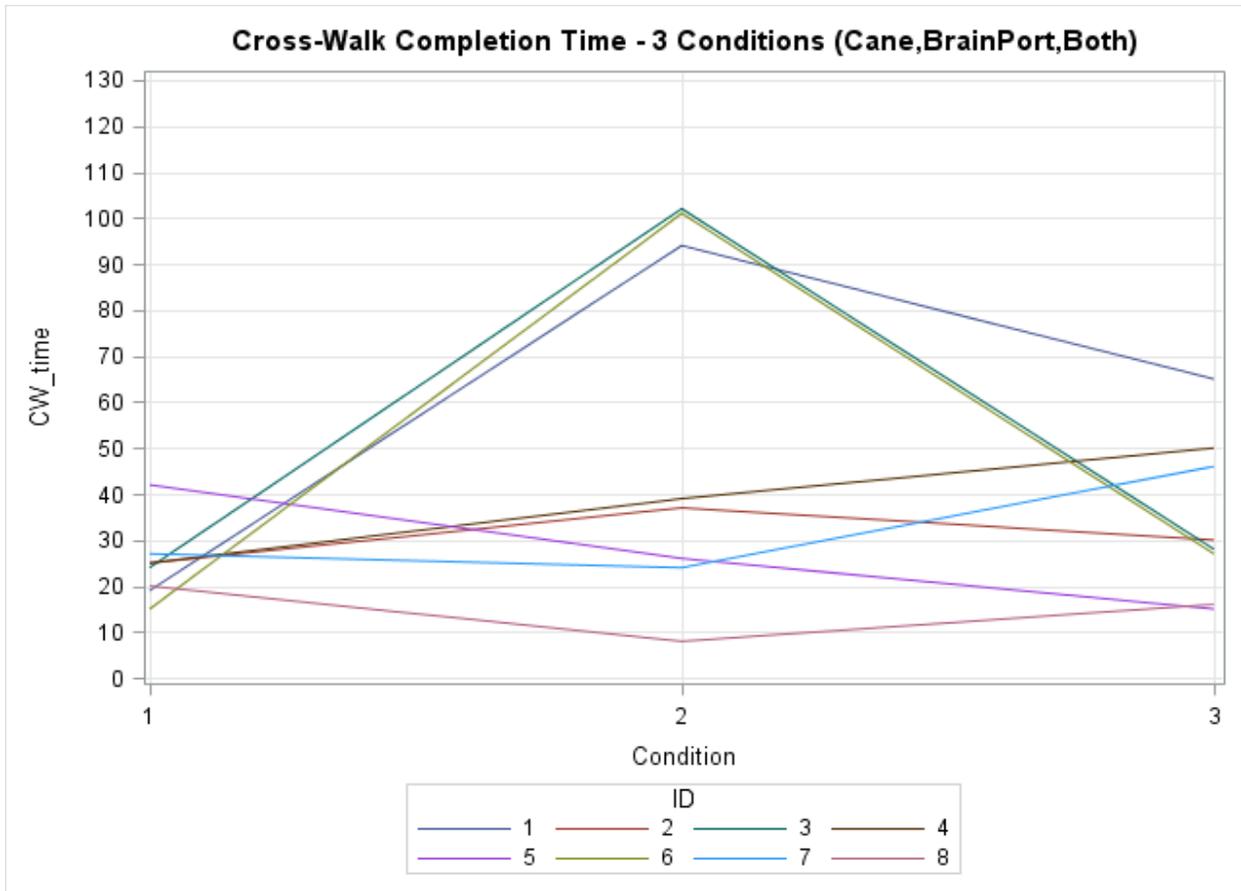
#### **5.2.4 Individual differences in performance for time traveled.**

In the cane only condition, most of the participants performed similarly in regards to the two obstacle course performances. For six of the participants, they each traveled slower at Session Four than they did at Session One. For two participants, they were able to travel faster at Session Four. In the BrainPort only condition, most of the participants performed slower at Session Four than they were at Session One. Six of the participants traveled slower and two of the participants were able to travel faster. In the BrainPort and cane combined condition, most of the participants also traveled slower at Session Four compared to Session One. Five of participants were much slower at Session Four, while the other three were either faster or were within a few seconds of their time at Session One. For the two participants that traveled faster at Session Four with the BrainPort, they also traveled faster or about the same speed in the BrainPort and cane combined condition. For the participant who had the least amount of experience with the BrainPort, this participant also traveled faster in each condition with the BrainPort at Session Four. For comparisons across conditions, most participants were slower in the BrainPort condition compared to either of the other two conditions (Figure 6). Participant times also varied greatly with several under 100 seconds and one time over 450 seconds. For crosswalk time, there was a

similar trend with most participants performing similarly in the cane condition and the BrainPort and Cane condition (Figure 7). While three participants had much longer times compared to the other two conditions, a few participants had about the same time or faster with the BrainPort compared to the other two conditions.



**Figure 5.** Spaghetti plot for course time for each participant in each condition.



**Figure 6.** Spaghetti plot for crosswalk time for each participant in each condition.

### 5.3 FINDINGS RELATED TO QUESTION 2

What impact does the BrainPort system have on an individual’s ability to detect and avoid obstacles in a novel outdoor environment?

In order to determine what effect the BrainPort had on an individual’s ability to avoid obstacles, an average score was computed from the total contacts at Session One and Session Four. These averages were ranked across participants for each travel condition. The Friedman’s ANOVA results of the ranked scores were significant for total number of obstacles contacted. For the

three travel conditions, the average means between sessions were 5.81 (Rank Avg= 1.88) for the Cane condition, 4.19 (Rank Avg= 1.31) for the BrainPort condition, and 6.62 (Rank Avg= 2.81) for the BrainPort and cane condition (Table G1; Table G2). The total number of obstacles contacted changed significantly between travel conditions,  $\chi^2(2, N=8) = 9.800, p=.007$  (Table G3).

### **5.3.1 Cane travel condition for obstacle contacts.**

Participants' number of obstacles contacted decreased from Session One to Session Four from what was recorded for the number of obstacles contacted with the body or the cane for the cane only condition. The mean number of total obstacles contacted for the cane condition decreased from 6.50 (SD=2.33) at Session One (Table G4) to 5.13 (SD=1.25) at Session Four (Table G5). For the total number of obstacles contacted in the cane condition, values ranged from three to 11 contacts in Session One and then three to seven contacts in Session Four. The total number of obstacles contacted was divided between body contacts and cane contacts. The mean number of obstacle body contacts for the cane condition was 1.38 (SD=0.916) at Session One (Table G6) and 0.88 (SD=0.641) at Session Four (Table G7). Participants' number of obstacle contacts at Session One ranged from zero to three contacts and then zero to two contacts at Session Four. The mean number of cane contacts for the cane condition was 5.13 (SD=1.96) at Session One (Table G8) and 4.25 (SD=1.70) at Session Four (Table G9). Participants' number of cane contacts for the cane condition ranged from three to nine contacts at Session One and then from two to seven contacts at Session Four.

### **5.3.2 BrainPort travel condition for obstacle contacts.**

Participants' number of obstacles contacted decreased from Session One to Session Four from what was recorded for the BrainPort only condition. The mean total number of obstacles contacted for the BrainPort condition increased slightly from 4.00 (SD=2.00) at Session One (Table G4) to 4.38 (SD=0.92) at Session Four (Table G5). Participants' total number of contacts ranged from one to seven contacts at Session One and then from three to six contacts at Session Four. The total number of obstacles contacted was divided between body contacts and cane contacts for the other conditions, but only counted the obstacles contacted by the body since the participant did not use a long cane in the BrainPort condition.

### **5.3.3 BrainPort and cane travel condition for obstacle contacts.**

Participants' number of obstacles contacted decreased from Session One to the Session Four for the BrainPort and cane combined condition. The mean total number of obstacles contacted for the BrainPort and cane combined condition decreased from 7.38 (SD=2.39) at Session One (Table G4) to 5.88 (SD=2.23) at Session Four (Table G5).

For the total number of obstacles contacted in the BrainPort and cane combined condition, values ranged from four to 10 contacts in Session One and then three to 10 contacts in Session Four. The total number of obstacles contacted was divided between body contacts and cane contacts. The mean number of obstacle body contacts for the BrainPort and cane combined condition was 1.75 (SD=1.28) at Session One (Table G6) and 1.25 (SD=0.707) at Session Four (Table G7). Participants' number of obstacle contacts at Session One ranged from zero to three contacts and then zero to two contacts at Session Four. The mean number of cane contacts for the BrainPort

and cane combined condition was 5.63 (SD=2.45) at Session One (Table G8) and 4.63 (SD=2.26) at Session Four (Table G9). Participants' number of cane contacts for the BrainPort and cane combined condition ranged from two to 10 contacts at Session One and then from two to nine contacts at Session Four.

#### **5.3.4 Sizes and types of obstacles contacted.**

For the obstacles contacted, the size of each obstacle was recorded; small, medium, large, and whether it was a hanging obstacle. The total number of obstacles contacted for each size obstacle and each travel condition is reported in Table. For the number of small obstacles contacted in the cane condition, the mean number of contacts decreased from 2.63 (SD=1.51) at Session One (Table G10) to 2.25 (SD=1.04) at Session Four (Table G11). The number of small obstacles contacted ranged from zero to four at Session One and then from one to four at Session Four. For the number of small obstacles contacted in the BrainPort condition, the mean contacts increased from 1.63 (SD=1.19) at Session One to 2.25 (SD=.707) at Session Four. The number of small obstacles contacted ranged from zero to three at Session One and then from one to three at Session Four. For the number of small obstacles contacted in the BrainPort and cane combined condition, the mean contacts decreased from 2.13 (SD=.835) at Session One to 1.63 (SD=1.30) at Session Four. The number of small obstacles contacted ranged from one to three at Session One and then from zero to four at Session Four.

For the number of medium obstacles contacted in the cane condition, the mean contacts decreased from 1.50 (SD=.535) at Session One (Table G12) to 0.50 (SD=.535) at Session Four (Table G13). The number of medium obstacles contacted ranged from one to two at Session One and then from zero to one at Session Four. For the number of medium obstacles contacted in the

BrainPort condition, the mean contacts remained the same at 0.75 (SD=.707) at Session One and Session Four. The number of medium obstacles contacted ranged from zero to two contacts at both sessions. For the number of medium obstacles contacted in the BrainPort and cane combined condition, the mean contacts decreased from 2.13 (SD=1.25) at Session One to 1.63 (SD=.744) at Session Four. The number of medium obstacles contacted ranged from zero to four at Session One and then from one to three contacts at Session Four.

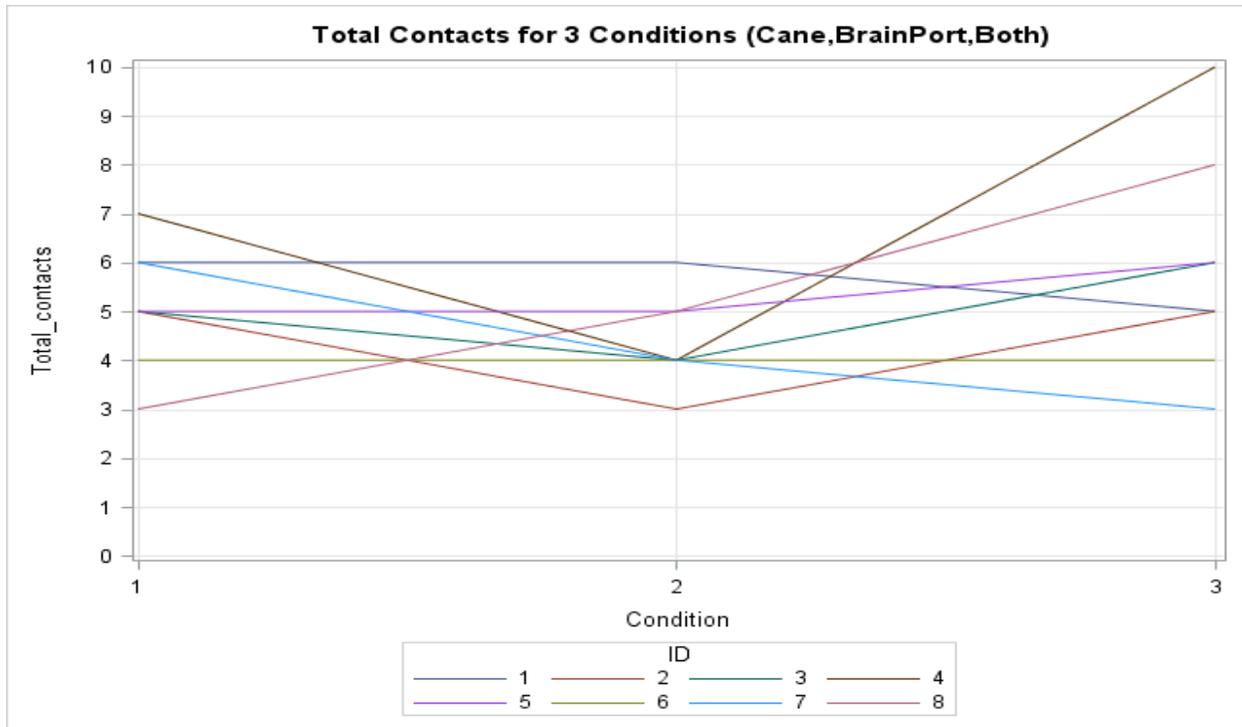
For the number of large obstacles contacted in the cane condition, the mean contacts decreased from 2.25 (SD=.707) at Session One (Table G14) to 2.00 (SD=1.20) at Session Four (Table G15). The number of large obstacles contacted in the cane condition ranged from two to four at Session One and then from one to four at Session Four. For the number of large obstacles contacted in the BrainPort condition, the mean contacts increased from 0.14 (SD=.744) at Session One to 1.38 (SD=.744) at Session Four. The number of large obstacles contacted in the BrainPort condition ranged from one to three contacts at Session one and then zero to two contacts at Session Four. For the number of large obstacles contacted in the BrainPort and cane combined condition, the mean contacts decreased from 3.13 (SD=1.13) at Session One to 2.50 (SD=1.07) at Session Four. The number of large obstacles contacted in the BrainPort and cane combined condition ranged from one to four at both sessions.

For the number of hanging obstacles contacted in the cane condition, the mean contacts decreased from 1.00 (SD=.535) at Session One (Table G16) to 0.75 (SD=.707) at Session Four (Table G17). The number of hanging obstacles contacted in the cane condition ranged from zero to two at Session One and Session Four. For the number of hanging obstacles contacted in the BrainPort condition, the mean contacts increased from 0.50 (SD=.756) at Session One to 0.75 (SD=.707) at Session Four. The number of hanging obstacles contacted in the BrainPort

condition ranged from zero to two contacts at Session one and Session Four. For the number of hanging obstacles contacted in the BrainPort and cane combined condition, the mean contacts decreased from 1.38 ( $SD=.744$ ) at Session One to 0.88 ( $SD=.641$ ) at Session Four. The number of large obstacles contacted in the BrainPort and cane combined condition ranged from zero to two at both sessions.

### **5.3.5 Individual differences for the number of obstacles contacted.**

Most of the participants were able to reduce the number of obstacles they contacted in each of the travel conditions. In the cane condition, five participants reduced the number of obstacles contacted. Two participants showed no change from Session One to Session Four and only one participant demonstrated an increase in this number of contacts. For the BrainPort only condition, four participants increased their number of obstacle contacts from Session One to Session Four. Three participants reduced the number of obstacle contacts while one participant showed no change in performance. In the BrainPort and cane combined condition, five participants reduced the number of obstacles they contacted from Session One to Session Four. The other three participants increased the number of obstacles they contacted. Most of the participants performed consistently from Session One to Session Four by decreasing obstacle contacts across all of the travel conditions. For the number of total contacts, each participant had a lower number in the BrainPort condition and about the same in the other two conditions (Figure 8).



**Figure 8.** Spaghetti plot for the number of total contacts for each participant in each condition.

### 5.3.6 Obstacle detection task.

In the object detection task, participants were asked to point to obstacles, which they perceived with the BrainPort. The results were recorded for which size of obstacles were detected and whether the participant was accurate or inaccurate for each obstacle. For the obstacle detection task, it was recorded whether the participant accurately or inaccurately identified an obstacle. For the number of obstacles accurately detected, the mean number of obstacles was 1.25 ( $\underline{SD}$ =1.49) at Session One and 2.63 ( $\underline{SD}$ =2.26) at Session Four. The number of obstacles accurately detected ranged from zero to three obstacles at Session One and then zero to six obstacles at Session Four. For the number of obstacles inaccurately detected, the mean number

of obstacles was 0.75 (SD=1.035) at Session One and then 1.50 (SD=1.51) at Session Four. The number of obstacles inaccurately detected ranged from zero to two obstacles at Session One and then zero to four obstacles at Session Four. The Spearman Rho Correlation was significant for the accurate detections from Session One to Session Four ( $\rho = .813$ ,  $p = .007$ ) and accurate and inaccurate detections at Session Four ( $\rho = -.692$ ,  $p = .029$ ). The Wilcoxon-Signed Rank Test was significant for accurate detections ( $z = -2.032$ ,  $p = .042$ ) (Table 11).

