Comparing Performance of Monohaptic and Bihaptic Vibrational Feedback Spatial Devices in a Blindfolded Pathfinding Maze Study

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Abstract

Abstract: Assistive depth perception devices for blind people are currently on the market but are not as widespread as white canes have only at best, basic depth perception. This study proposes a solution to improve depth perception by use of two depth sensing haptic feedback devices in tandem (bihpatic conditions(BC)) and compare its performance in maze navigation to the use of one such device (monohaptic conditions(MC). 42 adult sighted participants (n=42) took part in a study to test performance of Bihaptic conditions(BC) vs Monohaptic conditions(MC) in a blindfolded maze navigation study. Participants were scored on the Time to Complete(TTC) the maze and the Number of Collisions(NOC) made with 8 cardboard obstacles. BC was found to have significantly less NOC than MC($p=0.03$). MC had lower TTC than BC but was not significant($p=0.198$).In conclusion BC was better than MC for detection of obstacles in a blindfolded maze without significantly affecting TTC.

Keywords: Bihaptic; Monohaptic; blind; visually impaired; maze; navigation; ultrasensor; vibration; haptic; feedback.

1. Introduction

This section discusses motivations and aims of this paper, then defines various terms that will be used throughout the paper.

1.1 Motivation and aims of this paper

Vision conveys a huge amount of information to humans. Those with visual impairments from birth or those who have lost their sight later in life face great challenges which affect their everyday life. Society can address these issues on many levels by making public spaces, homes and technology more accessible for those affected. In addition there are many assistive devices, apps and technical aids for the visually impaired which are constantly being developed to help those with visual impairments. Two common, commercially available aids are the white cane and guide dogs(Kilian, Neugebauer, Scherffig & Wahl, 2022). Guide dogs are however not widespread (1% of blind people in the USA, 2008) (Roentgen, Gelderblom, Soede, & De Witte, 2008). Although the white cane is extremely useful once mastered, it has the drawback of having a limited range of 1 meter and cannot identify protruding, above ground objects such as tree branches. Even with users of both a white cane and guide dog, 40% report head injuries at least once a year and as a result 34% only leave their normal routes only once or several times a month while 6% never do (Manduchi & Kurniawan, 2011).
A device that could detect, at a distance, both ground level and above ground objects would therefore be incredibly useful. There are currently many assistive devices for the visually impaired on the market such as the brainport, unfolding space glove, iSonic cane or the C-5 Laser Cane. These devices have sensors, such as a camera, ultrasonic sensor or infrared sensor, which give the user information about their surroundings through stimuli such as electrical current, vibrational, auditory feedback. The problem with most of these devices is that they only offer very basic depth perception. One reason for this lack of depth perception may be due to these devices having one sensor and one feedback stimulus, as humans use mainly binocular vision to perceive depth.
This paper seeks to investigate human depth perception and visual aid devices in order to understand limits and pitfalls of current technology. With this knowledge it is the hope to design a new device that will improve on some of the shortfalls of these devices. It is proposed that using two such assistive devices at

the same time may be one solution to improve depth perception. Depth perception would be incredibly beneficial to obtaining information about the users environment as well one of the most important aspects of day to day life, navigation of the users surroundings.
The challenges that blind people face everyday plus the danger to their safety give us much incentive to develop technology to help with these issues. Any device that could improve on the current technology to give a basic spatial-visual perception of their surroundings would, I believe, improve their quality of life in a significant way. Therefore, the main goal of this paper is to investigate whether the use of two assistive depth sensing devices would increase the performance of users in depth perception tests, relative to using one such device. None of the lists included in this report of devices, technology, methods or technical details are exhaustive and are intended as a partial overview of past and recent technology.

In this paper we begin with a background exploring robotic/animal perception, depth sensing devices and their testing, with examples. We then discuss a Pilot study of vibration perception on the back of the hand. After this, methods and materials of the main study of blindfolded maze navigation with Bihaptic/Monohaptic devices are discussed, followed by results of the main study. Results from the main study are then analyzed in the discussion section, followed by a conclusion of the findings from the main study. Acknowledgements, References and Appendix sections are also included at the end of this paper.

1.2 Terms

Sensory substitution will be defined, in this report, as a perception of a stimulus through another sense that is not the usual sense that is used for that stimulus. For example, using sound to perceive if a room is big or small by the echo it produces or determining an object's shape through touch, of which both are typically visually perceived. By this definition, even beginners can achieve sensory substitution.

Brain plasticity will be defined, in this report, as the brain's ability to adapt by forming new neurons, potentially strengthening the link between separate areas of the brain to allow for increased performance in a task which utilizes multiple brain regions. In regards to brain plasticity and sensory substitution, training over many weeks or months may allow the brain to adapt to allow the user to be more effective at using sensory substitution for its intended effect.

DV glove will be defined, in this report, as a distance/ spatial-sensing, vibrational-feedback glove. The DV glove has only 1 input (ultrasensor) and one output (microvibrator).

Monohaptic will be defined, in this report, as a condition where a participant has only 1 DV glove worn on the dominant hand. Due to the DV glove only having one sensor and 1 feedback stimulus then this is considered to be monohaptic as the participant feels only 1 haptic feedback stimulus which is representing the distance sensed by the ultrasensor. This is similar to monocular perception where a person uses 1 eye to perceive something.

Bihaptic will be defined, in this report, as a condition where the participant wears 2 DV gloves, one on each hand. This is considered bihaptic as the participant is feeling and perceiving two stimuli which are independent of each other and happening at the same time. Each stimulus is also representing a different distance sensor input worn on a different hand. This is similar to binocular perception where a person uses 2 eyes to perceive something.

2. Background

In this section the background behind both animal and robotic perception and depth perception will be explored as well as related works of existing devices which assist depth perception as to give a solid foundation for this research.

2.1 Human depth perception

In this section human visual depth perceptual will be discussed. Human vision has many cues for gauging depth perception using both eyes(binocular) or one eye(monocular). Firstly two binocular cues will be discussed as they are the most dominant and sensitive cues, followed by eight monocular cues.

2.1.1 Binocular Cues

One of the two main binocular cues is convergence. This occurs when we observe a near object, our eyes point inward and is mainly used for objects <10 m. The second cue is binocular parallax, where the images sensed by the left and right eye are different. Human visual system is very sensitive to these differences, making binocular parallax the most important depth cue for medium distances(Teittinen, 1993). Our ability to make use of subtle differences between the images received by each eye allows us to perceive stereoscopic depth, which is important for visual perception of three-dimensional space. Binocular neurons in the visual cortex combine signals from both eyes and studying their role in different perceptual tasks has advanced our understanding of stages within the visual cortex that lead to binocular depth perception*(Parker, 2007)*.

2.1.2 Monocular Cues

The eight monocular cues for depth perception include: accommodation (focal length of the eye lens changes with distance), movement parallax (differences in images right after each other with one eye), retinal image size (real size of an object compared to viewed size), linear perspective (straight roads converging on the horizon), texture gradient (smoother textures from farther away), overlapping (closer object blocking farther one), aerial perspective (haziness of distant landmarks), and shades and shadows (location of a light source and shadows cast)*(Teittinen, 1993).*

2.2 Non-human depth perception

Now that human depth perception has been covered, this paper will now cover non-human depth perception, then investigate how robots use depth sensors. Combining this with human depth perception, this will give a good overview of depth perception across species and technology.