Participants identified the same number of small obstacles 0.50 (SD=.535) at Session One to 0.50 (SD=.756) at Session Four. The number of small obstacles detected ranged from zero to one at Session One and zero to two at Session Two. For the medium size obstacles, participants did not detect any obstacles at Session One and 0.75 (SD=.707) at Session Two. The number of medium obstacles ranged from zero to two at Session Two. For the large sized obstacles, the mean number of obstacles detected was 0.75 (SD=1.035) at Session One and 1.00 (SD=.926) at Session Four. The number of large obstacles ranged from zero to two at both sessions. For the hanging obstacles, the mean number of obstacles detected was 0.25 (SD=.463) at Session One and 0.50 (SD=.756) at Session Four. The number of hanging obstacles ranged from zero to one obstacles at Session One and then zero to two obstacles at Session Four. The mat was only identified as an obstacle once for all of the sessions. There is not a mean reported here for the floor mat detection.

### **5.3.6.1 Individual differences in obstacle detection.**

Three of the participants showed no change in the number of obstacles they were able to detect from Session One to Session Four. The other five participants all improved in the number of obstacles they detected with the BrainPort (Figure 9). There were five participants that demonstrated no change in their number of false detections (Figure 10). Only one participant

was able to reduce the number of false detections and the other two participants increased the frequency of false detections.

Four of the participants did not have any responses for obstacle detection at Session One. Two of these participants still did not have any response at the fourth session for this same task. For the other six participants, they each improved their performance from Session One to Session Four. Two participants were able to improve accuracy and identify five and six obstacles accurately of the 12 total obstacles. As the number of true obstacle detections increased for most of the participants, the number of false obstacle detections increased as well.

**Table 10.** Spearman Rho Correlations for the obstacle detection tasks and accurate/inaccurate detections from Session One to Session Four.

			Spearman Rho Correlations			
			Accurate	Inaccurate	Accurate	Inaccurate
			ID	ID	ID 2	ID 2
Spearman's rho	True ID	Correlation	1.000	.926**	.813**	.350
		Coefficient				
		Sig. (1-tailed)	.	.000	.007	.198
		N	8	8	8	8
	False ID	Correlation	.926**	1.000	.624*	.174
		Coefficient				
		Sig. (1-tailed)	.000	.	.049	.340
		N	8	8	8	8
	True2	Correlation	.813**	.624*	1.000	.692*
		Coefficient				
		Sig. (1-tailed)	.007	.049	.	.029
		N	8	8	8	8
False2	Correlation	.350	.174	.692*	1.000	
	Coefficient					
	Sig. (1-tailed)	.198	.340	.029	.	
	N	8	8	8	8	

\*\* . Correlation is significant at the 0.01 level (1-tailed).

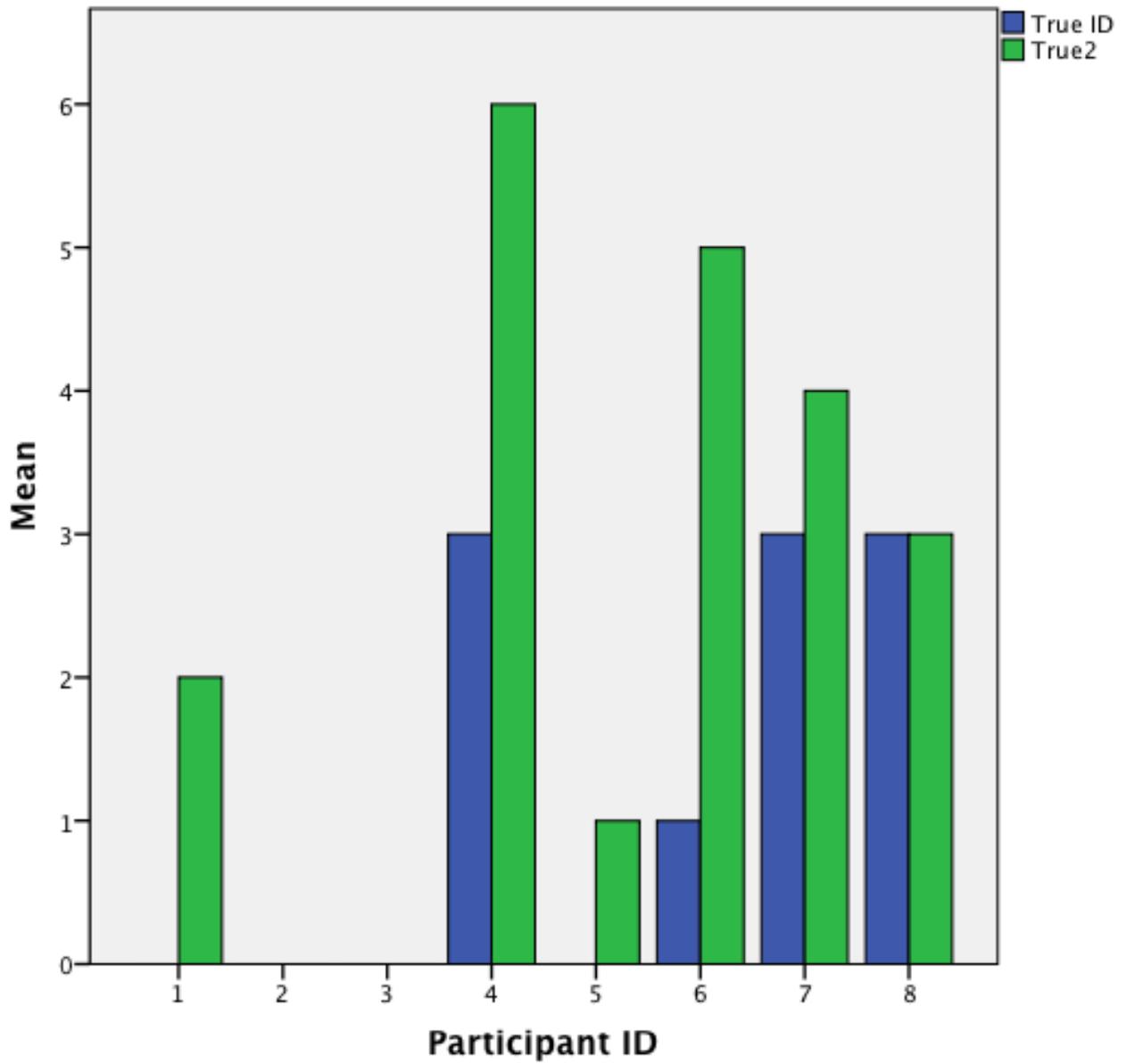
\* . Correlation is significant at the 0.05 level (1-tailed).

**Table 11.** Wilcoxon- Signed Ranks Test for inaccurate and accurate detections between sessions.

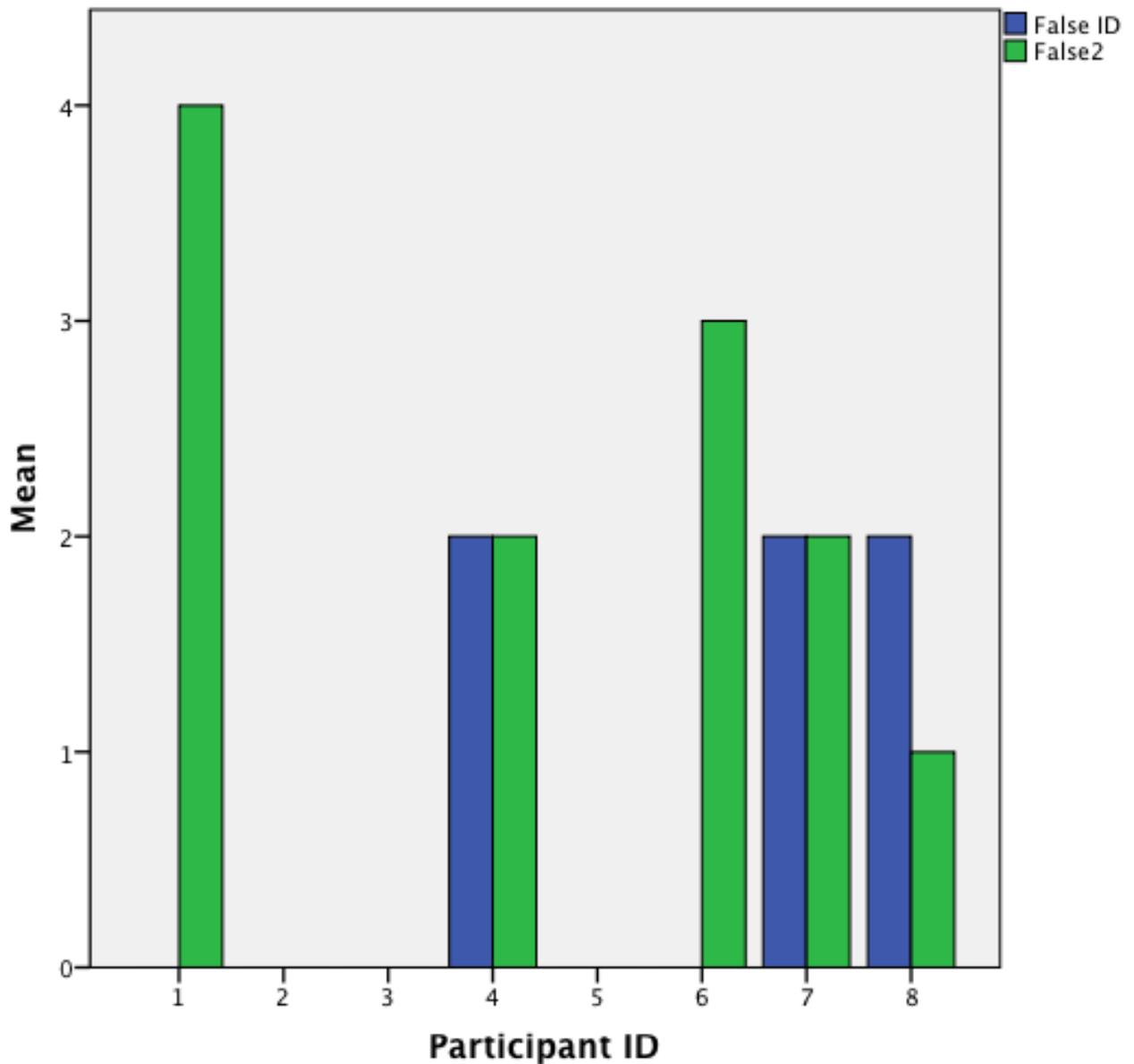
Test Statistics <sup>a</sup>		
	Accurate	Inaccurate
	ID	ID
Z	-2.032 <sup>b</sup>	-1.069 <sup>b</sup>
Asymp. Sig. (2-tailed)	.042	.285

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.



**Figure 7.** Number of obstacles correctly identified for each participant in the obstacle identification task.



**Figure 8.** Number of obstacles incorrectly identified for each participant in the obstacle identification task.

## 5.4 FINDINGS RELATED TO QUESTION 3

What impact does the BrainPort system have on an individual's ability to maintain an optimal straight path of travel in a novel outdoor environment?

In order to determine what effect the BrainPort had on an individual's ability to maintain a straight path of travel, an average score was computed from the number of total veers at Session One and Session Four. These averages were ranked across participants for each travel condition. The Friedman's ANOVA results of the ranked scores were significant for the total number of veers. For the three travel conditions, the average means between sessions were 1.13 (Rank Avg= 2.00) for the Cane condition, 2.00 (Rank Avg= 2.81) for the BrainPort condition, and 0.69 (Rank Avg= 1.19) for the BrainPort and cane condition (Table H1; Table H2). The total number of veers changed significantly between travel conditions,  $\chi^2(2, N=8) = 12.071, p=.002$  (Table H3).

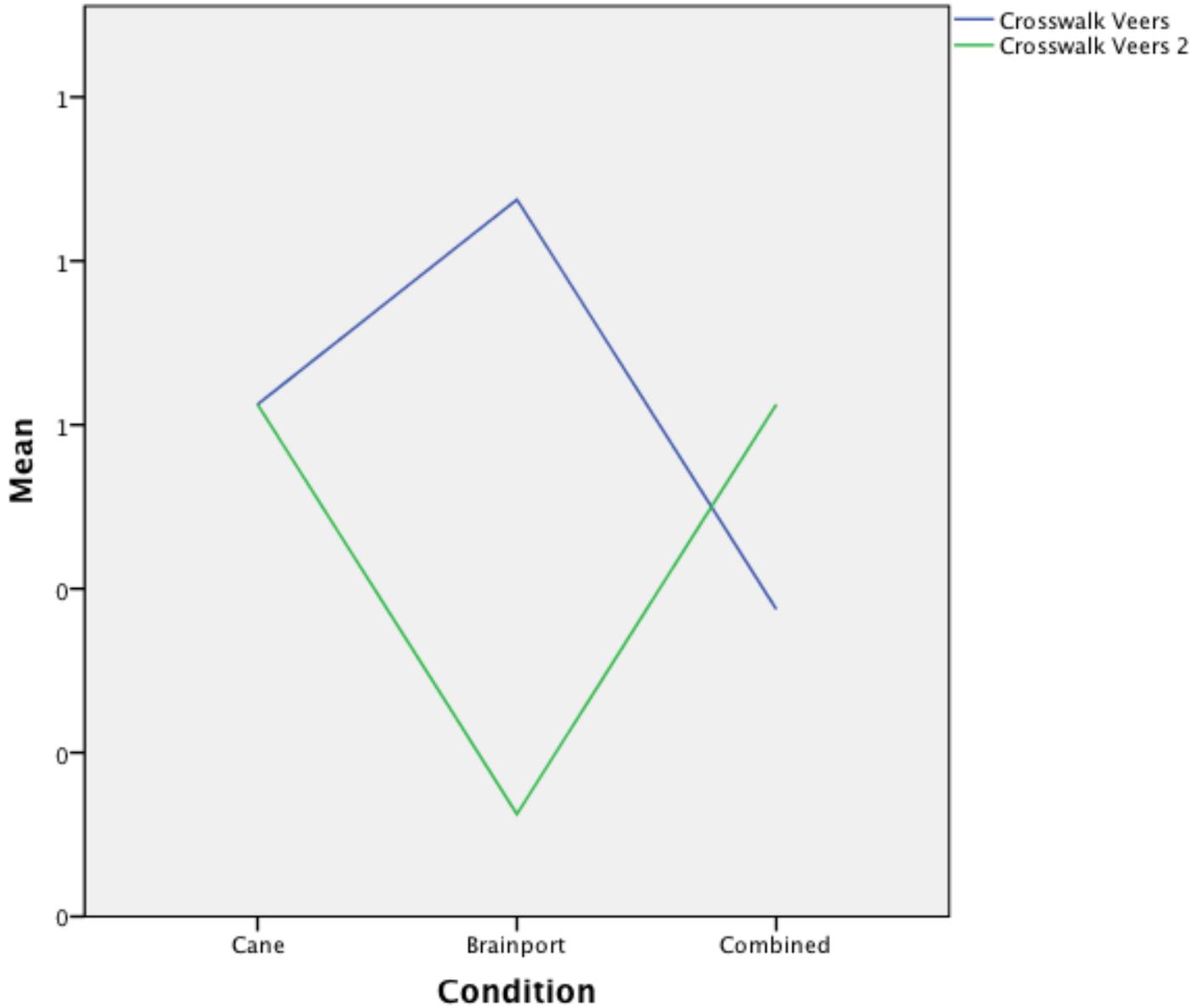
### 5.4.1 Cane travel condition for veering.

The mean performance of frequency of veering for the cane condition was 1.00 (SD=0.76) at Session One (Table H4) and 1.25 (SD=1.04) at Session Four (Table H5). For the total number of veers in the cane condition, values ranged from zero to two veers in Session One and then zero to three veers in Session Four. The total number of veers was divided between course veers and crosswalk veers. The mean number of course veers for the cane condition was 0.38 (SD=0.744) at Session One (Table H6) and 0.63 (SD=0.744) at Session Four (Table H7). Participants' number of course veers at Session One ranged from zero to two veers and then zero to two veers at Session Four. The mean number of crosswalk veers for the cane condition was 0.63

(SD=.518) at Session One (Table H8) and exactly the same at Session Four (Table H9). Participants' number of crosswalk veers ranged from zero to one for the cane condition in both Session One and Session Four.