2.2.3 Animal/ Biological depth perception

In this section we will compare human & animal depth perception, identify visual performance & explore non-visual strategies animals use to perceive depth which give animals advantage in non-optimal conditions, like low light conditions.

2.2.3.1 Binocular vision in animals

Binocular parallax cues are the most dominant in telling whether an animal has good visual depth perception. Animals with eyes far apart, such as owls, have excellent depth perception compared to most birds which have eyes close together and thus have poor depth perception.

2.2.3.2 Sonar/ Echolocation

Bats have good depth perception as they use sonar to accurately fly around obstacles (Corcoran & Conner, 2014). Dolphins use echolocation and ultrasonic hearing to navigate dark waters(Jones, 2005).

2.2.3.3 Heat Vision

Pit vipers have heat-sensing pits under each eye, giving them binocular heat vision. This, combined with their poor eyes lacking a fovea, enables them to locate moving prey(Goris, 2011).

2.2.3.4 Electrolocation

Sharks passively sense weak electric fields given off by nerve and muscle tissues, allowing them a unique depth perception in dark conditions. Certain weakly electric fish actively electrolocate by sending out electric fields to detect distortions when it returns (Von der Emde, 1999), similar to sonar.

2.2.4 Robotic depth perception

Thus far we've looked at animal depth perception. Now we'll examine how robots sense depth and use it to perceive their environment.

2.2.4.1 Lidar, Radar, Sonar

Robots use lidar, sonar, and radar to detect the environment, emitting light, sound, or radio waves and measuring the reflected wave. Sonar is commonly used underwater and uses echoes of sound to discern properties about the environment such as distance to the ocean floor. Lidar and radar both use electromagnetic radiation. Radar is used to detect aircraft, cars, and snowstorms. Lidar aids geologists in land surveying, cars in assisted parking, and iphones in improving photos(*Luetzenburg, Kroon & Bjørk, 2021).* Lidar technology which can monitor environments and objects at 100-1500m, operating at 1550 um *(Deems, Painter & Finnegan, 2013).* Human eyes absorb wavelengths above 1400 um, so Lidar's 1550nm is safe. 905 um Lidar is harmful, so technology adjusts the emitted pulse energy to make it safe. Current Lidar on the market is Class 1 eye-safe (IEC 60825-1:2014)*(Kutila et al.,2018).* Lidar was used from an iphone that allowed a geological survey of an area in great detail. The iPhone 12 uses high powered lidar with pulse technology, making it safe and providing superior resolution and depth perception*(Luetzenburg, Kroon & Bjørk, 2021)*. Replacing the standard camera of a brainport device with the sensors of an iPhone 12 would presumably increase users' perception of their environment and greatly improve depth perception.

2.2.4.2 Infrared stereo

Lidar uses visible/ultraviolet light, but infrared devices use infrared light (longer wavelength,invisible and can be felt as heat). Walking robots use Kinect v2 to perceive depth and navigate, which uses an infrared camera and time of flight. Stereo Cameras often accompany infrared cameras for depth perception. Infrared cameras also enable night vision and seeing through smoke, dust and fog. (Fankhauser et al., 2015).

2.2.4.3 Triangulation

Robots use triangulation between two cameras to detect depth, similar to animals' binocular parallax perception. Stereo triangulation uses differences in the spatial domain and has poor performance in homogeneous environments. Time coded structured light triangulation uses changing illumination and algorithms to calculate depth of each pixel. Spacetime triangulation combines spatial (stereo) and temporal (structured light) techniques, no longer needing special lighting and improving resolution in homogenous scenes.*(Davis, Ramamoorthi & Rusinkiewicz, 2003).*

2.3 Augmented human perception

Thus far we have discussed animal and robot depth perception. This section covers augmented human perception, including click echolocation, sensory substitution, the brain's plasticity, and tactile devices and finally listing examples of technology used to extend human senses beyond natural parameters.

2.3.1 Sensory Substitution

People who are blind usually still have the capacity to see. They lose their peripheral sensory system(the retina) but the central visual mechanisms still remain intact. The same is for deaf people who lose the function of the peripheral structures(the cochlea or vestibular apparatus). Inputs from the sensory substitution system can reach brain parts related to lost sensory modality. Kilian, Neugebauer, Scherffig & Wahl have suggested 14 prerequisites for a sensory substitution (SSD) device for a target group, which are as follows; learning, training, latency, dissemination, cognitive load, orientation of the sensor, spatial depth, contrast, resolution, costs, motor potential, preservation of sensory and motor habits, user experience and joy of use, and aesthetic appearance(Kilian, Neugebauer, Scherffig & Wahl, 2022). Sensory substitution devices typically have 3 parts: input (sensor, e.g. camera), processor (computer/brain) and output (interface, usually touch but could be auditory, etc.).

2.3.1.1 Brain plasticity

Brain plasticity can be defined as ‘adaptive capacities of the central nervous system, its ability to modify its own structural organization/functioning’, making sensory substitution possible(*Bach-y-Rita & Kercel, 2003).*

2.3.1.2 Braille

Braille is the most successful sensory substitution system to date, allowing information usually acquired visually to be acquired through the sense of touch(*Bach-y-Rita & Kercel, 2003).*

2.3.1.3 Click Echolocation

A study investigated the effects of blindness and age on learning click echolocation. Participants trained 20 2-3 hour sessions over 10 weeks. Both sighted and blind groups became almost experts, with 83% reporting increased independence and well being. The training focused on determining size and angles of objects and maze navigation.(Norman, Dodsworth, Foresteire & Thaler, 2021). Daniel Kish, a blind echolocation user, gave a talk on TED. He said “ My brain is activated and I have visual cortex images from using echolocation” (Kish, 2015). According to Daniel, this means that he experiences visual images in his mind of his environment when he uses click echolocation.

2.3.1.4 Future development of sensory substitution

Development of sensory substitution devices should aim for accessibility to patients with sensory loss, expand human senses and be used to study brain plasticity non-invasively(Bach-y-Rita & Kercel, 2003).

2.3.2 Tactile devices and perception

Previous sections discussed perception with a focus on depth perception. Sensory substitution devices take an input (sensor) to observe and perceive the environment, with an output typically being the sense of touch. This section will cover tactile interface and user perception limits.

2.3.2.1 Tactile interfaces

The human haptic sense is composed of two submodalities, kinesthetic (force, motion) and tactile (texture, roughness, temp., shape). Tactile technology apps are used in teleoperation, sensory substitution, 3D surfaces, Braille systems and games. The most used technology is electromagnetic actuation due to its portability. SMA wire technology is widely used but suffers from poor performance. Piezoelectricity is used for commercial apps such as Braille systems due to high bandwidth and forces. MEMS, ER fluid and Polymers are interesting to study groups but not widely used yet. None of the devices discussed have a fusion of necessary parameters to reproduce textures (temperature, vibration, pressure). Suggested requirements and parameters to reproduce tactile feelings: 1mm distance between two micro-actuators; 300 Hz bandwidth for each actuator; 0.5MPa pressure threshold; a mechanical actuator coupled with a thermal actuator; 10°C-45°C temperature interval(*Benali-Khoudja et al., 2004).*

2.3.2.2 Tactons

Tactons are structured tactile messages used to communicate non-visually, using touch instead of vision (Icons) or hearing (Earcons). They have parameters such as frequency, amplitude, waveform and duration of a tactile pulse, plus body location, and are useful for blind people and on mobile and wearable devices*(Chouvardas, Miliou, & Hatalis, 2008).*

2.3.2.3 Tactile Displays

Tactation is the sense of touch. Skin has seven classes of mechanoreceptors, four of nociceptors, two of thermoreceptors & three of proprioceptors. It has lower information capacity than other human sensors but faster temporal acuity (5ms vs. eye's 25ms). Tactation has four modalities: vibration (detected by Pacinian corpuscles, optimal around 250hz); pressure/stroking; skin stretch, & texture/light stroking/fluttering. Tactile devices use static pressure/vibration, electrical stimulation & thermal flow. Other technologies that stimulate skin receptors are ultrasound & surface acoustic waves*(Chouvardas, Miliou, & Hatalis, 2008).*

Hapticons are haptic icons that communicate info via vibration patterns, e.g. on the fingers, back, thigh, and abdomen. Subjects trained on the back can recognise the same patterns on the thigh/abdomen(Craig & Sherrick, 1982). Haptics is to feel virtual environments, with three main parts: collision detection algorithms, force response algorithms (determines force) and control algorithms(returns a force). These technologies are constantly improving portability, function and costs. (Kenneth, Francois & Federico, 2004).

2.3.2.3 Human tactile perception

In this section the various parameters of human perception will be discussed in regards to tactile interfaces frequency, amplitude, waveform and body location. These parameters are important when designing how and where the interface will interact with the user's skin. The frequency range of human skin perception of vibrations is 20-1000Hz, max sensitivity at 250Hz, max 9 levels should be used. Amplitude should not exceed 28 dB, max 4 levels. Waveform & body location impact perception(Gill, 2003). Stimuli lasting less than 0.1 s were perceived as taps or jabs whereas stimuli of longer duration were perceived as smoothly flowing tactile phrases. The tempo/ rhythm can also change. Furthermore there is the parameter of Waveform. Users can differentiate sine waves and square waves but more subtle differences are difficult. This limits the number of different values that can be encoded(Gunther, 2001). Body location for tactile devices affect sensitivity, spatial acuity and drawing patterns (*Brewster & Brown, 2004).* Touch can be split into Kinaesthetic (muscles/joints) and Cutaneous (mechanoreceptors/skin) perception. Braille is kinaesthetic & Tadoma is cutaneous, by placing the hand on another's face to feel vibrations of speech, they can understand words and even accents at high speeds. Point interaction models, such as exploring a virtual world with a stick, is taxing on short term memory. Without cutaneous feedback, like wearing thick gloves, edge detection is harder*(Chouvardas, Miliou, & Hatalis, 2008).*

2.3.3 Augmented human perception devices

In this section we will discuss various augmented human perception and sensory substitution devices, as well as studies & experiences of self-identified cyborgs.

2.3.3.1 Brainport

The Brainport is a portable/wearable device allowing blind people to feel simple shapes/letters. It uses a tongue display array connected to a camera or balance sensor. It provides good resolution due to the sensitivity of the tongue. (Grant et al., 2016). The brainport was found to be comparable to those with native ultra-low vision in their performance of three basic household tasks, showing the Brainport can quickly determine an object's resolution. (Adeyemo, Geruschat, & Dagnelie, 2017).

2.3.3.2 Brainport balance device

Bach-y-Rita designed a tactile display for the skin, then the tongue display, later modified by Mitch Tyler to represent balance, resulting in the brainport balance device, which gave patient Cheryl Schiltz remarkable improvement in balance. Remarkably the effects lasted up to 4 months after removing the device. (Fisher, 2007). A group of children with balance disorders trained with the Brainport balance device. 29% reported improvements & some reported new activities, such as riding a bike. (Harbourne, Corr, Arpin, & Kurz, 2022).

2.3.3.3 Unfolding Space Glove

A study using the Unfolding Space Glove (depth sensing Time-of-Flight camera & 3x3 vibrating array) was carried out. Blind/blindfolded people were trained for 6 hrs, successfully navigating obstacle courses, though not as fast as with a cane. The camera was worn on the back of the hand, allowing users to "see" with their hand. (Kilian, Neugebauer, Scherffig & Wahl, 2022).

2.3.3.4 Kevin Warwick and the ultraviolet nervous system sensor

Kevin Warwick, a researching scientist, conducted a study with a microelectrode array (MEA) implanted in his arm, connected to his nervous system which received signals from an ultrasonic depth sensor worn on the forehead, stimulating Warwick's nervous system directly, not through another sense. He reported this as feeling a new sense*(Warwick, Gasson, Hutt & Goodhew, 2005).* In another study, a volunteer had an electrode implanted in their arm and used it to control an electric wheelchair to navigate a maze in another country. No issues arose but the device was removed due to wire degradation. (Warwick et al., 2003).

2.3.3.5 Niel Harbinson and the cochlear color sensor

Niel Harbinson is in the Guinness Book of Records as world's first cyborg artist, claiming he can hear shades via a surgically-implanted sensor which vibrates his skull depending on hue/shade of color. The British Government has recognised him as a cyborg.*(Yasenchak, 2013).*

2.3.3.6 Peter Meijers and The vOICe

In 1992, Dutch engineer Peter Meijers created "The vOICe", which converts visuals to sound. After months of use, two blind participants reported "perceived visual effects", suggesting synesthesia(Ward & Meijer, 2010).

2.3.3.7 David eagleman and The VEST

The VEST (Versatile Extra-Sensory Transducer), designed by David Eagleman, has 32 vibrating motors to convey any input such as auditory, visual and even stock market info.(Novich & Eagleman, 2015).

2.3.3.8 Feelspace Belt

9 blind and 2 deaf-blind participants wore the feelspace belt for 7 and 3-4 weeks respectively. It contained a compass that vibrated true north, extending humans' perceptual capabilities to help with navigation. Results showed participants improved navigation and orientation, especially in unfamiliar areas, and corrected errors of estimating turning degrees and walking around a bend.(Brandebusemeyer, 2020).

2.3.3.9 Assistive sticks for the visually impaired

Assistive sticks for the blind are available on the market, ranging from landmarking with near-infrared light/ radio, to object detecting ultrasonic devices such as K sonar, Ultra cane, Miniguide, Palmsonar and iSonic cane. Laser devices like Teletact and the C-5 Laser Cane can also assist with detecting objects and are lighter, cheaper and consume less power than ultrasonic versions. (*Nada, Fakhr & Seddik, 2015).*

2.3.3.10 **Table A.** Augmented perception devices and techniques for humans.