#### **5.4.2 BrainPort travel condition for veering.**

The mean performance of veering in the BrainPort condition was 2.00 (SD=0.76) at Session One (Table H4) and 2.00 (SD=1.07) at Session Four (Table H5). For the total number of veers in the BrainPort condition, values ranged from one to three veers in Session One and then one to four veers in Session Four. The total number of veers was divided between veering in the crosswalk and the rest of the course. The frequency of veering decreased significantly in the crosswalk from 0.88 (SD= 0.35) at Session One (Table H8) to 0.13 (SD= 0.35) at Session Four (Table H9). The frequency of crosswalk veers in the BrainPort condition was much lower at the Session Four and in general lower compared to the two other travel conditions (Figure 11). Participants' number of crosswalk veers ranged from zero to one for the BrainPort condition in both Session One and Session Four. The mean number of course veers for the BrainPort condition was 1.13 (SD=0.641) at Session One (Table H6) and 1.88 (SD=1.25) at Session Four (Table H7). Participants' number of course veers at Session One ranged from zero to two veers and then zero to four veers at Session Four.



**Figure 9.** Line graph of number of crosswalk veers for each travel condition.

**5.4.3 BrainPort and cane combined travel condition for veering.**

The mean performance for veering in the BrainPort and cane combined condition increased slightly from 0.63 (SD=0.74) at Session One (Table I4) to 0.75 (SD=0.71) at Session Four (Table

H5). For the total number of veers in the BrainPort and cane combined condition, values ranged in the same range from zero to two veers for Session One and Session Four. The total number of veers was divided between veering in the crosswalk and veering on the rest of the course. The frequency of veering increased significantly in the crosswalk from 0.38 (SD= 0.518) at Session One (Table H8) to 0.63 (SD= 0.518) at Session Four (Table H9). Participants' number of crosswalk veers ranged from zero to one for the BrainPort and cane combined condition in both Session One and Session Four. The mean number of course veers for the BrainPort condition was 0.25 (SD=0.463) at Session One (Table H6) and 0.13 (SD=.354) at Session Four (Table H7). Participants' number of course veers ranged from zero to one for the BrainPort and cane combined condition in both Session One and Session Four.

#### **5.4.4 Individual differences in the frequency of veering.**

The rate of veering depended on the participant and on the specific travel condition. For the cane only condition, participants performed inconsistently with several participants increasing, some decreasing, and some maintaining the same frequency of veers. In the BrainPort only condition, only three participants were able to decrease the frequency of veering off of the course. In the BrainPort and cane combined condition, only two participants were able to decrease their frequency off veering off of the course or out of the crosswalk. Most of the participants performed consistently by increasing or decreasing similarly in each travel condition from Session One to Session Four. Two of the participants performed well by reducing their frequency of veering using the BrainPort in each condition.

## 5.5 ADDITIONAL RESULTS

### 5.5.1 Performance in different natural lighting conditions.

Natural lighting levels were measured for each session with each participant. This information was recorded as luminescence and was examined in regards to participant performance. The luminescence was categorized according to the lighting level (low = 0 to 14,999 lux, medium = 15,000 to 29,999, and high = 30,000 to 44,999). There was only one session where the luminescence was above the high lighting level, which was 51,600 lux. Since only one session was outside of this range, it was recorded as being in the high light level category. Luminescence from 10,000 to 25,000 Lux is considered full daylight with indirect sunlight, and direct sunlight is 32,000 to 100,000 Lux. Participants reduced the number of obstacles they contacted from Session One to Session Four for just about all of the lighting levels.

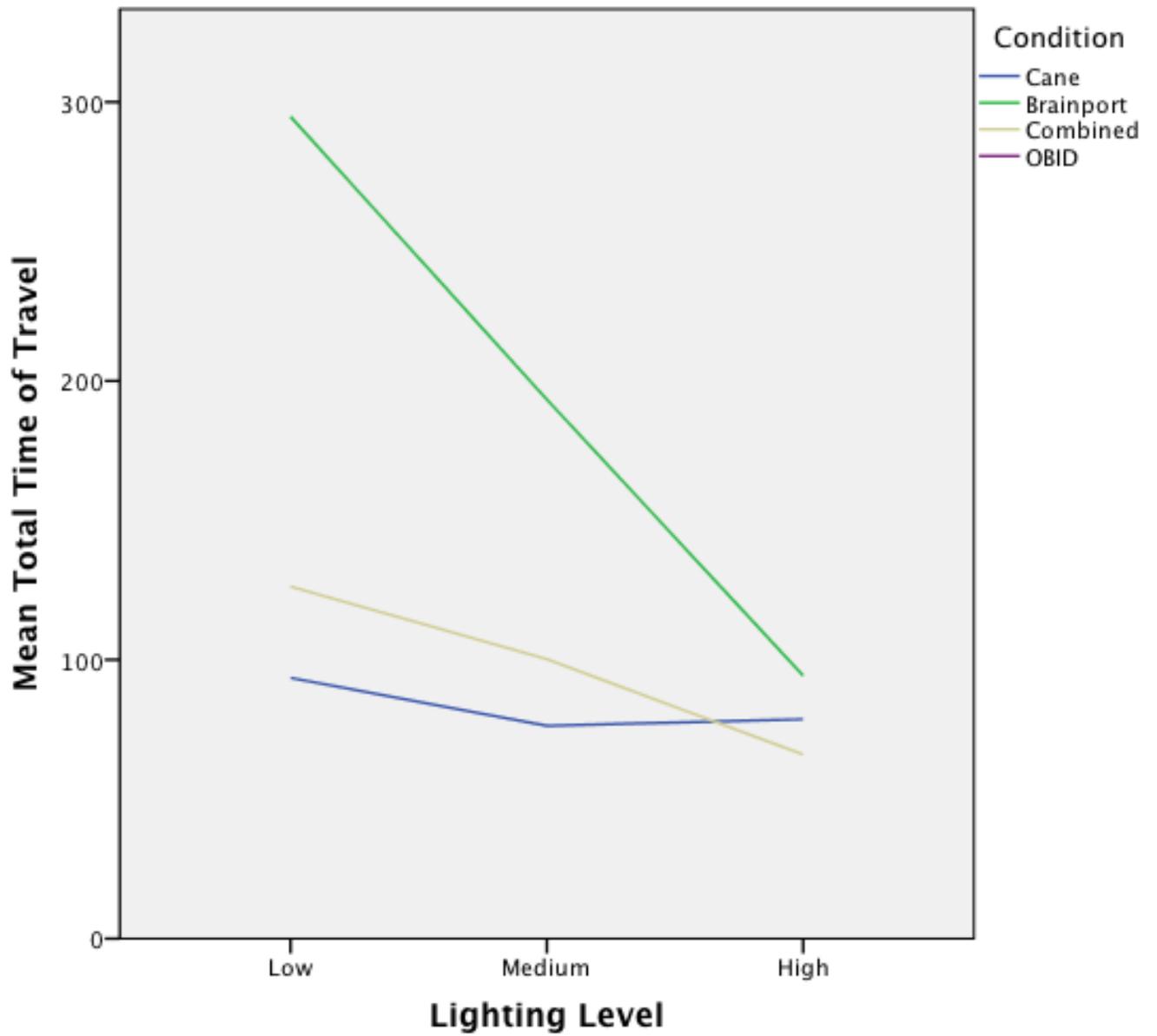
For the low lighting level, participants' total time of travel was 137.67 (SD=64.33) at Session One and then 151.50 (SD=84.20) at Session Four. The time of travel ranged from 64 to 218 seconds at Session One and then from 77 to 266 seconds at Session Four. For the medium lighting level, participants' total time of travel was 112.08 (SD=73.43) at Session One and then 145.17 (SD=79.09) at Session Four. The time of travel ranged from 50 to 328 seconds at Session One and then from 55 to 565 seconds at Session Four. For the high lighting level, participants' total time of travel was 77.83 (SD=33.23) at Session One and then 151.50 (SD=84.20) at Session Four. The time of travel ranged from 50 to 142 seconds at Session One and then from 77 to 300 seconds at Session Four. The Spearman Rho results suggest that there is a significant correlation between the total time of travel and the lighting level ( $\rho = -.393$ ,  $p = .006$ ). Participants' time of travel decreased as the lighting level increased suggesting that there was a

correlation as well (Figure 12). There was also a significant correlation between total time of travel and the total number of veers ( $\rho = .326$ ,  $p = .024$ ). The Spearman Rho correlation was also found to be significant for total time in relation to body contacts ( $\rho = .387$ ,  $p = .007$ ) and cane contacts ( $\rho = .416$ ,  $p = .003$ ).

For the low lighting level, participants' number of total contacts was 7.50 ( $SD = 2.43$ ) at Session One and then 5.50 ( $SD = 2.51$ ) at Session Four. The total number of obstacles contacted in the low lighting level ranged from four to 11 seconds at Session One and then from four to 10 seconds at Session Four. For the medium lighting level, participants' number of total contacts was 4.92 ( $SD = 2.35$ ) at Session One and then 5.17 ( $SD = 1.34$ ) at Session Four. The total number of obstacles contacted in the medium lighting level ranged from one to 10 seconds at Session One and then from three to eight seconds at Session Four. For the high lighting level, participants' number of total contacts was 6.50 ( $SD = 2.67$ ) at Session One and then 4.67 ( $SD = 1.21$ ) at Session Four. The total number of obstacles contacted in the high lighting level ranged from two to 10 seconds at Session One and then from three to six seconds at Session Four.

For the low lighting level, participants' number of total veers was 0.83 ( $SD = .753$ ) at Session One and then 1.17 ( $SD = .753$ ) at Session Four. The total number of veers in the low lighting level ranged from zero to two veers at Session One and at Session Four. For the medium lighting level, participants' number of total veers was 1.42 ( $SD = 1.08$ ) at Session One and then 1.08 ( $SD = .996$ ) at Session Four. The total number of veers in the low lighting level ranged from zero to three veers at Session One and at Session Four. For the high lighting level, participants' number of total veers was 1.17 ( $SD = .753$ ) at Session One and then 2.00 ( $SD = 1.27$ ) at Session Four. The total number of veers in the low lighting level ranged from zero to two

veers at Session One and then one to four veers at Session Four.



**Figure 10.** Line graph of mean travel time for lighting levels across travel conditions.

### 5.5.2 Questionnaire answers at Session one and Four.

A questionnaire was answered by participants at Session One (Appendix C1) and then another questionnaire (Appendix C2) at Session Four. Results showed that all participants had received prior O&M training with at least 61 hours of instruction (Table 8). All participants had received prior

training with the BrainPort and all but one had received at least 61 hours of training. One participant had only received less than 20 hours of instruction. Only one participant had prior experience with any other sensory substitution system, which was a device called a Mowat Sensor. Participants answered almost exactly the same on the first and second questionnaire regarding their frequency of traveling independently or in unfamiliar environments. For one of the questions regarding travel habits, most of the participants responded that they sometimes traveled without a human guide. Most of the participants also answered that they rarely or never traveled independently in new or unfamiliar environments. Participants' answers for traveling without a sighted guide and in unfamiliar environments were almost exactly the same from Session One to Session Four. For the question regarding confidence traveling with the BrainPort, the mean was 1.88 ( $SD=.835$ ) for traveling with only the BrainPort and 4.50 ( $SD=.535$ ) for traveling with the BrainPort and the cane. Participants who were congenitally blind reported a lower confidence level at 1.25 ( $SD=.500$ ) compared to 2.50 ( $SD=.577$ ) for participants who lost their vision later in life. For the question regarding the participants' age when losing their vision, the mean was 13.13 ( $SD=15.62$ ). There were no significant Spearman Rho correlations between the onset of vision loss and any of the main dependent variables. There was a high correlation between the onset of vision loss and the reported confidence with the BrainPort ( $\rho =.808$ ,  $p=.000$ ) and BrainPort and cane together ( $\rho =1.000$ ,  $p=.000$ ).

**Table 10. Results from questionnaires one and two.**

ID	Questionnaire 1		Questionnaire 2			
	No human guide <sup>a</sup>	Novel environments <sup>a</sup>	No human guide <sup>a</sup>	Novel environments <sup>a</sup>	Confidence-BrainPort (Rating 1 to 5)	Confidence-BrainPort and Cane (Rating 1 to 5)
1	Rarely	Never	Rarely	Never	2	5
2	Sometimes	Never	Sometimes	Rarely	3	4
3	Sometimes	Never	Sometimes	Never	1	5
4	Rarely	Never	Rarely	Never	2	4
5	Rarely	Rarely	Rarely	Rarely	3	4
6	Sometimes	Rarely	Sometimes	Rarely	1	5
7	Sometimes	Never	Sometimes	Rarely	1	5
8	Sometimes	Rarely	Sometimes	Rarely	2	4
Average (out of 5)	2.6	1.1	2.6	1.6	1.8	4.5

<sup>a</sup> Ratings are based on options on descriptive ratings relative to 1 to 5 scale (Never, Rarely, Sometimes, Usually, Always).

## **6.0 DISCUSSION**

### **6.1 RESEARCH QUESTION 1**

What impact does the BrainPort system have on an individual's rate of travel in a novel outdoor environment?

A comparison of the means at Session One and Session Four are of interest particularly for the BrainPort condition and the BrainPort and long cane condition together to determine the effect that training and practice have on accuracy and performance. There is also expected to be more of a discrepancy between performances at Session One and Session Four for any condition using the BrainPort. Overall, the participants' time of travel increased for all of the travel conditions from Session One to Session Four. This increase was more substantial for the conditions involving the BrainPort. Initially, participants were using the BrainPort without being able to understand the information and therefore not really paying attention to it. The BrainPort training, which focused on interpreting environmental information and avoiding obstacles, occurred between Sessions One and Four. At Session Four, participants took more time to explore features of the environment, tried to figure out where the obstacles were, and tried to navigate between them. Participants had been trained to use the crosswalk lines for alignment with the BrainPort. This was part of the reason the crosswalk time was also longer for most of the participants from Session One to Session Four.

Since the participants were novice users of the BrainPort in regards to mobility, they had to adjust to how to use the BrainPort successfully for independent travel. Traveling with the BrainPort requires simultaneous focus on multiple sources of sensory information. Individuals must learn to focus on the feedback on their tongue at the same time as what they normally detect with the long cane. By Session Four, participants had been instructed on how to adjust the BrainPort settings optimally to detect environmental features. Therefore, it also took participants longer to travel through each part of the obstacle course as they stopped to adjust the settings more frequently. Participants developed skills with the BrainPort at different rates, which was why there was a wide range of performance times. While most of the participants seemed to slow down as they were still learning to use the BrainPort, two of the participants acquired skills with the device quickly and improved their time of travel in both of the BrainPort travel conditions. This was especially interesting since one of these participants had the least amount of prior experience with the BrainPort. It seems that certain individuals may be more suited to learning to use the BrainPort quickly. The prior experience with the BrainPort for other tasks and training may be somewhat unrelated to use of the device for outdoor mobility.

## **6.2 RESEARCH QUESTION 2**

What impact does the BrainPort system have on an individual's ability to detect and avoid obstacles in a novel outdoor environment?

The frequency of contacting obstacles reduced for each condition from Session One to Session Four. This frequency being reduced in the cane condition suggests that there was a learning effect associated with the obstacle courses. Since there was no training focused just on avoiding

obstacles with the cane, it would be expected that the number of contacts would be consistent in the cane only condition. Since the number of contacts decreased, it is possible that participants learned where to expect the obstacles to be and how to avoid them. In the BrainPort condition, the number of obstacles contacted decreased as well. This was likely due to the same learning effect and to the participant learning to detect obstacles with the BrainPort. It was difficult to compare results for obstacle contacts between the different conditions. The cane only condition and the combined condition were similar because in both cases the participant could contact obstacles with the cane or body. The BrainPort only condition could not be accurately compared to the other two conditions because the participants did not use the long cane. This resulted in more body contacts since they did not have the cane to detect the obstacles. The number of obstacles contacted decreased in nearly all of the conditions except for the BrainPort condition.

Each participant performed differently with the BrainPort and seemed to acquire skills for its use at different rates. The majority of participants increased their number of obstacles contacted in the course sessions. The obstacle detection task was probably the best assessment used for perception with the BrainPort. While both the number of accurate and inaccurate detections increased from Session One to Session Four, the accurate detections increased more than the inaccurate detections. With additional practice, it would be expected that the number of accurate detections would continue to increase with proficiency and the number of inaccurate detections would decrease. The improvement in this task shows that an individual can accurately detect obstacles when given adequate time to explore the environment. It would seem reasonable that with additional training, the participant's performance would continue to improve.

### **6.3 RESEARCH QUESTION 3**

What impact does the BrainPort system have on an individual's ability to maintain an optimal straight path of travel in a novel environment?

The frequency of veering either remained the same or increased in nearly all of the travel conditions from Session One to Session Four. The BrainPort was expected to help participants reduce the frequency of veering. The training focused on detecting crosswalk lines and using them for alignment as well as detecting the edges of the sidewalk to maintain a straight line of travel. The participants were able to significantly reduce veering outside of the crosswalk due to the training focused on this skill with the BrainPort. Since the participants were able to take their time to focus on the crosswalk lines, their crosswalk times increased while veering within the crosswalk decreased. This less efficient, but safer travel should be acceptable for most individuals with visual impairments. The BrainPort seemed to have this effect for the crosswalk, but not for the rest of the course. The number of veers increased in the cane condition and also in the BrainPort only condition. While the total number of veers increased in the BrainPort condition, the number of crosswalk veers decreased significantly. Since the number of veers in each condition with the cane increased, this makes the significant decrease in crosswalk veers in the BrainPort condition even more noticeable.