Name	Input/ Sensor	Output/ user senses	Monohaptic/Bihaptic	Benefits	Deficits	Reference
Click Echolocation	*Visual,clicking noise*	*Auditory/ echos*	*Bihaptic*	*No required equipment*	*Basic depth perception*	*(Norman, Dodsworth, Foresteire & Thaler, 2021).*
Braille	*Visual/ fingers*	*Tactile touch*	*Bihaptic*	*Most successful sensory substitution*	*Technology is expensive*	*(Bach-y-Rita & Kercel, 2003).*
VEST	*Anything*	*32 vibrating motor display, torso*	*Monohaptic/ Bihaptic*	*Programmable for any input and good resolution*	*Inputs need to be programmed*	*(Novich & Eagleman, 2015).*
Brainport	*Visual/ camera*	*Tongue display/ current*	*Monohaptic*	*High resolution, basic depth perception*	*Basic depth perception, tongue display restricts mouth*	*(Adeyemo, Geruschat, & Dagnelie, 2017).*
Brainport balance	*Gravity/ balance sensor*	*Tongue display/ current*	*Monohaptic*	*Fantastic results with 4 month carry on effect*	*Tongue display restricts mouth*	*(Fisher, 2007).*
Feelspace belt	*Magnetic North/ compass*	*Tactile/ Belt vibration*	*Monohaptic*	*Moderately helps navigating*	*Not so useful familiar areas*	*(Brandebusemeyer, 2020).*
Unfolding Space Glove	*Visual/ Depth sensor camera*	*Tactile/ vibrating display back of hand*	*Monohaptic*	*Successfully navigate obstacles*	*Poor resolution,not as fast as with a cane*	*(Kilian, Neugebauer, Scherffig & Wahl, 2022).*
Ultrasonic nervous system	*Visual/ Ultrasonic Depth Sensor*	*Direct via nervous system*	*Monohaptic*	*Fast acting and feels like a new sense*	*Degradation of parts and long time to learn*	*(Warwick et al., 2003).*

Voice	*Visual 2d images*	*Auditory/ Sounds*	*Monohaptic*	*Caused a form of synesthesia in 2 blind users*	*More of an artistic device than functional*	*(Ward & Meijer, 2010).*
Cochlear color sensor	*Visual/ Color sensor*	*Auditory, cochlear implant*	*Monohaptic*	*Niel Harbinson claims to see color with this device*	*A study of N=self and so not conclusive for future users*	*(Yasenchak, 2013).*
Assistive sticks for the visually impaired	*Visual/ laser,infrared,ultrasonic, camera*	*Sound, buzzing ,earpiece with voice*	*Monohaptic*	*Sticks are very useful and extra sensors improve depth perception*	*Some devices are expensive*	(*Nada, Fakhr & Seddik, 2015).*

2.3.3.11 **Table B**. Sensors and their capabilities.

Sensor	**Approximate wavelength detection**	**Notes**	**Reference**
Human Eyes	400 -700 nm	Visible light spectrum. Human eyes are most sensitive to 555 nm, the green region.	*(Mahmoud, Hexsel, Hamzavi, & Lim, 2008)*
Camera	400 - 1000 nm	A low cost, standard CCD or CMOS camera. Most sensitive around 555 nm, green region.	(Jerram et al., 2010)
Underwater Sonar	≈1.5 cm	Used by the navy for geo mapping underwater areas and locating wrecks.	(Hansen, Callow, Sabo & Synnes, 2011)
Sonar/ Ultrasonic	≈1.5 cm	Emits pulses at 10us	(Gbenga, Shani & Adekunle, (2017)
Lidar	905 or 1550 nm	1550 nm is safe and 905nm employs techniques to render it safe to human eyes.	*(Kutila et al.,2018)*
Radar	≈1 cm	Good in all weather but has lower resolution than Lidar	*(Kutila et al.,2018)*
Active Infrared	0.7 to 300 µm	Sends out infrared radiation and measures reflected signal and its time of Flight(similar to sonar)	(Abidin & Ahuja, 2016)
Passive Infrared	0.7 to 300 µm	Passively detects infrared radiation emitted by warm objects such as human body heat which is in the 8 -14 µm range.	(Moghavvemi & Seng, 2004)

2.4 Augmented human depth perception

Previously we have discussed human, animal and robot depth perception and human augmented perception. Now in this section we combine both topics to investigate augmented human depth perception such as Kevin Warwick's ultraviolet nervous system depth sensor, the Unfolding Space Glove and the brainport.

2.4.1 Ultrasonic depth perception direct via nervous system

Kevin Warwick had an electrode array connected to his median nerve fibers. After 6 weeks training he could recognise new signals. 6 minutes after combining it with an ultrasonic sensor he could detect an object's distance.He felt it as a new sense and when something approached him quickly he got scared. Due to noise/movement of the device, it was later removed(Warwick, Gasson, Hutt & Goodhew, 2005).

2.4.2 Unfolding Space Glove

The Unfolding Space Glove uses a depth sensing “Pico Flexx” Time of Flight (ToF) camera to send signals to a 3x3 vibrating motor array worn on the back of the hand. Both blind and blindfolded users who trained for 6 hrs could complete obstacle courses (albeit slower than with a cane). The camera was worn on the back of the hand, pointing forward, as if "seeing" with their hand.(Kilian, Neugebauer, Scherffig & Wahl, 2022).

2.4.3 Brainport depth perception

A study using the brainport measured artificial depth perception, with moderate success for simple tasks such as telling the distance of boxes within 1.75 foot error. Results showed the device gave a crude form of depth perception(Arnoldussen et al., 2012).

2.4.4 Possible Extra Senses

Sensory substitution devices are not limited to replacing lost senses and can receive input beyond human senses, like Lidar, Compass, Infrared, Night Vision and Zoom.

2.5 Assessing depth perception

So far we have discussed design parameters of depth perception devices and studies/experiences of such devices. Here we will discuss how depth perception devices performance is tested. The uses of Visual Aids can be separated into 3 categories which are Information gathering (what is written there?), interfacing (using objects and machines) and navigation (wayfinding, walking)(Kilian, Neugebauer, Scherffig & Wahl, 2022).

2.5.1 Information gathering

Keven Warwick tested depth perception by having a paper move quickly towards his head, showing he could estimate the object's distance & speed (Warwick, Gasson, Hutt & Goodhew, 2005). Click echolocation was used to retrieve info on size & orientation of distant objects(Norman, Dodsworth, Foresteire & Thaler, 2021). The Brainport device to estimate distance & orientation of boxes in a room (Arnoldussen et al., 2012).

2.5.2 Interfacing with objects task

Participants in a study used the Brainport device in an interfacing/object manipulation task to move two cylinders closer together on a table with moderate success(Arnoldussen et al., 2012).

2.5.3 Navigating

The Unfolding Space Glove was designed, created and used in a navigation study to test the device, participants walked a 7m maze with 8 obstacles(tall and thin cardboard boxes). They successfully navigated the maze, though not as quickly as with a cane.(Kilian, Neugebauer, Scherffig & Wahl, 2022). In a similar maze navigation study, participants successfully completed a maze via echolocation and by the end of the study were as good as experts.(Norman, Dodsworth, Foresteire & Thaler, 2021).