### **6.4 BRAINPORT PERCEPTION AND THE ENVIRONMENT**

The BrainPort provides feedback about the surrounding environment, but the level of detail is limited. Obstacles appear as blobs with the BrainPort and specific features of an object cannot

be identified easily. The BrainPort only perceives objects in two dimensions. A participant cannot easily determine depth or distance with the BrainPort, which makes traveling on steps or curbs especially difficult. This deficiency also makes it difficult to determine how far away an obstacle is. Participants were given some time to adjust the settings on the BrainPort to suit their preferences.

Lighting is an important variable for effectiveness of the BrainPort. Natural lighting is variable and uncontrollable in an outdoor setting. The presence of sunlight can create shadows on the ground. Whether or not a shadow is present will also depend on the time of day and position of the sun in the sky. Shadows appear as dark shapes on the ground, which may be interpreted as obstacles when viewed with the BrainPort. The brightness of the sun may affect the darkness of the shadow and how distinctively it shows up with the BrainPort. Since the BrainPort is only showing contrasting colors, a shadow and a hole in the ground would appear very similar.

#### **6.4.1 Participants' characteristics and questionnaire results.**

Participants with an acquired vision loss were more confident about traveling with the BrainPort compared to participants with a congenital visual impairment. This difference may be due to visual memory and how it can help to understand the spatial environment and related concepts for mobility. Participants who lost their vision later in life performed better in regards to the number of obstacles contacted compared to participants who were congenitally blind (Table I1). The participants in general did not report traveling more independently or with more confidence with the BrainPort. It seems that more training is required to develop proficiency and confidence required for more independent travel with the device. Given that only one participant had prior

experience with another sensory substitution device for mobility, the Mowat Sensor, it appeared that this experience had little effect on performance since no significant difference was seen in her performance. All except one of the participants had over 60 hours of experience with the BrainPort participant. This participant was one of the only two to demonstrate an improvement in travel time using the device from Session One to Session Four. From the anecdotal notes about this participant's training and obstacle course performance, she naturally picked up the skills with the BrainPort and quickly became adept at detecting and navigating with the device. Given the potential exhibited in this short amount of time, additional training could lead to proficiency quickly for this participant. Also, given the lack of prior additional training, this omission could have allowed her to come into this program without preconceived notions about the BrainPort. The prior training had focused mainly on motor tasks and near perceptual activities, which use the BrainPort in ways that may not transfer very well to mobility and navigation skills.

#### **6.4.2 BrainPort training program.**

The training program focused on getting individuals used to adjusting the settings on the BrainPort to suit the environmental conditions. The intensity level was set in the range from 20 to 45. The invert setting works especially well for crosswalks given the significant contrast between the white crosswalk lines on the darker street. Participants can use the crosswalk line to maintain a straight line of travel. The high contrast setting was used throughout the course conditions. If it was exceptionally sunny outside, the contrast setting was changed to normal.

The training program was short due to the constraints on availability of the devices and participants. Even with this short training program, participants were able to demonstrate some

improvement in travel performance with the BrainPort. Participants each completed between 6 and 8 hours of training with the BrainPort or related mobility activities. It was apparent that individuals had improved their skills with the BrainPort, but they were not yet proficient with the device. For a participant to develop minimal proficiency with the BrainPort, training should be at least 20 hours focused on O&M skills. This training should be structured similar to other O&M training where the participant works with an O&M specialist and then has time to practice independently. Additional training would allow the participant to master how the different settings can be used in various environments and how settings may be adjusted depending on the task the participant is trying to accomplish. Participants frequently seemed to just rely on their cane and ignore the information they were receiving from the BrainPort. Training would help them to develop confidence using the device and trust the stimuli they were receiving from the BrainPort.

The training program focused on teaching skills to improve travel and perception with the BrainPort. Interpreting environmental information with the BrainPort is similar to how individuals with low vision learn to use their remaining vision efficiently for mobility purposes. The training program also focused on teaching individuals some of these visual concepts. For example, a participant may be unaware of how sunlight from behind a participant creates a shadow extending out in front of them. As part of the training, participants were to practice looking out in front of them to determine approximately where the obstacles were and then determine where the open pathway was between the obstacles. Participants' performance seemed to improve as lighting levels increased. For the medium and high lighting level, the total time of travel and the total number of contacts both were better in comparison to the low light level.

### **6.4.3 Visual concepts.**

Facial vision or object perception is being able to detect the presence of something without actually touching or seeing it. This is typically accomplished cutaneously by interpreting the sound waves reacting to the presence of the object. Many of the participants reported having the ability to accurately use object perception in their daily routines. Although it was difficult to detect the presence of many of the obstacles given their proximity to the ground, it was still possible that object perception could have had an effect upon their locating the obstacles. Individuals could be sensing environmental information using object perception and not paying attention to the feedback from the BrainPort.

Many individuals who have no remaining vision, especially with a congenital vision loss, have limited understanding of visual concepts. How the position of the sun can cause a shadow to form on the ground is a concept, which individuals without vision may not have any experience. It's also important for the participant to understand that the time of day will affect whether there is a shadow present or not. Individuals who are blind may also not understand that their body creates a shadow and this shadow may be present directly in front of them. As part of the training program, participants were instructed on how shadows may appear as obstacles, how their bodies may create a shadow, and how the position of the sun may affect the presence and position of a shadow. Other visual concepts needed to be explicitly taught as well. When a participant is looking at each of the crosswalk lines, the lines appear to come closer together as they move farther away from the participant. This is called the vanishing point, which is where parallel lines appear to meet off in the distance. Perception with the BrainPort requires training focused visual concepts needed to interpret environmental stimuli.

#### **6.4.4 Limitations**

The purpose of this study was to examine the capabilities of the BrainPort sensory substitution system to assist individuals with visual impairments to travel independently and avoid obstacles in a novel outdoor naturalistic environment. There were a limited number of participants because of the exploratory nature of this research. The proposed study had limitations for using a real environment and some lack of control of the variables associated with it. There were variations in pedestrian and vehicular traffic, children in the outdoor school environment, ambient noise, weather conditions, lighting, and changes to the environment due to construction or other factors. On windy days, the hanging obstacles would swing, which could make them possibly easier to perceive with the BrainPort. The wind could make the participant more or less likely to contact the obstacle because of its movement. There were a different number of small and medium obstacles used between the course versions. While there did not seem to be an effect for the course version on performance, the inequality makes it difficult to accurately compare the number of specific sizes of obstacles contacted in different course versions.

The participants were taking part in other BrainPort research through UPMC and were only available on certain days/times. Given the significant cost of the BrainPort devices and associated software, the researcher had to rely on the equipment available through UPMC. The BrainPort devices were borrowed from the UPMC Sensory Substitution Lab and were available on certain days and times. For an accurate comparison between typical travel conditions, the participant was traveling with the long cane. By having the participant use a long cane, the participant may have detected an obstacle first without having the opportunity to perceive it with the BrainPort. Also by using the cane, the participant could be more likely to find the obstacle with the cane instead of contacting it with the body. The use of the long cane makes it difficult

to compare obstacle contacts in the BrainPort condition with obstacle contacts with the cane or the body in the other two travel conditions. The incidence of visual impairments limited the number of participants available for this type of research. By relying on video for data recording, there were limitations in what was seen on the previously recorded video.

#### **6.4.5 Educational implications.**

The implications of this research for education or mobility instruction are limited. The BrainPort is still not a commercially available device, which severely limits how it can be used by individuals with visual impairments. The results of this research present a number of implications for training and instruction with the BrainPort or any type of sensory substitution system. The training program details provided in this study describe how to introduce and facilitate independent and functional skills with sensory substitution systems. The O&M specialist must take into account the participant's prior visual experience and explain any possible visual concepts, which may be unfamiliar. It is important to consider lighting issues, shadows, alignment, weather, and characteristics of the participants when designing any instructional plan with these devices. Sensory substitution systems are an ideal way to introduce visual perception to someone without sight. This additional sensory information can allow an individual to perceive visual concepts, such as shadows, colors, depth, and lighting changes.

#### **6.4.6 Future research**

The rate at which technology progresses ensures that there are areas of sensory substitution research and technology, which need further investigation in order for the device to be used in

more naturalistic or real-world settings. The navigation research on the BrainPort to date was limited to the indoor, controlled environments. The clinical work, while promising, limits the ability to make claims about its use in the outdoor, naturalistic setting. This study addressed the gaps in the current clinical research in sensory substitution for independent navigation, and conducted an initial investigation of the efficacy of the device in an outdoor novel environment. This study also addressed the lack of research on the efficacy of using the BrainPort in conjunction with the long cane, which is the typical mobility tool for most individuals. The BrainPort offers a significant technological innovation to improve the sensory information available to individuals with visual impairments. Any information related to its use and performance will help to promote successful research and development in the area of O&M technology.

Future research endeavors should explore additional functional mobility tasks involving the BrainPort. The BrainPort should continue to be evaluated in outdoor environments and with larger sample sizes. The BrainPort was shown to be effective for using a visual shoreline, such as a crosswalk line, to maintain a straight line of travel. It should be further researched whether the BrainPort can be used for street crossings in various other settings. The BrainPort should be tested against other sensory substitution systems out there including the voICe. Retinal implants are being explored more in-depth and this should be explored in comparison to the BrainPort. Research involving the BrainPort should involve a longer training phase and opportunities for participants to have the device at home using it independently or when traveling with another participant. The training recommendations for this device should continue to be researched to determine what methods are most effective, what skills need to be explicitly taught, and how an

O&M specialist should go about doing this. The training period requirements should also be tested to determine what is the optimal length of training to develop proficiency with the device.

The BrainPort also needs to be explored with more diverse populations. As acquiring proficiency with sensory substitution systems is a slow learning process, this instruction may be most effective with children while they are still developing. This type of novel technology may present children with motivation for learning and curiosity for exploring. The BrainPort has not been adequately researched with individuals with low vision. It is especially interesting to see how perception with the device would differ between individuals with low vision, individuals who are congenitally blind, and individuals who lost their sight later in life. It seems clear that visual memory plays a key role in accurate perception with the BrainPort.

## **6.5 CONCLUDING REMARKS**

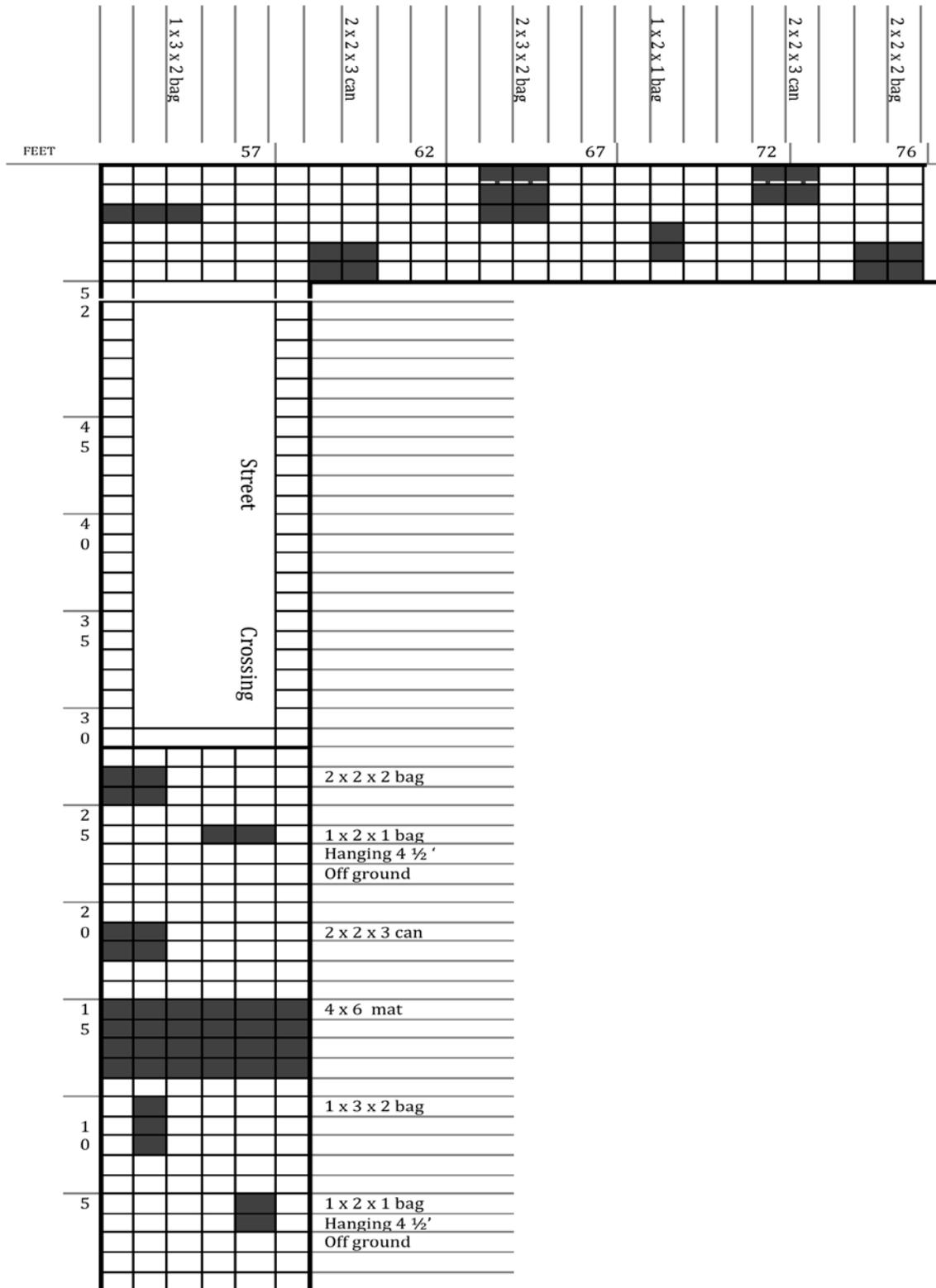
By using the BrainPort sensory substitution system, participants were able to improve their independent travel in some aspects. Participants' time of travel increased while decreasing their obstacle contacts and veers. For proficiency with the device, additional training would be required beyond what was provided in this study. The individuals in this study seemed to be able to use the BrainPort and the cane together as a viable option for independent mobility. The training program provides recommendations on how to effectively provide instruction on sensory substitution perception for navigation and independent travel. The results of this study provide numerous options for additional research with the BrainPort and for evaluating its effectiveness for independent mobility.

## **APPENDIX A**

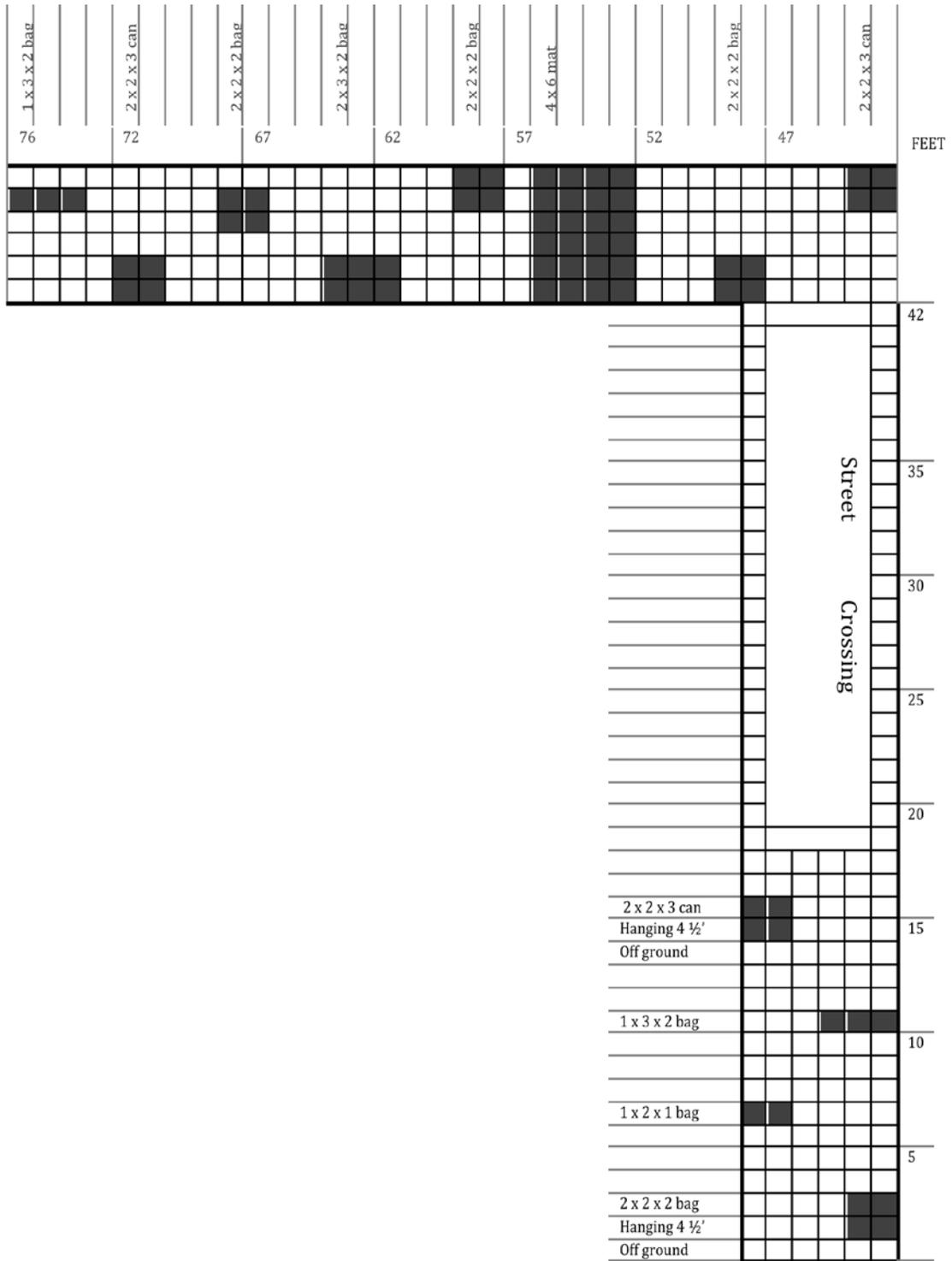
### **OBSTACLE COURSE ONE AND TWO DESIGNS WITH OBSTACLE PLACEMENTS AND COURSE ANALYSIS**

The diagrams included in the appendices represent the sidewalk as a white background with a 1-foot by 1-foot grid pattern. The entire course is drawn to scale with respect to each different feature and obstacle. Bold, dark lines on the grid represent the perimeter of the course/sidewalk. Obstacles are shaded 75% darker in the appropriate placement on the course. The course length is marked on each diagram every five feet with a few exceptions where this is not possible. Dimensions for each of the obstacles are marked on the diagrams as well. The location of each of the street crossings and crosswalks are clearly marked on each course diagram.

#### **A.1 OBSTACLE COURSE 1 DESIGN**



## A.2 OBSTACLE COURSE 2 DESIGN



### A.3 OBSTACLE COURSE ANALYSES FOR EACH DESIGN

**Table A 1.** Course analysis for vertical and horizontal paths.

Course ID	Number of 3 foot forward paths	Number of 2 foot forward paths	Number of 1 foot forward paths	Number of 4 foot sideways paths	Number of 3 foot sideways paths	Number of turns
1	4	3	1	7	3	6
2	3	3	2	8	2	5

## **APPENDIX B**

### **DOCUMENTS RELATED TO PARTICIPANT RECRUITMENT AND CONSENT**

#### **B.1 PHONE AND EMAIL SCRIPT FOR PARTICIPANT RECRUITMENT**

##### **Phone Script**

###### **“Using the BrainPort for Independent Travel and Obstacle Avoidance”**

Hello. Thank you for your interest in this study regarding the BrainPort. My name is Justin Kaiser and I am a Certified Orientation and Mobility specialist and doctoral candidate in the Department of Instruction and Learning at the University of Pittsburgh under the direction and supervision of Dr. Amy Nau and Dr. George J. Zimmerman.

I am currently conducting a doctoral dissertation research study (“Using the BrainPort for Independent Travel and Obstacle Avoidance”) with individuals who are visually impaired using the BrainPort device while walking through an outdoor obstacle course in a controlled environment on the campus of the Western Pennsylvania School for Blind Children (WPSBC). I am recruiting individuals who have prior experience using the BrainPort to participate in my study. Participants will be asked to walk a pathway/course containing several obstacles. I will monitor your safety and record your obstacle avoidance behavior.

If you choose to participate in this study, I will ask you to come to the WPSBC in Oakland four times (or two times if you are able to participate in two sessions in the same day) within 1 to 4 weeks for training and assessment using the BrainPort on the WPSBC campus. Each session will be between 1 and 3 hours.

Participants will be paid a total of \$150 for completion of all visits. Participants will be paid \$25 at each visit (or \$50 for two visits on the same day) and then an additional \$50 at the completion of all research requirements.

You will be asked through the course in each of the following conditions:

- 1) BrainPort only
- 2) Long cane only
- 3) BrainPort and the long cane combined

During the first visit, I will provide you with instruction on independent mobility, avoiding obstacles, and using the long cane in combination with the BrainPort.

After the first visit, I will schedule three additional visits (unless you are able to participate twice in the same day) for additional assessment and training. There will be training during sessions two and three, and then training and assessments during Session Four.

Does this sound like something you would be interested in participating in?

IF YES: Please answer the following:

- 1) Are you 18 years or older?
- 2) Do you have prior experience using the BrainPort device?
- 3) Do you have residual visual capacity no better than light perception only?
- 4) Do you independently travel using a long cane?

If the potential participant is a woman, please answer the following question:

- 1) Since the BrainPort is not yet approved by the FDA, it is recommended that pregnant women refrain from using the device. Are you sure that you are currently not pregnant?

If you answered No and you may be currently pregnant, you will not be eligible to participate in the study.

If NO to any question: I am sorry, you are not eligible to participate in this study. Thank you for your time.

If YES to all questions: Great, you may be eligible to participate in this study. Let's set-up a time to further discuss the study in detail. If at that time you agree to participate in the study, I will ask for your consent to participate in the study, record some basic information about you and schedule the first visit with the obstacles and initial training.

I'll include my contact information so you can call me with any questions. **724-562-4188** or **jtk33@pitt.edu**

Thank you very much for your time and consideration and I look forward to having you participate in my study!

## B.2 CONSENT FORM FOR RESEARCH PARTICIPATION

University of Pittsburgh School of Education

### CONSENT TO ACT AS A PARTICIPANT IN A RESEARCH STUDY

**TITLE:** Using the BrainPort for Independent Travel and Obstacle Avoidance

**PRINCIPAL INVESTIGATOR:**

Justin Kaiser, A.B.D., COMS  
Doctoral Candidate, Vision Studies Program  
Teaching Fellow,  
Dept. of Instruction and Learning  
University of Pittsburgh School of Education  
W.W. Posvar Hall Room 5142  
230 South Bouquet Street  
Telephone: 724-562-4188

**CO-PRINCIPAL INVESTIGATOR:** Dr. Amy Nau, Dr. George Zimmerman

**Source of Support:** Financial compensation for participants comes directly from the PI, and also from the University of Pittsburgh through the Bertha C. Kretschmar Fund, which is reserved for promoting education and instruction of individuals who are blind.

**Why is this study being done?**

This study will test a device that is placed on a person's tongue (BrainPort vision device) that allows a blind person to better understand the immediate surroundings and determine if it can improve one's ability to safely travel on their own.

Please consider this form carefully. The study staff will review the information in this form with you and answer your questions. If you agree to take part in this study, you need to sign this form. Your signature means that you have been told about the study and what the risks are. Your signature on this form also means that you want to take part in this study.

### **How many people will take part in this research study?**

There will be 8 subjects who are older than 18 years of age.

### **How long will you be in this research study?**

The study will consist of 4 sessions. Each study session lasts up to 3 hours. We can schedule these visits to accommodate your schedule, work and travel needs. The time from the first session to completion of the study can be anywhere from 1 to 4 weeks depending on completion of the training program and scheduling options. The training program will be completed during the 4 sessions. Up to 2 sessions can be scheduled in the same day, morning and afternoon, to make participation easier.

### **What will happen in this research study?**

You will spend the sessions with the study team so that we can obtain initial mobility assessments, train you how to use the BrainPort and then repeat the assessment tests. A more detailed description of what to expect follows:

An outdoor obstacle course has been created in a controlled environment. The obstacle course consists of paper and plastic obstacles that are light and easily moved. The obstacle course is 77 feet long and includes a 24 foot simulated street crossing over a driveway. The obstacle course is placed on the outdoor Urban Trail created at the Western Pennsylvania School for Blind Children to provide a realistic residential environment in a controlled setting.

As part of the training for this protocol at each of the session, you will travel with the BrainPort and the long cane and asked to identify and avoid different environmental features. After the BrainPort training has been completed, you will be asked to travel through the obstacle course in each of the different conditions again.

Most of the testing will occur at the Western Pennsylvania School for Blind Children. All testing will be supervised by trained study staff.

### **Detailed Description by Study session**

**Session One:** Procedures will include informed consent, review of inclusion and exclusion criteria, study questionnaire, repeated travel on

course 3 times: with the long cane, with the BrainPort, and with both devices together.

**Session Two:** Training with the BrainPort.

**Session Three:** Training with the BrainPort

**Session Four:** Procedures will include completion of a study questionnaire, repeated travel on course 3 times: with the long cane, with the BrainPort, and with both devices together.

### **Description of the BrainPort and experimental procedures**

The BrainPort vision device consists of a small camera mounted on the bridge on the nose of a pair of sunglasses. The device consists of a lollipop that is put on the tongue, which has consists of 20 x 20 steel plated electrodes on your tongue that has many small individual electric stimulators. Each of the stimulators will produce a vibrating or tingling sensation on the tongue when activated. The video camera provides information about objects in its field of view to the controller. The controller then relays this information back to the electrical array on your tongue. You control the strength of the electrical signal on your tongue. There is also a safety circuit to prevent the electrical activity from being too strong. You will be asked to wear the special glasses with a camera mounted on top. You will be taught how to interpret the information that forms on your tongue. Each outdoor course session will last up to 3 hours. All of these sessions will be conducted at Western Pennsylvania School for Blind Children or at the University of Pittsburgh.

### **What procedures will be performed for research purposes?**

Experimental Procedures: If you qualify to take part in this research study, you will undergo the following experimental procedures.

1. Initial assessment walking through obstacle course to determine normal walking speed.
2. Researcher will place obstacles on the course and ask the participant to walk through a version of the obstacle course in 3 different conditions: with the BrainPort, with the long cane, and with the BrainPort and long cane together. The course will be rearranged or a different part of the Urban Trail will be used for each travel condition. The sequence of which travel condition is 1<sup>st</sup>, 2<sup>nd</sup>, or 3<sup>rd</sup> will be randomized for each participant.

3. Researcher will remain in close physical proximity for safety reasons.
4. Obstacle course trials will be video-recorded for later reference and data collection.
5. Training procedures focus on outdoor mobility, understanding environmental features with the BrainPort, traveling routes with the BrainPort, and using the BrainPort and long cane together.

**Risks of the screening and research procedures:**

Orientation and mobility tasks are all standard procedures that would normally be supervised by a Certified Orientation and Mobility specialist. There is a risk of falling on the sidewalk or tripping over an obstacle. The researcher will be walking with the participant to ensure their safety and will stop them if they are in danger. It is possible that the stimulus on your tongue may become too strong and produce discomfort. You have complete control of the sensation strength, and can adjust it to your preference. However, you can also simply remove the electrical stimulator at any time or press a button to end the stimulus. No information is presently available on the effects of long-term electrical stimulation in the mouth. A Breach of Confidentiality is a rare, but possible risk. There are circumstances beyond the researcher's control that could result in research information being inappropriately released. The primary researcher will do everything possible to keep this information private.

There is not enough medical information to know what the risks might be to a breast-fed infant or to an unborn child carried by a woman who takes part in this study. Any woman who is pregnant will be excluded from this study since the device is not yet FDA approved. If you are pregnant, it is your responsibility to inform the primary researcher of this prior to completing any research procedures. The researcher will ask you if you are pregnant prior to beginning the study.

**Are there benefits to taking part in this research study?**

You may not directly benefit from your participation in this study. The information learned from this study may help investigators provide better instruction for those who are blind in the future.

**Will I be paid for taking part in this research study?**

Yes, you will be paid \$150 for completing all four sessions. Participants will be paid \$25 at the end of each of the 4 sessions and an additional \$50 when the participant completes all research procedures. This money is

provided for the participants' time at the 4 sessions, parking and transportation to the site.

**Who do I contact if I have questions about the study?**

You may contact Justin Kaiser at 724-562-4188

**Who will know about my participation in this research study?**

Any information about you obtained from this research will be kept as confidential (private) as possible. All records related to your involvement in this research study will be stored in a locked file cabinet. Your identity on these records will be indicated by a number rather than by your name, and the information linking these numbers with your identity will be kept separate from the research records. You will not be identified by name in any publication of the research results unless you sign a separate consent form giving your permission (release). Course trials will be video recorded for data collection purposes. These videos will only be reviewed by the research staff and will be destroyed upon completion of the study.

**Is my participation in this research study voluntary?**

Your participation in this research study is completely voluntary. If you do not provide your consent for the use and disclosure of your identifiable information for the purposes described above, you will not be allowed to participate in the research study. Whether or not you provide your consent for participation in this research study will have no effect on your current or future relationship with the University of Pittsburgh.

\*\*\*\*\*

***VOLUNTARY CONSENT***

The above information has been explained to me and all of my current questions have been answered. I understand that I am encouraged to ask questions, voice concerns or complaints about any aspect of this research study during the course of this study, and that such future questions, concerns or complaints will be answered by a qualified individual or by the investigator(s) listed on the first page of this consent document at the telephone number(s) given. I understand that I may always request that my questions, concerns or complaints be addressed by a listed investigator. I understand that I may contact the Human Subjects Protection Advocate of the IRB Office, University of Pittsburgh (1-866-212-2668) to discuss

problems, concerns, and questions; obtain information; offer input; or discuss situations that occurred during my participation. By signing this form, I agree to participate in this research study. A copy of this consent form will be given to me.

\_\_\_\_\_  
Participant's Signature

\_\_\_\_\_  
Printed Name of Participant

\_\_\_\_\_  
Date

\_\_\_\_\_  
Time

\_\_\_\_\_  
Signature of Witness

\_\_\_\_\_  
Date

\_\_\_\_\_  
Time

### **CERTIFICATION OF INFORMED CONSENT**

I certify that I have explained the nature and purpose of this research study to the above-named individual(s), and I have discussed the potential benefits and possible risks of study participation. Any questions the individual(s) have about this study have been answered, and we will always be available to address future questions as they arise. I further certify that no research component of this protocol was begun until after this consent form was signed.

\_\_\_\_\_  
Printed Name of investigator

\_\_\_\_\_  
Role in Research Study

\_\_\_\_\_  
Signature of Person Obtaining Consent

\_\_\_\_\_  
Date

\_\_\_\_\_  
Time

## APPENDIX C

### STUDY QUESTIONNAIRES FOR PARTICIPANT CHARACTERISTICS AND CONFIDENCE FOR INDEPENDENT TRAVEL

#### C.1 STUDY QUESTIONNAIRE FOR SESSION ONE

**Please answer questions yes or no, or with one of the appropriate choices where indicated.**

- 1) Did your vision loss occur at birth or later in life? Acquired later or at birth
- 2) Please tell me if you have residual visual perception.
  - a. Please tell me if you are able to perceive anything with your vision right now, even just light.
- 3) How long ago did your vision loss progress to its current level? \_\_\_\_\_
- 4) How old were you when your vision loss progressed to its current level? \_\_\_\_\_
- 5) Did you participate in a BrainPort research study? YES / NO
  - a. Approximately, how many hours of training and/or practice have you had with the BrainPort?
    - i. 0 to 20
    - ii. 21 to 40
    - iii. 41 to 60
    - iv. 61 or more
- 6) Have you completed Orientation and Mobility training? YES / NO
  - a. Approximately, how many hours of Orientation and Mobility training have you completed?

- i. 0 to 20
- ii. 21 to 40
- iii. 41 to 60
- iv. 61 or more

7) Have you used another electronic device besides the BrainPort for mobility?

YES / NO

a. Please name these devices\_\_\_\_\_

\_\_\_\_\_

8) In the last month, how often have you traveled independently without a sighted guide?

Always          Usually          Sometimes          Rarely          Never

8) In the last month, how often have you traveled in new or unfamiliar environments independently?

Always          Usually          Sometimes          Rarely          Never

## C.2 STUDY QUESTIONNAIRE FOR SESSION FOUR

Please answer each of the questions for your specific travel habits.

1. In the last month, how often have you traveled independently without a sighted guide?

Always      Usually      Sometimes      Rarely      Never

2. In the last month, how often have you traveled in new or unfamiliar environments independently?

Always      Usually      Sometimes      Rarely      Never

Please answer the following questions on a scale from 1 to 5 with five being the highest and one being the lowest.

3. How comfortable do you feel using only the BrainPort for independent mobility?

1                  2                  3                  4                  5

4. How comfortable do you feel using the BrainPort and the long cane together for independent mobility?

1                  2                  3                  4                  5

## **APPENDIX D**

### **OBSTACLE COURSE DOCUMENTS**

#### **D.1 VERBAL SCRIPT READ BY THE RESEARCHER AT EACH OBSTACLE COURSE SESSION**

##### **BrainPort Obstacle Course Verbal Instructions**

The participant will be taken sighted guide to the beginning of the route. The participant will be prompted to turn on the BrainPort for the appropriate experimental condition.