2.6. Project sensor/input, mapping and output/stimulus

In this section, various sensors, mappings and stimuli will be investigated to assess which would be most suitable to be integrated into the depth perception device needed for this study.

2.6.1 Input/sensors

Depth perception devices receive input from sensors such as ultrasonic sensors, infrared sensors, video cameras and Lidar which will be discussed here.

2.6.1.1 Ultrasonic sensors

An ultrasonic sensor (e.g. HC-SR04) consists of a transmitter and receiver, emitting ultrasonic sound and measuring time of flight between transmitter and receiver(2-400 cm range). Ultrasonic sensors have low latency, are inexpensive, quite reliable and work well in many environments. However they don't work well on small objects against large backgrounds and materials that absorb sound waves(Morgan, 2014).

2.6.1.2 Infrared sensors

Infrared sensors are lightweight, cheap, low power, fast response, accurate, detect many surfaces & detect objects up to 200 cm, such as In one study on an infrared sensor-based smart stick(*Nada, Fakhr & Seddik,2015).* Infrared sensors are however affected by light and are less reliable than ultrasonic sensors.

2.6.1.3 Video Cameras

Video cameras can detect the human visual spectrum, producing 2D images which can be used with a display to interpret visual data. This method lacks depth cues, instead stimuli represents brightness, enabling edge detection, giving users basic depth perception(Adeyemo, Geruschat, & Dagnelie, 2017).
The "Pico Flexx" Time-of-Flight (ToF) camera, used in the Unfolding Space Glove study, detects distances with sound waves so outperforms normal cameras. The downsides are its high cost (~300 euro) and with a range of 0.1-4 meters cannot detect objects <10cm . (Kilian, Neugebauer, Scherffig & Wahl, 2022).

2.6.1.4 Lidar

Lidar is safe for eyes when used with certain technology, like the iPhone 12's. It can range 1-1000 m, providing great temporal & spatial resolution, but struggles with some materials at close range (e.g. brass)(Luetzenburg, Kroon & Bjørk, 2021). Lidar is expensive yet fairly accessible through modern phones.

2.6.2 Mapping

Various examples of how input from sensors is translated into stimuli for users is discussed here.

2.6.2.1 Unfolding Space Glove- Vibration mapping

The Unfolding Space Glove is a haptic, vibratory feedback, visual spatial device with a ToF camera and uses a raspberry pi 4. It splits the camera input into 9 sections/tiles, each represented by a histogram of 0-255 distance bins (10cm from camera). If an object > 4 cm is detected, the distance determines the amplitude and vibration strength of the corresponding motor (0-255)(Kilian, Neugebauer, Scherffig & Wahl, 2022).

2.6.2.2 BrainPort V100 Vision Aid - Electrical current mapping

Brainport has 400 non-implanted electrodes in a 20x20 array on the tongue, sending electric currents based on grayscale pixels from a video camera. Currents are 0-0.51mA, voltages 0-1.4V, electrode size 762μm, spaced 558μm apart for safety. Despite no color or depth cues, test participants have demonstrated basic depth perception, made possible due to perceptual cues. *(Stronks, Mitchell, Nau & Barnes, 2016)*

2.6.2.3 Sound mapping

A cane with an ultrasonic sensor was designed to detect and announce stairs going up/down and obstacles in 4 ranges (20 cm, 21-50 cm, 51-100 cm, 101-200 cm) via headphones. (*Nada, Fakhr & Seddik,2015).*

2.6.3 Output/stimulus

The choice of stimuli for depth perception devices is important and the benefits/drawbacks of vibrations, heat, sound, electrical current and linear rollers are discussed here.

2.6.3.1 Vibration

Vibrations can be felt all over the body, are non-invasive, non-harmful, do not heat up to painful temperatures,have low latency, are inexpensive, are quite reliable and durable. Vibration motors, however, consume more power, are more cumbersome, and have larger minimum spacing for detection than current. Range of intensities & pulses/rhythms offer extra output range(Kilian, Neugebauer, Scherffig & Wahl, 2022).

2.6.3.2 Heat

Humans are generally good at detecting safe levels of heat, but it consumes more power than other stimuli(eg. sounds/small currents). A study of Vr gloves with heated/cooled air sacs found they could distinguish 5 levels of temperature between very cold and very warm.(Cai, Ke, Narumi & Zhu, 2020).

2.6.3.3 Sound

Sound is low-energy, inexpensive, with low latency and a large range (20-20,000 Hz) distracts users from other sounds, e.g. warnings of a vehicle reversing. Depth perception devices use voice output with good spatial resolution but at the cost of higher latency and energy consumption.y(*Nada, Fakhr & Seddik, 2015).*

2.6.3.4 Electrical current

Devices such as the brainport demonstrate the usefulness of safe electrical current levels, offering a good spatial resolution and low latency. However, they are more expensive than sound devices, and using their tongue display restricts the participant's use of their mouth. *(Stronks, Mitchell, Nau & Barnes, 2016).*

2.6.3.5 Linear roller

A linear roller uses a motor to roll a wheel along the skin for a wide range of output, but with higher latency than sound/vibration stimuli.

3. Pilot Study

Vibration was proposed to be the stimuli for the depth sensing device required for the main study of this paper, due to its safe use, low latency, large range of outputs and other benefits mentioned in section 2.6.3.1 Since literature on the perception of vibrations on the back of the hand is limited, A Pilot study was carried out to investigate this, using micro vibration motors on the back of the hands of 21 adult participants.

3.1 Abstract

Abstract: A Pilot study was performed to investigate perception of vibrational strength and spatial resolution on the back of the hand using small micro vibration motors on adult 21 participants(*n*=21). 4 Pilot tests were performed with Pilot 1 testing perceptual effects of differences in vibrational strength, Pilot 2 testing perceptual effects of vibrational strength, Pilot 3 testing perceptual effects of duration and Pilot 4 testing the spatial resolution of vibrations. Results showed the probability of getting a correct answer when PWM difference was 7000 compared to 0 was significantly lower ($p=<.001$). The probability of getting a correct answer for PWM differences of 14000 ($p=0.142$) and 21000 ($p=0.458$) compared to 0 were not significantly different. The probability of getting a correct answer when the PWM difference was 28000 compared to 0 was significantly higher($p= 0.019$). The probability of getting a correct answer when the average PWM was at 54500 compared to 37000 was significantly lower($p=0.005$). The probability of getting a correct answer when the average PWM was at 61500 compared to 37000 significantly lower($p=0.029$). The probability of getting a correct answer when the durations of the vibrations were 1 second different, was not significantly ($p=0.638$) different compared to when the durations were the same. There was no significant difference between the probability of getting a correct answer for spatial differences of vibrations of 1cm($p=0.319$), 2cm($p=0.235$) and 3cm($p=0.562$) compared to 0cm. Participants' perception of vibration strength resolution was between 7000 and 14000 PWM. Participants' perception of vibration strength resolution decreased with increased strength. Participants' perception of vibration strength resolution was not affected by differences of 1 second when the duration of vibrations is between 2 and 3 seconds. Participants' perception of vibration spatial resolution was smaller than 1cm.