##### ***Initial Verbal Prompt***

“I am going to ask you to walk a route along a sidewalk and including a street crossing. There are currently not obstacles on the sidewalk. The course is 77 feet long and 6 feet wide. There is some slight variation due to the outdoor design. I am going to ask you to walk at your normal pace using your long cane. The course is on the sidewalk with a controlled and simulated street crossing over a driveway. The street crossing includes an Accessible Pedestrian Signal providing auditory feedback and just involves crossing over a driveway leading to the parking lot for the school for the blind. I want you to complete the street crossing safely and as fast as you feel comfortable. I will be walking with you the entire time to ensure your safety. I will prompt you when it is the appropriate time to turn on the course or if there is a safety issue.

After establishing the participant’s Preferred Walking Speed and placing obstacles on the course:

“I am now going to ask you to travel the same course with obstacles placed on it. The obstacle course is similar to the one used indoors with styrofoam obstacles. The obstacles are created from garbage cans, floor mats, and black garbage bags filled with paper.”

“I will have you travel through a version of the course three times: once with the BrainPort, once using your long cane, and once using both the long cane and the BrainPort. Your performance will be video-recorded for later reference and data collection purposes.”

### **Repeated Prompt for Each Condition**

“The course is on the sidewalk with a controlled and simulated street crossing over a driveway. The course is 77 feet long and six feet wide. I want you to complete the street crossing safely and as fast as you feel comfortable. Please stay within the crosswalk lines as much as possible. I will be walking with you the entire time to ensure your safety. I will prompt you when it is the appropriate time to turn on the course or if there is a safety issue. In this trial, you will be traveling using the \_\_\_\_\_ (BrainPort, long cane, or BrainPort and long cane). Please travel in the most efficient path avoiding obstacles and walking at your normal pace as much as possible. There will be handrails on part of the course on each side and possibly other objects besides the obstacles created for the course. The course will include one turn, which you will be prompted to complete by the O&M specialist. There will be obstacles on the ground to walk around, obstacles flat on the ground to walk on, or obstacles hanging from above to avoid as well. Please remain on the sidewalk and within the crosswalk as much as possible. This is not a race. There is no reward for finishing faster than any other participant. The researcher will be walking close to you throughout the course to ensure your safety while traveling. Please let me know if you have any questions.”

### **Detection of Obstacles Conditions**

“I am going to have you walk with the BrainPort and point to each obstacle that you can detect or perceive with the device. This will not be timed so you can walk at whatever pace is comfortable.”

## APPENDIX E

### TRAINING AND DATA COLLECTION DOCUMENTS

#### E.1 BRAINPORT TRAINING PROGRAM DOCUMENT

##### BrainPort Training Procedures

Task	Date	Training Procedures - (review at each session)	Notes
1)		Look in front, left, and right to detect presence of obstacles	
		Focus on the object and determine approximate distance	
		Walk up to the obstacle without touching it	
		Locate the obstacle and explore it with a hand or the cane	
		Repeat process for other obstacles	
2)		Walk sighted guide through route identifying obstacles	
		Locate two obstacles and safely walk around/between them without contacting them	
4)		Stop on the truncated domes before reaching the street and turn off the invert setting on the BrainPort	
		Scan to the left and right to determine the location of each crosswalk line	

		Cross the street remaining between crosswalk lines and keep one line in view while crossing Shoreline visually similar to how a participant uses this technique with a cane	
5)		Approach where the floor mat is located, and scan up and down and determine where the mat starts and stops	
		Look for horizontal lines at top and bottom of floor mat	
6)		Scan left and right to find the opening of the gazebo	
		Become familiar with how vertical and horizontal lines look with the BrainPort	
7)		Determine left and right edges of sidewalk through contrast	
		Determine if there were surface changes through the light and dark colors detected	
		Follow visual shoreline by keeping the sidewalk edge in view	
		Practice finding changes in the surface through contrast	
8)		Walk with the BrainPort and cane to maintain attention to all sensory information	
		Traveling specific routes around the area by the WPSBC	
		Identify curbs and drop offs, truncated domes, sidewalks, building line, street furniture, benches, trash cans, street signs, flower beds, bushes, trees, poles, etc.	
		Adjust settings on the BrainPort to explore what works for various environments	
		Examine shaded and sunny areas (if possible) to view characteristics with BrainPort	
9)		Independent travel along novel route with BrainPort and long cane, and then with just the BrainPort	
		Walk slowly to see if you can detect the presence of obstacles with the BrainPort before finding them with the long cane	

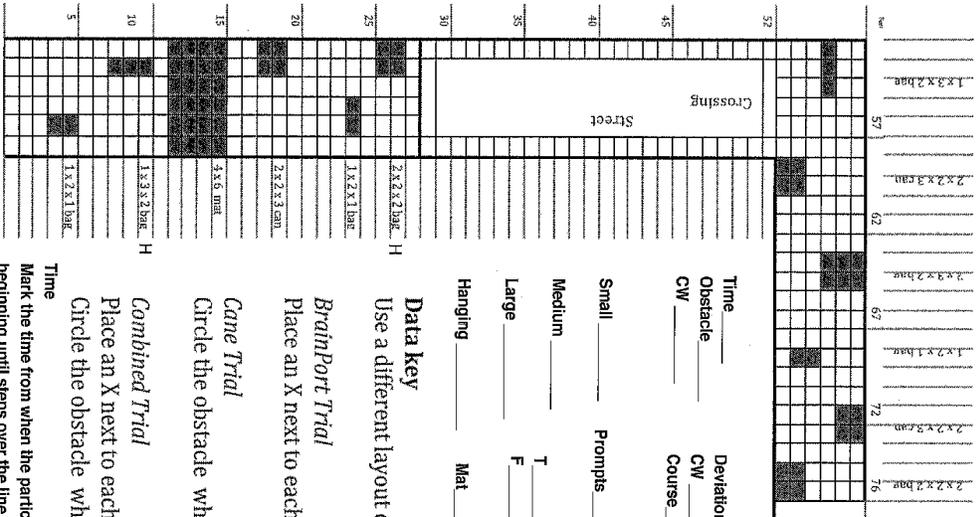
10)		Repeat procedures in each training sessions increasing complexity in different environments (Urban trail, sidewalks, intersections, and crosswalks)	
		Explore familiar environments to connect prior environmental knowledge and current perceptions with BrainPort	

**E.2 COURSE LAYOUT SHEET FOR DATA COLLECTION**

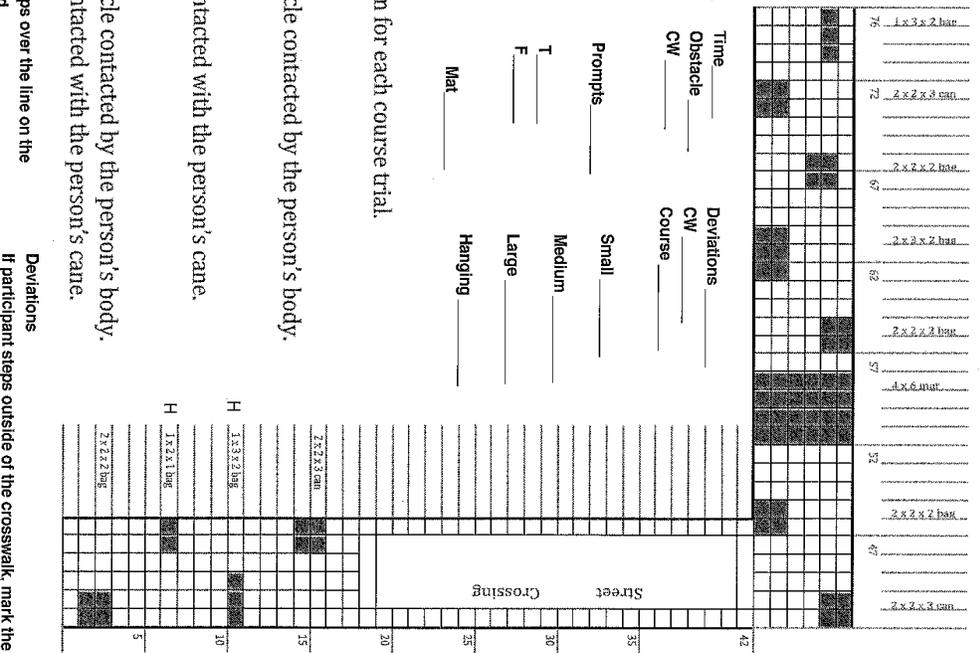
Course version \_\_\_\_\_  
 Condition \_\_\_\_\_  
 Order \_\_\_\_\_

Course Version \_\_\_\_\_  
 Condition \_\_\_\_\_  
 Order \_\_\_\_\_

Participant \_\_\_\_\_  
 Date \_\_\_\_\_



**OBID - Circle correctly identified objects**  
 Place an X over false identifications



**OBID - Circle correctly identified objects**  
 Place an X over false identifications

**Deviations**  
 If participant steps outside of the crosswalk, mark the area with a triangle.  
 If the participants steps off of the sidewalk or contacts the handrail, mark the course area with a square.

Time \_\_\_\_\_ Deviations \_\_\_\_\_  
 Obstacle \_\_\_\_\_ CW \_\_\_\_\_  
 Course \_\_\_\_\_

Small \_\_\_\_\_ Prompts \_\_\_\_\_  
 Medium \_\_\_\_\_ T \_\_\_\_\_  
 Large \_\_\_\_\_ F \_\_\_\_\_

Handing \_\_\_\_\_ Mat \_\_\_\_\_  
 Mat \_\_\_\_\_

**Data key**  
 Use a different layout diagram for each course trial.

**BrainPort Trial**  
 Place an X next to each obstacle contacted by the person's body.

**Cane Trial**  
 Circle the obstacle where contacted with the person's cane.

**Combined Trial**  
 Place an X next to each obstacle contacted by the person's body.  
 Circle the obstacle where contacted with the person's cane.

**Time**  
 Mark the time from when the participant steps over the line on the beginning until steps over the line at the end.

Mark the time separately from when the participant steps onto the truncated domes with one foot until the participant steps off the truncated domes on the opposite side of the street.

**E.3 DATA SUMMARY SHEET USED TO RECORD PARTICIPANT  
PERFORMANCE**

**Data Summary Sheet**

Participant ID: \_\_\_\_\_ Date: \_\_\_\_\_ Time: \_\_\_\_\_

Notes \_\_\_\_\_

PWS (Time for Ss to walk without obstacles) \_\_\_\_\_

	Session 1 Date _____			Session 4 Date _____		
<b>Luminescence Reading</b>						
<b>Weather:</b> Sunny/ Cloudy						
<b>Trials</b>	<i>1</i>	<i>2</i>	<i>3</i>	<i>1</i>	<i>2</i>	<i>3</i>
<b>Course route</b> (1,2) (Forward/Reverse)						
<b>BrainPort (BP)</b> <b>Long cane (C)</b>						
Street crossing deviations						
Deviations off the sidewalk						
<b>Total Deviations</b>						
Course Time						
Crosswalk Time						
<b>Time to complete course</b>						
1 point body contact						
1 point cane contact						
<b>Total Contact points</b>						
Small						
Medium						
Large						
Hanging						

	<b>Session 1</b>	<b>Session 2</b>
<b>Total Objects Identified</b>		
<b>Course Version</b>		

<b>Object ID</b>	<b>Description</b>	<b>Dimensions (LxWxH)</b>	<b>Obstacles identified</b>
A	Small Bag	1 x 2 x 2	
B	Medium bag	1 x 3 x 2	
C	Medium bag	2 x 2 x 2	
D	Large bag	2 x 3 x 2	
E	Garbage can	2 x 2 x 3	
F	Floor mat	6 x 4	

**Primary Researcher** \_\_\_\_\_

**Staff** \_\_\_\_\_

## **APPENDIX F**

### **FRIEDMAN'S ANOVA RESULTS FOR TOTAL TIME OF TRAVEL BETWEEN CONDITIONS**

#### **F.1 SPEARMAN RHO CORRELATIONS FOR COURSE VERSION AND DEPENDENT VARIABLES**

### Spearman Rho Correlations

**Table F 1.** Spearman Rho Correlations for age, session, and lighting across dependent variables.

		Age	Visit	Lighting Level	New Course	Total Time of Travel	Total Contacts	Total Veers
Age	Coefficient	1.000	.000	-.128	-.137	.099	.043	.006
	Sig. (2-tailed)	.	1.000	.386	.352	.505	.774	.966
Visit	Coefficient	.000	1.000	-.091	-.097	.212	-.192	.041
	Sig. (2-tailed)	1.000	.	.539	.511	.148	.191	.782
Lighting Level	Coefficient	-.128	-.091	1.000	.054	- .393**	-.032	-.066
	Sig. (2-tailed)	.386	.539	.	.715	.006	.828	.655
New Course	Coefficient	-.137	-.097	.054	1.000	.010	-.142	-.247
	Sig. (2-tailed)	.352	.511	.715	.	.944	.335	.090
Total Time of Travel	Coefficient	.099	.212	-.393**	.010	1.000	-.141	.326*
	Sig. (2-tailed)	.505	.148	.006	.944	.	.340	.024
Total Contacts	Coefficient	.043	-.192	-.032	-.142	-.141	1.000	-.248
	Sig. (2-tailed)	.774	.191	.828	.335	.340	.	.089
Total Veers	Coefficient	.006	.041	-.066	-.247	.326*	-.248	1.000
	Sig. (2-tailed)	.966	.782	.655	.090	.024	.089	.

**F.2 FRIEDMAN’S ANOVA RESULTS FOR RESEARCH QUESTION 1 REGARDING  
TIME OF TRAVEL**

**Table F2.** Mean and standard deviation for average time of travel mean ranks for each travel condition.

Mean Ranks of Average Time of Travel Between Sessions

Descriptive Statistics

	Mean	Std. Deviation	Minimum	Maximum
Cane Condition	81.0625	17.19310	52.50	108.50
BrainPort Condition	183.5625	79.73547	92.50	314.00
BrainPort and Cane Condition	100.3125	28.54187	62.00	132.00

**Table F3.** Mean ranks for average time of travel for participants between travel conditions.

Ranks	
	Mean Rank
Cane Condition	1.13
BrainPort Condition	2.88
Combined Travel Condition	2.00

**Table F4.** Friedman's ANOVA statistics for total time of travel.

Friedman Test Statistics	
N	8
Chi-Square	12.250
df	2
Asymp. Sig.	.002

## **F.2 SPEARMAN RHO CORRELATIONS ACROSS INDEPENDENT AND DEPENDENT VARIABLES**

**Table F 5.** Spearman Rho Correlations for time, contacts, and veers.

		Spearman Rho Correlations								
		Total Time of Travel	Crosswalk Time	Obstacle Time	Total Contacts	Obstacle Body Contacts	Cane Contacts	Total Veers	Crosswalk Veers	Course Veers
Total Time of Travel	Coefficient	1.000	.854**	.962**	-.141	.387**	-.416**	.326*	-.068	.391**
	Sig. (2-tailed)	.	.000	.000	.340	.007	.003	.024	.646	.006
Crosswalk Time	Coefficient	.854**	1.000	.696**	-.198	.205	-.344*	.368*	.181	.295*
	Sig. (2-tailed)	.000	.	.000	.176	.163	.017	.010	.218	.042
Obstacle Time	Coefficient	.962**	.696**	1.000	-.097	.429**	-.408**	.263	-.196	.393**
	Sig. (2-tailed)	.000	.000	.	.512	.002	.004	.071	.181	.006
Total Contacts	Coefficient	-.141	-.198	-.097	1.000	-.052	.748**	-.248	-.032	-.258
	Sig. (2-tailed)	.340	.176	.512	.	.726	.000	.089	.829	.077
Body Contacts	Coefficient	.387**	.205	.429**	-.052	1.000	-.643**	.349*	-.160	.461**
	Sig. (2-tailed)	.007	.163	.002	.726	.	.000	.015	.276	.001
Cane Contacts	Coefficient	-.416**	-.344*	-.408**	.748**	-.643**	1.000	-.465**	.049	-.531**
	Sig. (2-tailed)	.003	.017	.004	.000	.000	.	.001	.739	.000
Total Veers	Coefficient	.326*	.368*	.263	-.248	.349*	-.465**	1.000	.401**	.848**
	Sig. (2-tailed)	.024	.010	.071	.089	.015	.001	.	.005	.000
Crosswalk Veers	Coefficient	-.068	.181	-.196	-.032	-.160	.049	.401**	1.000	-.111
	Sig. (2-tailed)	.646	.218	.181	.829	.276	.739	.005	.	.453
Course Veers	Coefficient	.391**	.295*	.393**	-.258	.461**	-.531**	.848**	-.111	1.000
	Sig. (2-tailed)	.006	.042	.006	.077	.001	.000	.000	.453	.

\*\* . Correlation is significant at the 0.01 level (2-tailed).

\* . Correlation is significant at the 0.05 level (2-tailed).

**Table F 6.** Spearman Rho Correlations for participant characteristics across variables.

		Spearman Rho Correlations						
		Age	Gender	Onset of Vision Loss	When Vision Loss Occurred	Average Total Time	Average Total Contacts	Average Total Veers
Age	Coefficient	1.000	-.384	-.659**	.755**	.083	.028	.016
	Sig. (2-tailed)	.	.064	.000	.000	.701	.896	.942
Gender	Coefficient	-.384	1.000	.500*	-.655**	.072	.103	-.253
	Sig. (2-tailed)	.064	.	.013	.001	.737	.630	.233
Onset of Vision Loss	Coefficient	-.659**	.500*	1.000	-.873**	-.132	-.195	-.185
	Sig. (2-tailed)	.000	.013	.	.000	.537	.362	.387
When Vision Loss Occurred	Coefficient	.755**	-.655**	-.873**	1.000	.068	.193	.157
	Sig. (2-tailed)	.000	.001	.000	.	.751	.367	.463
Average Total Time	Coefficient	.083	.072	-.132	.068	1.000	-.012	.420*
	Sig. (2-tailed)	.701	.737	.537	.751	.	.955	.041
Average Total Contacts	Coefficient	.028	.103	-.195	.193	-.012	1.000	-.303
	Sig. (2-tailed)	.896	.630	.362	.367	.955	.	.150
Average Total Veers	Coefficient	.016	-.253	-.185	.157	.420*	-.303	1.000
	Sig. (2-tailed)	.942	.233	.387	.463	.041	.150	.

\*\* . Correlation is significant at the 0.01 level (2-tailed).

\* . Correlation is significant at the 0.05 level (2-tailed).

**Table F7.** Spearman Rho Correlations for participant characteristics across variables.

		Spearman Rho Correlations						
		Age	Gender	Onset of Vision Loss	When Vision Loss Occurred	Total Time of Travel 2	Total Contacts 2	Total Veers 2
Age	Coefficient	1.000	-.384	-.659**	.755**	.286	-.449*	.069
	Sig. (2-tailed)	.	.064	.000	.000	.175	.028	.749
Gender	Coefficient	-.384	1.000	.500*	-.655**	.145	.173	-.215
	Sig. (2-tailed)	.064	.	.013	.001	.500	.419	.312
Onset	Coefficient	-.659**	.500*	1.000	-.873**	-.229	.167	-.380
	Sig. (2-tailed)	.000	.013	.	.000	.282	.436	.067
When	Coefficient	.755**	-.655**	-.873**	1.000	.099	-.283	.290
	Sig. (2-tailed)	.000	.001	.000	.	.647	.180	.169
Total Time of Travel 2	Coefficient	.286	.145	-.229	.099	1.000	-.204	.436*
	Sig. (2-tailed)	.175	.500	.282	.647	.	.338	.033
Total Contacts 2	Coefficient	-.449*	.173	.167	-.283	-.204	1.000	.023
	Sig. (2-tailed)	.028	.419	.436	.180	.338	.	.913
Total Veers 2	Coefficient	.069	-.215	-.380	.290	.436*	.023	1.000
	Sig. (2-tailed)	.749	.312	.067	.169	.033	.913	.

\*. Correlation is significant at the 0.05 level (2-tailed).

\*\* . Correlation is significant at the 0.01 level (2-tailed).

**Table F 8.** Spearman Rho Correlations for participant characteristics and questionnaire results.

		Age	Gender	Onset	When	Independent	New	Travel	Travel
						travel	environments	with	with
						2	2	BrainPort	BrainPort-
									Cane
Age	Coefficient	1.000	-.384	-.659**	.755**	.680**	.227	-.621**	.659**
	Sig. (2-tailed)	.	.064	.000	.000	.000	.287	.001	.000
Gender	Coefficient	-.384	1.000	.500*	-	-.258	-.258	.462*	-.500*
	Sig. (2-tailed)	.064	.	.013	.001	.223	.223	.023	.013
Onset of Vision Loss	Coefficient	-.659**	.500*	1.000	-	-.258	.258	.808**	-1.000**
	Sig. (2-tailed)	.000	.013	.	.000	.223	.223	.000	.
When Vision Loss Occurred	Coefficient	.755**	-.655**	-.873**	1.000	.507*	-.056	-.945**	.873**
	Sig. (2-tailed)	.000	.001	.000	.	.011	.794	.000	.000
Independent Travel 2	Coefficient	.680**	-.258	-.258	.507*	1.000	.467*	-.477*	.258
	Sig. (2-tailed)	.000	.223	.223	.011	.	.022	.018	.223
New Environments 2	Coefficient	.227	-.258	.258	-.056	.467*	1.000	.179	-.258
	Sig. (2-tailed)	.287	.223	.223	.794	.022	.	.403	.223
Travel with BrainPort	Coefficient	-.621**	.462*	.808**	-	-.477*	.179	1.000	-.808**
	Sig. (2-tailed)	.001	.023	.000	.000	.018	.403	.	.000
Travel with BrainPort Cane	Coefficient	.659**	-.500*	-	.873**	.258	-.258	-.808**	1.000
	Sig. (2-tailed)	.000	.013	.	.000	.223	.223	.000	.

\*\* . Correlation is significant at the 0.01 level (2-tailed).

\* . Correlation is significant at the 0.05 level (2-tailed).

**Table F 9.** Spearman Rho Correlations between performance at Session One and Session Four.

		Spearman Rho Correlations					
		Total Time of Travel	Total Contacts	Total Veers	Total Time of Travel 2	Total Contacts 2	Total Veers 2
Total Time of Travel	Coefficient	1.000	.002	.217	.613**	-.004	.379
	Sig. (2-tailed)	.	.992	.308	.001	.984	.068
Total Contacts	Coefficient	.002	1.000	-.466*	.080	.135	-.039
	Sig. (2-tailed)	.992	.	.022	.712	.531	.856
Total Veers	Coefficient	.217	-.466*	1.000	-.023	-.336	.212
	Sig. (2-tailed)	.308	.022	.	.915	.108	.321
Total Time of Travel 2	Coefficient	.613**	.080	-.023	1.000	-.204	.436*
	Sig. (2-tailed)	.001	.712	.915	.	.338	.033
Total Contacts 2	Coefficient	-.004	.135	-.336	-.204	1.000	.023
	Sig. (2-tailed)	.984	.531	.108	.338	.	.913
Total Veers 2	Coefficient	.379	-.039	.212	.436*	.023	1.000
	Sig. (2-tailed)	.068	.856	.321	.033	.913	.

\*\* . Correlation is significant at the 0.01 level (2-tailed).

\* . Correlation is significant at the 0.05 level (2-tailed).

**Table F 10.** Spearman Rho Correlations for performance at Session Four and environmental and participant characteristics.

		Spearman Rho Correlations							
		Total Time of Travel 2	Total Contacts 2	Total Veers 2	Lighting Level 2	Condition	Course Version	Onset of Vision Loss	BrainPort Training Hours
Total Time of Travel 2	Coefficient	1.000	-.204	.436*	-.411*	.266	.074	-.229	.464*
	Sig. (2-tailed)	.	.338	.033	.046	.210	.732	.282	.022
Total Contacts 2	Coefficient	-.204	1.000	.023	.026	.091	-.236	.167	-.009
	Sig. (2-tailed)	.338	.	.913	.902	.673	.268	.436	.965
Total Veers 2	Coefficient	.436*	.023	1.000	-.296	-.213	-.277	-.380	.105
	Sig. (2-tailed)	.033	.913	.	.160	.317	.190	.067	.624
Lighting Level 2	Coefficient	-.411*	.026	-.296	1.000	.000	.153	.189	-.095
	Sig. (2-tailed)	.046	.902	.160	.	1.000	.477	.376	.658
Condition	Coefficient	.266	.091	-.213	.000	1.000	.301	.000	.000
	Sig. (2-tailed)	.210	.673	.317	1.000	.	.153	1.000	1.000
Course Version	Coefficient	.074	-.236	-.277	.153	.301	1.000	.000	.057
	Sig. (2-tailed)	.732	.268	.190	.477	.153	.	1.000	.791
Onset of Vision Loss	Coefficient	-.229	.167	-.380	.189	.000	.000	1.000	-.378
	Sig. (2-tailed)	.282	.436	.067	.376	1.000	1.000	.	.069
BrainPort Training Hours	Coefficient	.464*	-.009	.105	-.095	.000	.057	-.378	1.000
	Sig. (2-tailed)	.022	.965	.624	.658	1.000	.791	.069	.

\*. Correlation is significant at the 0.05 level (2-tailed).

**Table F11.** Mean and standard deviation for total time of travel across conditions at Session One.

		Descriptives			
	Condition		Statistic	Std. Error	
Total time of travel	Cane	Mean	75.38	7.683	
		Variance	472.268		
		Std. Deviation	21.372		
		Minimum	50		
		Maximum	121		
		Range	71		
		Skewness	1.416		.752
		Kurtosis	2.516		1.481
		BrainPort	Mean		166.75
	Variance		6884.214		
	Std. Deviation		82.971		
	Minimum		58		
	Maximum		328		
	Range		270		
	Skewness		.964	.752	
	Kurtosis		1.153	1.481	
	Combined		Mean	87.63	.844
		Variance	788.554		
		Std. Deviation	28.081		
		Minimum	50		
		Maximum	130		
		Range	80		
		Skewness	.296	.752	
		Kurtosis	-1.301	1.481	

**Table F12.** Mean and standard deviations across travel conditions for time of travel at Session Four.

Descriptives					
	Condition		Statistic	Std. Error	
Total Time of Travel 2	Cane	Mean	86.75	6.408	
		Variance	328.500		
		Std. Deviation	18.125		
		Minimum	55		
		Maximum	111		
		Range	56		
		Skewness	-.474		.752
		Kurtosis	-.277		1.481
		Brain port	Mean		233.50
	Variance		24528.000		
	Std. Deviation		156.614		
	Minimum		83		
	Maximum		565		
	Range		482		
	Skewness		1.451	.752	
	Kurtosis		2.585	1.481	
	Combined		Mean	113.00	12.939
		Variance	1339.429		
		Std. Deviation	36.598		
		Minimum	56		
		Maximum	152		
Range		96			
Skewness		-.737	.752		
Kurtosis		-1.320	1.481		

**Table F13.** Mean and standard deviations across travel conditions for crosswalk times at Session Four.

		Descriptives		
	Condition		Statistic	Std. Error
Crosswalk Time 2	Cane	Mean	24.63	2.847
		Variance	64.839	
		Std. Deviation	8.052	
		Minimum	15	
		Maximum	42	
		Range	27	
	Brain port	Mean	53.88	13.645
		Variance	1489.554	
		Std. Deviation	38.595	
		Minimum	8	
		Maximum	102	
		Range	94	
	Combined	Mean	34.63	6.187
		Variance	306.268	
		Std. Deviation	17.501	
		Minimum	15	
		Maximum	65	
		Range	50	

**Table F14.** Mean and standard deviations across travel conditions for obstacle course time at Session Four.

		Descriptives		
	Condition		Statistic	Std. Error
Obstacle Time 2	Cane	Mean	62.13	5.367
		Variance	230.411	
		Std. Deviation	15.179	
		Minimum	35	
		Maximum	86	
		Range	51	
	BrainPort	Mean	179.63	45.755
		Variance	16747.982	
		Std. Deviation	129.414	
		Minimum	57	
		Maximum	471	
		Range	414	
	Combined	Mean	78.38	8.754
		Variance	613.125	
		Std. Deviation	24.761	
		Minimum	40	
		Maximum	111	
		Range	71	

## APPENDIX G

### FRIEDMAN'S ANOVA RESULTS FOR TOTAL CONTACTS BETWEEN CONDITIONS

#### G.1 FRIEDMAN'S ANOVA RESULTS FOR RESEARCH QUESTION 2 REGARDING TOTAL CONTACTS

**Table G1.** Mean and standard deviation from Friedman's ANOVA results for total contacts averaged between Session One and Session Four.

#### Total Number of Contacts

#### Descriptive Statistics

	Mean	Std. Deviation	Minimum	Maximum
Cane Condition	5.8125	1.60217	4.00	9.00
BrainPort Condition	4.1875	.79899	3.00	5.50
BrainPort and Cane Condition	6.6250	1.57548	5.00	9.50

**Table G2.** Mean ranks for Friedman's ANOVA for total contacts between conditions.

Ranks	
Condition	Mean Rank
Cane	1.88
BrainPort	1.31
BrainPort and Cane	2.81

**Table G3.** Results of Friedman's ANOVA for mean ranks of total contacts between conditions averaged between sessions.

Friedman Test Statistics	
N	8
Chi-Square	9.800
df	2
Asymp. Sig.	.007

**Table G4.** Means and standard deviations for number of total contacts across conditions at Session One.

		Descriptives				
	Condition		Statistic	Std. Error		
Total Contacts	Cane	Mean	6.50	.824		
		Variance	5.429			
		Std. Deviation	2.330			
		Minimum	3			
		Maximum	11			
		Range	8			
		Skewness	.723	.752		
		Kurtosis	1.737	1.481		
		BrainPort		Mean	4.00	.707
				Variance	4.000	
Std. Deviation	2.000					
Minimum	1					
Maximum	7					
Range	6					
Skewness	.000			.752		
Kurtosis	-.700			1.481		
Combined		Mean	7.38	.844		
		Variance	5.696			
		Std. Deviation	2.387			
		Minimum	4			
		Maximum	10			
		Range	6			
		Skewness	-.508	.752		
		Kurtosis	-1.079	1.481		

**Table G5.** Mean and standard deviation for number of total contacts at Session Four.

		Descriptives		
	Condition		Statistic	Std. Error
Total Contacts 2	Cane	Mean	5.13	.441
		Variance	1.554	
		Std. Deviation	1.246	
		Minimum	3	
		Maximum	7	
		Range	4	
		Skewness	-.304	.752
		Kurtosis	.146	1.481
	BrainPort	Mean	4.38	.324
		Variance	.839	
Std. Deviation		.916		
Minimum		3		
Maximum		6		
Range		3		
Skewness		.488	.752	
Kurtosis		.421	1.481	
Combined	Mean	5.88	.789	
	Variance	4.982		
	Std. Deviation	2.232		
	Minimum	3		
	Maximum	10		
	Range	7		
	Skewness	.824	.752	
	Kurtosis	.512	1.481	

**Table G6.** Mean and standard deviations for obstacle body contacts at Session One.

		Descriptives		
	Condition		Statistic	Std. Error
Obstacle Body Contacts	Cane	Mean	1.38	.324
		Variance	.839	
		Std. Deviation	.916	
		Minimum	0	
		Maximum	3	
		Range	3	
	BrainPort	Mean	4.00	.707
		Variance	4.000	
		Std. Deviation	2.000	
		Minimum	1	
		Maximum	7	
		Range	6	
	Combined	Mean	1.75	.453
		Variance	1.643	
		Std. Deviation	1.282	
		Minimum	0	
		Maximum	3	
		Range	3	

**Table G7.** Mean and standard deviations for number of obstacles contacted by the body across conditions at Session Four.

<b>Descriptives</b>				
	Condition		Statistic	Std. Error
Obstacle Body Contacts 2	Cane	Mean	.88	.227
		Variance	.411	
		Std. Deviation	.641	
		Minimum	0	
		Maximum	2	
		Range	2	
	BrainPort	Mean	4.38	.324
		Variance	.839	
		Std. Deviation	.916	
		Minimum	3	
		Maximum	6	
		Range	3	
	Combined	Mean	1.25	.250
		Variance	.500	
		Std. Deviation	.707	
		Minimum	0	
		Maximum	2	
		Range	2	

**Table G8.** Mean and standard deviations for cane contacts for the cane and combined device conditions at Session One.

		Descriptives <sup>a</sup>		
Condition			Statistic	Std. Error
Cane Contacts	Cane	Mean	5.13	.693
		Variance	3.839	
		Std. Deviation	1.959	
		Minimum	3	
		Maximum	9	
		Range	6	
		Combined	Mean	
	Variance	5.982		
	Std. Deviation	2.446		
	Minimum	2		
	Maximum	10		
	Range	8		

a. Cane Contacts is constant when Condition = BrainPort. It has been omitted.

**Table G9.** Mean and standard deviations for number of cane contacts across travel conditions at Session Four.

		Descriptives <sup>a</sup>		
Condition			Statistic	Std. Error
Cane Contacts 2	Cane	Mean	4.25	.590
		Variance	2.786	
		Std. Deviation	1.669	
		Minimum	2	
		Maximum	7	
		Range	5	
		Combined	Mean	
	Variance	5.125		
	Std. Deviation	2.264		
	Minimum	2		
	Maximum	9		
	Range	7		

a. Cane Contacts is constant when Condition = BrainPort. It has been omitted.