3.2 Introduction

To design the monohaptic/ bihaptic devices with the proposed vibratory stimulus on the back of the hand, 4 pilot tests were performed, investigating vibratory perception on the back of the hand. For the pilot study, small vibration motors were used that are commonly used in cellphones, with a very small electric current required to run, posing no safety concerns for these tests.

Pilot test 1 investigates whether perception of vibrations is affected by different strengths. The hypothesis is that vibrations of the same strength or big differences will be easy to tell apart but small differences will be difficult to perceive. **Pilot test 2** investigates whether perception of vibrations changes with strength. Same differences between each pair of vibrations were used. The hypothesis that 2 weak vibrations are easier to tell apart than 2 strong ones. **Pilot test 3** investigates whether vibration perception is affected by duration. It tested the hypothesis that 2 vibrations are more distinguishable when they are the same duration, with the same differences in strength. **Pilot test 4** investigates whether perception of vibrations is affected by the distance between two vibrations of the same strength (50000 PWM). The hypothesis is that 2 vibrations will be easy to perceive if in the same location or far apart, but harder when a small distance apart.

3.3 Method

Ethics

Details of this Pilot study were provided to the ethics board through Leiden university and accepted. All participants signed consent forms agreeing to participate in the Pilot study and to have their data and results recorded and used for this paper.

Procedure

Below is a summary of the procedures that are common for the 4 pilot tests. Before every stage the participant is informed about the procedures and asked if they are ready to continue.

Stage 1) Firstly , participants are asked to gently put on the device on their right hand. **Stage 2)** Next they are informed that a small vibration test will be run, at which point the vibration motor is switched on to make sure that the device is working correctly and that the user can perceive its vibrations. **Stage 3)** Then the participants are asked if they are right handed or left handed which is recorded. **Stage 4)** After this they are asked if they are ready to begin 1 of 4 pilot tests. Each Pilot test begins after the participant confirms they are ready and after a brief pause some background instrumental music is played from a speaker to cover the sound of the device's motors. **Stage 5)** The chosen Pilot test(1-4) trial begins. **Stage 6)** The participants are asked about their perception of the two vibrations. In Pilot 1-3, the participants must choose whether the vibration strength were the same or not, in Pilot 4 they must choose whether the vibrations are the same location or not. These answers are then recorded. **Stage 7)** Stages 5-6 are repeated until 30 trials are complete and the answers recorded.

When the Pilot tests begin, each trial of the two vibrations appears after which the participant then says whether they perceived the two vibrations to be the same or different strength. In the case of Pilot test 4 they will be asked whether the vibrations were felt in the same spot on the hand or not. Their answer is then recorded and the next trial is run until 20 trials are complete. The glove is then gently removed by the participant and the music and equipment are turned off, ending the Pilot test.

3.3.1 Pilot 1 Method

Pilot test 1 consists of two 1.5 second vibrations of different strength, separated by a 1.5 second gap of no vibration. The first vibration is of a random strength between 34000 PWM - 64000 PWM with the second vibration having an equal chance of being the same as or different strength as the first vibration. If the second vibration is different from the first then it has a 25% chance of being either 7000, 14000, 21000 or 28000 PWM different from the first vibration.

3.3.2 Pilot 2 Method

Pilot test 2 consists of two 1.5 second vibrations ,1 after another, separated by a gap of 1.5 seconds of no vibration. The vibrations for this test are grouped together as follows, (37-44, 44-51, 51-58, 58-65) which gives 4 groups of vibrations of a range between high and low vibration strength.

3.3.3 Pilot 3 Method

Pilot test 3 will consist of two vibrations played one after another separated by a gap of 1.5 seconds of no vibration. Either of the vibrations will have an equal chance of being either 2 seconds or 3 seconds in duration and an equal chance of either being at 42000 PWM or 50000 PWM giving 16 possible combinations for the two vibrations in duration(1-1, 2-2, 1-2, 2-2) and vibration strength(42000-42000, 50000-50000, 42000-50000, 50000-42000).

3.3.4 Pilot 4 Method

Pilot test 4 utilizes three motors(A, B, C) on the back of the hand. B is placed in the middle of the back of the hand. A is placed 1 cm closer to the fingers than B and C is placed 2 cm closer to the wrist than B. This test consists of 2 vibrations of the same duration (1 second) and vibration strength (50000 PWM) with a 1 second gap of no vibrations between them. The first vibration will have an equal chance of being either from motor A, B or C. The second vibration will have an equal chance of being the same or different motor. If different then will have an equal chance of being one of the other two motors. The distances between the motors are as follows; A - B: 1cm, B - C: 2cm and A - C: 3cm. The combinations of motor vibration locations therefore are AB, BC, AC, CB, BA, CA, AA, BB, CC. The results will allow us to see the spatial resolution of vibrations on the back of the hand from 1-3cm.

3.4 Results

This section includes graphical representations of those results as well as a summary of the findings from the Pilot study. For more in depth statistical analysis of the Pilot study results refer to appendix table D.

Plots of results from Pilots 1-4, showing probability of getting a correct answer under various conditions.

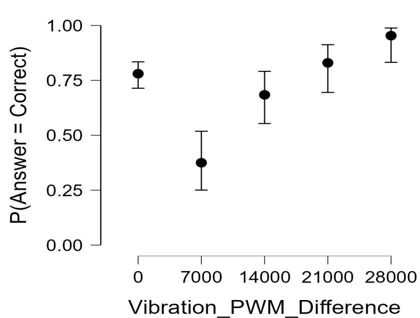


Figure 1. *Pilot 1: Probability of a correct answer vs vibration PWM difference, n=630.*

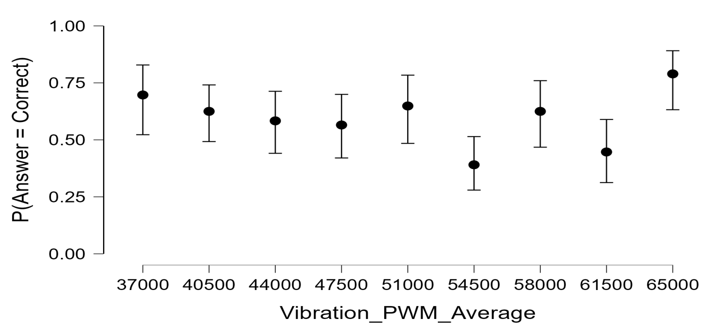


Figure 2. *Pilot 2: Probability of comparing vibrations correctly vs average PWM signal of the two vibrations, n=630.*

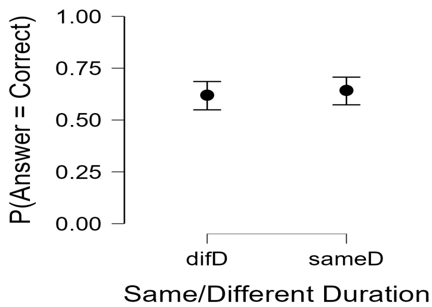


Figure 3. *Pilot 3: Probability of a correct answer vs same/ different duration of 2 vibrations, n=630.*

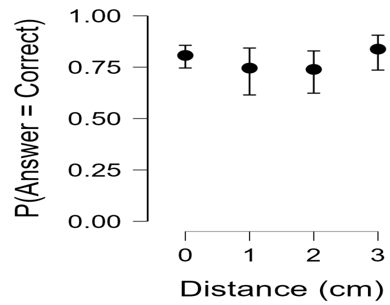


Figure 4. *Pilot 4: Probability of a correct answer vs distance between the vibration motors, n=420.*

Results showed that the probability of getting a correct answer, compared to a PWM difference of 0, that 7000 was much lower, 14000 and 21000 were not very different and 28000 was higher. Results showed that the probability of getting a correct answer when the average PWM was at 54500, compared to 37000, was lower and 61500, compared to 37000, was lower. Results showed that the probability of getting a correct answer when the duration of the vibration was 1 second different was similar compared to when the duration was the same. Results showed similar probabilities of getting a correct answer for spatial differences of vibrations of 1cm, 2cm and 3cm compared to 0cm.