**Table G10.** Mean and standard deviations for small sized obstacles at Session One across travel conditions.

		Descriptives		
	Condition		Statistic	Std. Error
Small	Cane	Mean	2.63	.532
		Variance	2.268	
		Std. Deviation	1.506	
		Minimum	0	
		Maximum	4	
		Range	4	
	BrainPort	Mean	1.63	.420
		Variance	1.411	
		Std. Deviation	1.188	
		Minimum	0	
		Maximum	3	
		Range	3	
	Combined	Mean	2.13	.295
		Variance	.696	
		Std. Deviation	.835	
		Minimum	1	
		Maximum	3	
		Range	2	

**Table G11.** Mean and standard deviations of number of small obstacles contacted across travel conditions at Session Four.

		Descriptives		
Condition			Statistic	Std. Error
Small 2	Cane	Mean	2.25	.366
		Variance	1.071	
		Std. Deviation	1.035	
		Minimum	1	
		Maximum	4	
		Range	3	
		BrainPort	BrainPort	Mean
Variance	.500			
Std. Deviation	.707			
Minimum	1			
Maximum	3			
Range	2			
Combined	Combined	Mean	1.63	.460
		Variance	1.696	
		Std. Deviation	1.302	
		Minimum	0	
		Maximum	4	
		Range	4	

**Table G12.** Mean and standard deviations across conditions for medium sized obstacles at Session One.

		Descriptives		
	Condition		Statistic	Std. Error
Medium	Cane	Mean	1.50	.189
		Variance	.286	
		Std. Deviation	.535	
		Minimum	1	
		Maximum	2	
		Range	1	
	BrainPort	Mean	.75	.250
		Variance	.500	
		Std. Deviation	.707	
		Minimum	0	
		Maximum	2	
		Range	2	
	Combined	Mean	2.13	.441
		Variance	1.554	
		Std. Deviation	1.246	
		Minimum	0	
		Maximum	4	
		Range	4	

**Table G13.** Mean and standard deviation for medium obstacles contacted across conditions for Session Four.

		Descriptives		
Condition			Statistic	Std. Error
Medium 2	Cane	Mean	.50	.189
		Variance	.286	
		Std. Deviation	.535	
		Minimum	0	
		Maximum	1	
		Range	1	
	BrainPort	Mean	.75	.250
		Variance	.500	
		Std. Deviation	.707	
		Minimum	0	
		Maximum	2	
		Range	2	
	Combined	Mean	1.63	.263
		Variance	.554	
		Std. Deviation	.744	
		Minimum	1	
		Maximum	3	
		Range	2	

**Table G14.** Mean and standard deviations across conditions for large sized obstacles at Session One.

		Descriptives		
	Condition		Statistic	Std. Error
Large	Cane	Mean	2.25	.250
		Variance	.500	
		Std. Deviation	.707	
		Minimum	2	
		Maximum	4	
		Range	2	
	BrainPort	Mean	1.63	.324
		Variance	.839	
		Std. Deviation	.916	
		Minimum	1	
		Maximum	3	
		Range	2	
	Combined	Mean	3.13	.398
		Variance	1.268	
		Std. Deviation	1.126	
		Minimum	1	
		Maximum	4	
		Range	3	

**Table G15.** Mean and standard deviations for number of large obstacles contacted across travel conditions at Session Four.

Descriptives				
	Condition		Statistic	Std. Error
Large 2	Cane	Mean	2.00	.423
		Variance	1.429	
		Std. Deviation	1.195	
		Minimum	1	
		Maximum	4	
		Range	3	
		BrainPort	BrainPort	Mean
Variance	.554			
Std. Deviation	.744			
Minimum	0			
Maximum	2			
Range	2			
Combined	Combined	Mean	2.50	.378
		Variance	1.143	
		Std. Deviation	1.069	
		Minimum	1	
		Maximum	4	
		Range	3	

**Table G16.** Mean and standard deviation across conditions for hanging obstacles contacted at Session One.

		Descriptives		
	Condition		Statistic	Std. Error
Hanging	Cane	Mean	1.00	.189
		Variance	.286	
		Std. Deviation	.535	
		Minimum	0	
		Maximum	2	
		Range	2	
	BrainPort	Mean	.50	.267
		Variance	.571	
		Std. Deviation	.756	
		Minimum	0	
		Maximum	2	
		Range	2	
	Combined	Mean	1.38	.263
		Variance	.554	
		Std. Deviation	.744	
		Minimum	0	
		Maximum	2	
		Range	2	

**Table G17.** Mean and standard deviations of number of hanging obstacles contacted across travel conditions at Session Four.

Descriptives				
	Condition		Statistic	Std. Error
Hanging 2	Cane	Mean	.75	.250
		Variance	.500	
		Std. Deviation	.707	
		Minimum	0	
		Maximum	2	
		Range	2	
	BrainPort	Mean	.75	.250
		Variance	.500	
		Std. Deviation	.707	
		Minimum	0	
		Maximum	2	
		Range	2	
	Combined	Mean	.88	.227
		Variance	.411	
		Std. Deviation	.641	
		Minimum	0	
		Maximum	2	
		Range	2	

## APPENDIX H

### STATISTICAL ANALYSIS AND FRIEDMAN'S ANOVA RESULTS FOR TOTAL VEERS BETWEEN CONDITIONS

#### H.1 FRIEDMAN'S ANOVA RESULTS FOR RESEARCH QUESTION 3 REGARDING TOTAL NUMBER OF VEERS

**Table H1.** Mean and standard deviation for total number of veers across conditions.

Total Veers Average from Session One to Session Four

#### Descriptive Statistics

Condition	Mean	Std. Deviation	Minimum	Maximum
Cane	1.1250	.74402	.00	2.00
BrainPort	2.0000	.46291	1.0	3.00
BrainPort and Cane	.6875	.37201	.00	1.00

**Table H 2.** Mean ranks of total number of veers averaged across sessions for each condition.

Mean Ranks of Total Veers	
Condition	Mean Rank
Cane	2.00
BrainPort	2.81
BrainPort and Cane	1.19

**Table H 3.** Results of Friedman's ANOVA for total number of veers averaged across sessions for each condition.

Friedman Test Statistics	
N	8
Chi-Square	12.071
df	2
Asymp. Sig.	.002

**Table H4.** Mean and standard deviations for number of total veers at Session One.

		Descriptives				
	Condition		Statistic	Std. Error		
Total Veers	Cane	Mean	1.00	.267		
		Variance	.571			
		Std. Deviation	.756			
		Minimum	0			
		Maximum	2			
		Range	2			
		Skewness	.000	.752		
		Kurtosis	-.700	1.481		
		BrainPort	BrainPort	Mean	2.00	.267
				Variance	.571	
Std. Deviation	.756					
Minimum	1					
Maximum	3					
Range	2					
Skewness	.000			.752		
Kurtosis	-.700			1.481		
Combined	Combined			Mean	.63	.263
				Variance	.554	
		Std. Deviation	.744			
		Minimum	0			
		Maximum	2			
		Range	2			
		Skewness	.824	.752		
		Kurtosis	-.152	1.481		

**Table H5.** Mean and standard deviations for total number of veers at Session Four.

		Descriptives		
	Condition		Statistic	Std. Error
Total Veers 2	Cane	Mean	1.25	.366
		Variance	1.071	
		Std. Deviation	1.035	
		Minimum	0	
		Maximum	3	
		Range	3	
		Skewness	.386	.752
		Kurtosis	-.448	1.481
	BrainPort	Mean	2.00	.378
		Variance	1.143	
		Std. Deviation	1.069	
		Minimum	1	
		Maximum	4	
		Range	3	
		Skewness	.935	.752
		Kurtosis	.350	1.481
	Combined	Mean	.75	.250
		Variance	.500	
		Std. Deviation	.707	
		Minimum	0	
		Maximum	2	
		Range	2	
		Skewness	.404	.752
		Kurtosis	-.229	1.481

**Table H6.** Mean and standard deviations for number of course veers across conditions at Session One.

		Descriptives		
	Condition		Statistic	Std. Error
Course Veers	Cane	Mean	.38	.263
		Variance	.554	
		Std. Deviation	.744	
		Minimum	0	
		Maximum	2	
		Range	2	
	BrainPort	Mean	1.13	.227
		Variance	.411	
		Std. Deviation	.641	
		Minimum	0	
		Maximum	2	
		Range	2	
	Combined	Mean	.25	.164
		Variance	.214	
		Std. Deviation	.463	
		Minimum	0	
		Maximum	1	
		Range	1	

**Table H7.** Mean and standard deviations for number of course veers across travel conditions at Session Four.

		Descriptives		
	Condition		Statistic	Std. Error
Course Veers 2	Cane	Mean	.63	.263
		Variance	.554	
		Std. Deviation	.744	
		Minimum	0	
		Maximum	2	
		Range	2	
	BrainPort	Mean	1.88	.441
		Variance	1.554	
		Std. Deviation	1.246	
		Minimum	0	
		Maximum	4	
		Range	4	
	Combined	Mean	.13	.125
		Variance	.125	
		Std. Deviation	.354	
		Minimum	0	
		Maximum	1	
		Range	1	

**Table H8.** Mean and standard deviations for number of crosswalk veers across conditions at Session One.

		Descriptives		
	Condition		Statistic	Std. Error
Crosswalk Veers	Cane	Mean	.63	.183
		Variance	.268	
		Std. Deviation	.518	
		Minimum	0	
		Maximum	1	
		Range	1	
	BrainPort	Mean	.88	.125
		Variance	.125	
		Std. Deviation	.354	
		Minimum	0	
		Maximum	1	
		Range	1	
	Combined	Mean	.38	.183
		Variance	.268	
		Std. Deviation	.518	
		Minimum	0	
		Maximum	1	
		Range	1	

**Table H9.** Mean and standard deviations for number of crosswalk veers across travel conditions at Session Four.

		Descriptives		
	Condition		Statistic	Std. Error
Crosswalk Veers 2	Cane	Mean	.63	.183
		Variance	.268	
		Std. Deviation	.518	
		Minimum	0	
		Maximum	1	
		Range	1	
	BrainPort	Mean	.13	.125
		Variance	.125	
		Std. Deviation	.354	
		Minimum	0	
		Maximum	1	
		Range	1	
	Combined	Mean	.63	.183
		Variance	.268	
		Std. Deviation	.518	
		Minimum	0	
		Maximum	1	
		Range	1	

## APPENDIX I

### CROSSTAB ANALYSIS OF CONDITIONS AND VARIABLES

#### I.1 CROSSTAB SUMMARY OF PERFORMANCE BY ONSET OF VISION LOSS

		Onset		Total
		Birth	Later	
Total	Improvement	2	6	8
Contacts	No Improvement	10	6	16
Total		12	12	24

## BIBLIOGRAPHY

- Bach-y-Rita, P., Tyler, M. E., & Kaczmarek, K. A. (2003). Seeing with the brain. *International Journal of Human Computer Interaction*, 15(2), 285-295.
- Baldwin, D. (2003). Wayfinding technology: A road map to the future. *Journal of Visual Impairment and Blindness*, 97, 612-620.
- Bologna, G., Deville, B., Gomez, J. D., & Pun, T. (2011). Toward local and global perception. *Neurocomputing*, 74(8), 1182-1190.
- Chebat, D. R., Schneider, F. C., Kupers, R., & Ptito, M. (2011). Navigation with a sensory substitution device in congenitally blind individuals. *NeuroReport*, 22, 342-347.
- Corn, A. L. & Erin, J. N. (2010). *Foundations of Low Vision: 2nd Ed.* New York NY: AFB Press.
- Friberg, T. R., Nau, A. C., Pintar, C., Fisher, C. N., & Chen, W. S. (2011, May). "Seeing" with your tongue: Sensory substitution using a simple alternative to the retinal chip. Paper presented at meeting of the Association for Research in Vision and Ophthalmology, Fort Lauderdale, FL.
- Gravetter, F. J. & Wallnau, L.B. (2007). *Statistics for the Behavioral Sciences: 7<sup>th</sup> Ed.* Belmont CA: Thomson Wadsworth.
- Havik, E. M., Steyvers, F. J. J., Velde, H. V., Pinkster, J. C., & Kooijman, A. C. (2010). Design and evaluation of a protocol to assess electronic travel aids for people who are visually impaired. *Journal of Visual Impairment and Blindness*, 104(2), 84-94.
- Hill, E. W. & Ponder, P. (1976). *Orientation and Mobility Techniques.* New York NY: AFB Press.
- Hill, E. W. & Rieser, J. J. (1993). How persons with visual impairments explore novel spaces: Strategies of good and poor performers. *Journal of Visual Impairment & Blindness*, 87(8): 295-302.

- Kay, L. (1974). A sonar aid to enhance spatial perception of the blind: Engineering design and evaluation. *Radio and Electronic Engineer*, 44(11), 605-627.
- Kitchin, R. M., Blades, M., & Golledge, R. G. (1997). Understanding spatial concepts at the geographic scale without the use of vision. *Progress in Human Geography*, 21(2) 225-242.
- LaGrow, S. J., Ponchillia, P. E., Ihrke, E., Sullins, C. D., Owiti, S. A., & Lewis, L. (2009). User perceptions of accessible GPS as a wayfinding tool. *AER Journal: Research and Practice in Visual Impairment and Blindness*, 2(3), 9-26.
- Lenay, C. Gapenne, O., Hanne-ton, S. , Marque, C. & Genouelle, C. (2003). Sensory substitution: Limits and perspectives. *Universite de Technologie de Compeigne Groupe Suppleance Perceptive*. 8/29/2003.
- Lozano, C. A., Kaczmarek, K. A., & Santello, M. (2009). Electrotactile stimulation on the tongue: Intensity, perception, discrimination, and cross-modality estimation. *Somatosensory and Motor Research*, 26(2-3), 50-63.
- National Research Council. (1986). Electronic travel aids: New directions for research. Washington D.C.: National Academy Press.
- Nau, A., & Fu, V. (2011). Clinical investigation plan: Sensory substitution for enhanced wayfinding in blinded veterans. Louis J. Fox Center for Vision Restoration/UPMC Eye Center.
- Nau, A. C., Pintar, C., Fisher, C., Jeong, J. H., & Jeong, K. (2014). A Standardized Obstacle Course for Assessment of Visual Function in Ultra Low Vision and Artificial Vision. *JoVE (Journal of Visualized Experiments)*, (84), e51205-e51205.
- Penrod, W., Bauder, D. K., Simmons, T., Brostek, D., & Matheson, L. (2010). A comparison of secondary electronic travel aids. *Internation Journal of Orientation and Moblity*, 3, 55-65.
- Ponchillia, P. E., MacKenzie, N., Long, R. G., Denton-Smith, P., Hicks, T. L., & Miley, P. (2007). Finding a target with an Accessible Global Positioning System. *Journal of Visual Impairment & Blindness*, 101(8), 479-489.
- Ponchillia, P. E., Rak, E. C., Freeland, A. L., & LaGrow, S. J. (2007). Accessible GPS: Reorientation and target location among users with visual impairments. *Journal of Visual Impairment & Blindness*, 101(7), 389-402.
- Renier, L. & De Volder, A. G. (2010). Vision substitution and depth perception: Early blind subjects experience visual perspective through their ears. *Disability and Rehabilitation: Assistive Technology*, 5(3), 175-183.

- Russell, L. (1966). Travel pathsounder and evaluation. In R. Dufton (Ed.), *Proceedings on the Conference on the Evaluation of Sensory Devices for the Blind* (pp. 293-297). London: St. Dunstan's.
- Siegle, J. H. & Warren, W. H. (2010). Distal attribution and distance perception in sensory substitution. *Perception*, 39, 208-223.
- Strumillo, P. (2010). Electronic interfaces aiding the visually impaired in environmental access, mobility and navigation. 3<sup>rd</sup> Conference on Human Systems Interactions. Rzeszow, Poland. May 13-15.
- Ward, J. & Meijer, P. (2010). Visual experiences in the blind induced by an auditory sensory substitution device. *Consciousness and Cognition*, 19, 492-500.
- Wicab, Inc. (2013). BrainPort V100. Retrieved from [http://www.wicab.com/en\\_us/v100.html](http://www.wicab.com/en_us/v100.html)
- Wiener, W. R., Welsh, R. L., & Blasch, B. B. (2010). *Foundations of Orientation and Mobility: 3rd Ed.* (Vols. 1-2). New York NY: AFB Press.
- Williams, M. D., Ray, C. T., Griffith, J. De l'Aune, W. (2011). The use of a tactile-vision sensory substitution system as an augmentative tool for individuals with visual impairments. *Journal of Visual Impairment and Blindness*, 104(1), 594-599.
- World Health Organization. (2010). Global data on visual impairments 2010. Retrieved from <http://www.who.int/blindness/GLOBALDATAFINALforweb.pdf>
- Zelek, J. S., Bromley, S., Asmar, D. & Thompson, D. (2003). A Haptic Glove as a Tactile Vision Sensory Substitution for Wayfinding. *Journal of Visual Impairment and Blindness*, 97 (10), 621-632.