3.5 Discussion

Figure 1 shows that vibrations were easy to tell apart except for when they had a 7000 PWM difference. Because a difference of 14000 PWM produced results that were similar compared to a difference of 0 PWM, this means that the strength resolution perception of the participants may lie somewhere between 7000 and 14000 PWM. Figure 2 shows that different vibrations were harder to tell apart when they were as strong as or stronger than 54500 PMW on average. Figure 3 shows that a duration difference of 1 second had little effect on the perceptions of vibrations when the vibrations were either 2 or 3 seconds. This means that a device can use these durations without affecting perception of vibrations too much. Figure 4 shows perception of vibrations were similar for spatial resolution differences of 1-3 cm compared to 0. This means that the participants' perception of vibration spatial resolution is smaller than 1cm. A device made for the back of hand that is 10cmx10cm could then fit 100 1cm vibration motors on a display and still perceive each motors vibrations

3.6 Conclusion

Participants’ perception of Vibration Strength resolution lies between 7000 and 14000 PWM. Participants' perception of Vibration Strength resolution decreases with increased strength. Participants' perception of Vibration Strength resolution is not affected by differences of 1 second when the duration of vibrations is between 2 and 3 seconds. Participants' perception of Vibration Spatial resolution is smaller than 1cm.

4. Materials & Method

In this section the design of the DV glove will be discussed followed by the design and procedures of the main study of this paper, the blindfolded maze navigation study.

4.1 DV Glove Design

In this section we will discuss the various influences from background research and Pilot studies that went into the design of the DV glove required for the main study of this paper.

4.1.1 Output Stimulus: Vibration

A micro vibration motor was chosen as the output stimuli for the haptic feedback, which was integrated into the depth sensing device required for the main study of this paper. This is due to its safe use with human skin, lower latency than linear rollers and large range of outputs. Due to my experience with EEGs during my bachelors research I am aware that electrical current would not be a good choice for the back of the hand as currents are affected by how firm the contact with the skin is, which would be affected by hairs, oil of the skin and movement. Sound was not chosen because it would distract the user and since this research uses 2 devices it would not be appropriate as the 2 sounds would interfere with each other.

4.1.2 Input: Ultrasonic depth sensor

The ultrasonic depth sensor HC-SR04 was chosen to be the input sensor for the device needed for the main study. This is due to its low latency, reliability and depth sensing range (2-400 cm range) which can detect objects closer than the pico TOF camera which can't sense objects closer than 10cm. Participants in the unfolding space glove study commented that they would like to sense objects closer than 10cm and so this would solve this issue(Kilian, Neugebauer, Scherffig & Wahl, 2022).

4.1.3 Mapping of input to output

Findings from the Pilot study influenced the mapping for depth to vibrations in the following ways. Participants' perception of Vibration Strength resolution lies between 7000 and 14000 PWM. The range of the vibrations was therefore larger than 14000 PWM. Participants' perception of Vibration Strength resolution decreases with increased strength. The perception of vibrations appears to decrease after 51000 PWM and so the maximum PWM was lower than this. Also increasing the perceptual resolution of each cm distance to an object, the detection radius of the device was chosen to be 1.5m instead of the full 4m capable range of the ultrasonic sensor. This is because the perceptual minimum limit of vibrations is 7000 PWM and so utilizing a smaller range would allow the user to detect each cm more clearly than if the PWN range was spread over a larger distance. Adding this 1.5m range to the length of the participants arm they would have a general detection range of over 2m, which is twice that of a cane and more than sufficient for this study. During testing of the vibration motor it was noticed that if the motor was turned off and then on, it would take about 0.5 seconds to respond, and opposed to the lower latency it would take to go from weak vibration to strong vibration. It was therefore decided that the vibration motor would be constantly on to increase response time of the device, when no object was detected the vibration motor would be on a very weak strength, as a 'base level' of 10,000 PWM. Over a long period of use this may have been annoying for some participants and even dulled their sense of vibrations due to the constant stimuli but the trials were so short this was not an issue. Pilot 3 was not extensive enough to yield much information about the effects of duration on vibration but it was noted that small differences in duration do not affect vibrational perception. Participants' perception of Vibration Spatial resolution is smaller than 1cm. This was investigated in the case that more vibration motors for each back of hand were required but this was deemed unnecessary as one vibration motor sufficed for this study. It was also noticed during testing that without proper training of the device, participants would not initially know where the top limit of the vibrations would be, that is to say when they are very close to an object. Therefore it

was decided to increase the vibrations dramatically when the participant came within 15 cm of an object, as a clear warning that they were about to touch an object.
Vibration strength would go from 10,000 PWM (>150 cm) to 22500 PWM (16 cm), increase rapidly to 32600 PWM (15 cm) and then to 34000 PWM (0 cm)

Participants from the unfolding space glove study also commented that it would be better if a power bank was not worn on the arm so in this study it was decided participants would wear a backpack with the powerbank contained within. Due to this and the ergonomic design of the glove based on freedom of movement of the hands and fingers, participants felt very comfortable when wearing the DV gloves(figure 6(left & right).

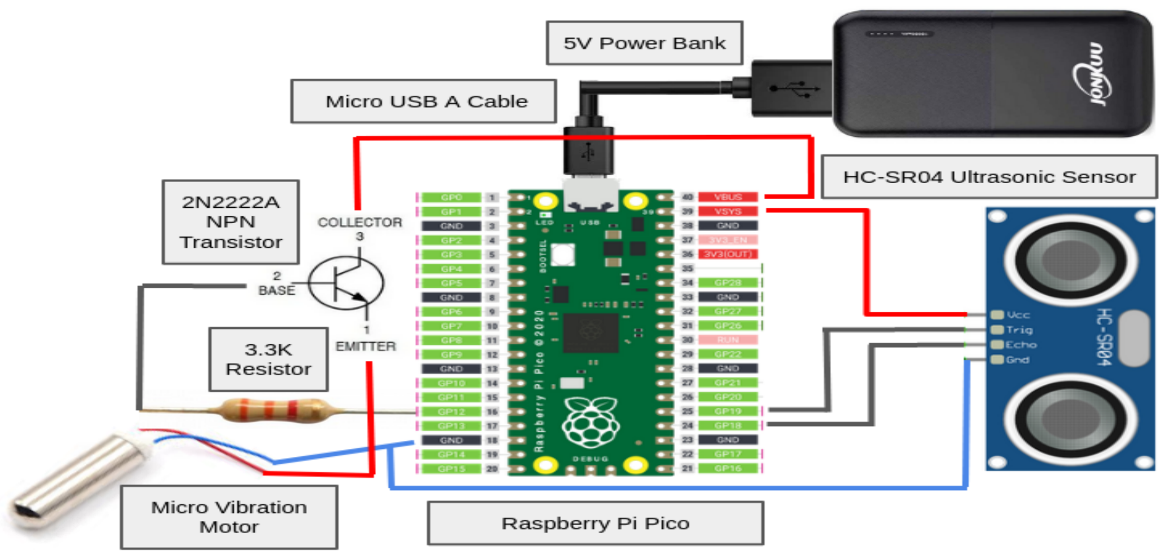


Figure 5. Diagram of single DV glove.

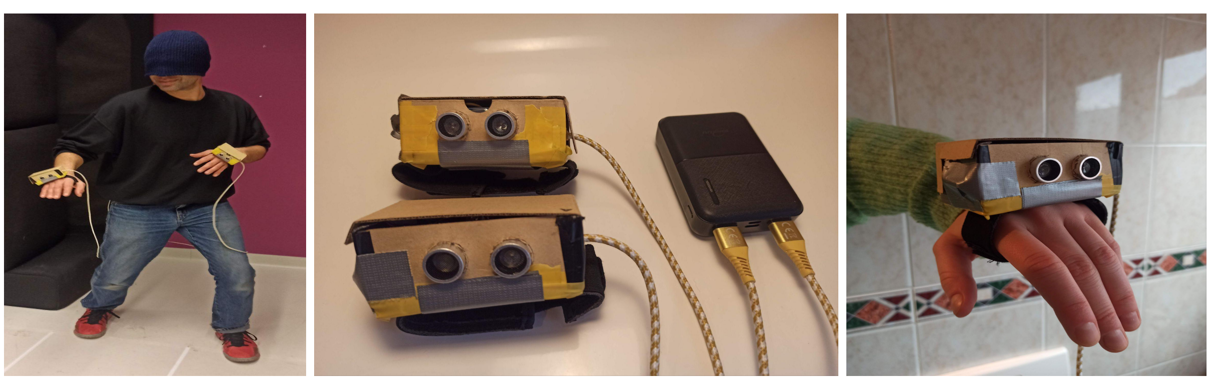


Figure 6. A Participant wearing 2 DV gloves(left) ,2 DV gloves and powerbank(middle), Worn DV glove(right).

4.2 Method

The test of this paper's main study(blindfolded maze navigation test) will consist of an obstacle course of cardboard boxes in a hall, which the participant will have to navigate, while blindfolded, using either 1 device worn on the dominant hand or 2 devices worn on both hands. The possible cardboard box arrangements for the course will be selected from a range of 6 pre-designed layouts, modeled after the unfolding space glove study (*Kilian et al., 2022)*. Each run of the test with each layout will be referred to as a trial. The participant will be scored on two things, the time that they took to complete the course from start to finish (TTC) and the Number of Collisions they made with the obstacles (NOC). The experimenter will not answer any of the questions of the participant during the test. The experimenter will only interact with the participant if the participant wishes to stop, take a break for any reason, or if the participant is about to walk into a wall then the experimenter will intervene to stop them. The total number of participants will be at least 20, with a total number of runs through the trials of 6. The order of the trials will be layout 1 to 6 for all participants. Half of the participants will go through layouts 1-3 with BC and then 4-6 with MC and the other half will go through layouts 1-3 with MC and layouts 4-6 with BC. Participants' data will be made anonymous and age, dominant hand, time of day, gender and preference for BC or MC will be collected to analyze with the results.

4.2.1 Ethics

Details of this paper's main study were provided to the ethics board through leiden university and accepted. All participants signed consent forms agreeing to participate in the main study and to have their data and results recorded and used for this paper. Participants who appear in photographs/videos have given their consent for these photographs/videos to appear in this paper and presentation.

4.2.2 Hypothesis

It is hypothesized that BC will outperform MC in terms of lower NOC without significantly affecting TTC.

4.2.3 Population

42 sighted adult participants took part in this study. 21 were males, 21 were females, 38 were right handed and 4 were left handed. The participants' ages ranged from 18 to 55 years old with the average age being 25.5 years old. The study was conducted between the hours of 10.35am and 6.48pm with the average time being 3.50pm.

4.2.4 Experiment Procedure

The experimenter asks the participant how they are feeling, states all the steps of the procedure states the aims of the test, which is to reach the end goal, where music can be heard and that they will be judged on Time to Complete(TTC) and Number of Collisions(NOC) which are counted and that both TTC and NOC are weighed equally. The experimenter then will conduct a performance test of each glove to test if it's working well and if the participant can perceive the vibration stimulus of each glove. The experimenter will guide them to the starting line of the obstacle room and point them towards the goal. The participant will then put on a blindfold. The experimenter then sets up the obstacles and asks if the participant is ready to begin the test. After confirmation is received the experimenter says “3, 2, 1, Go.” and the timer starts. The participant tries to navigate towards the goal using the DV glove/gloves. The experimenter counts the number of collisions with obstacles and stops the timer when the participant reaches the goal. These results are recorded. The participant removes the blindfold and repeats the previous steps until 6 trials are completed. Each trial should take a few minutes to complete so all trials should take between 10-20 minutes.

4.2.5 Safety concerns and prevention measures

Blindfolding participants puts them at risk of injury; to prevent this, the experimenter will stop them if they are about to walk into a wall, and the obstacle room will be clear of objects except for the required cardboard obstacles. The participant will be informed of test procedures, dangers and results. They'll be reminded of these before every trial and asked how they are feeling and if they wish to continue. They can quit or take a break at any stage. Since the participant is blindfolded they may feel claustrophobic during the main study. The blindfold is easy to remove and the devices on their hands do not restrict movement. The participant is informed they can quit or take a break at any time. The environment is shown beforehand to demonstrate it is free of objects they can trip and injure themselves on. An experimenter is present at all stages to ensure safety. Instrumental music (~55db) will cover the small buzzing sound of motors, avoiding the need for noise-canceling earphones that may add to users' claustrophobia. Pilot tests showed participants sometimes got pins and needles if the glove was too tight. The new glove should fix this, but participants will be asked if they experience this between each trial and recorded if so. The participant will be asked if the glove malfunctions between trials.

4.2.6 Experiment setup

The experiment for the main study of this paper was set up in Niels Bohrweg 2, 2333 CA Leiden, Netherlands, Leiden university, Huygens Laboratory, room 0.4.27. The experiment for the main study consists of a 7x4m area maze, with 8 0.4m width,0.4m length & 2m tall cardboard box obstacles placed in 6 different layouts for the 6 trials, the placement of which was indicated by marked tape on the floor which separated the maze into equal sections.

Figure 7. A test layout of the maze (left), The experimenter navigating the test layout of the maze(right)

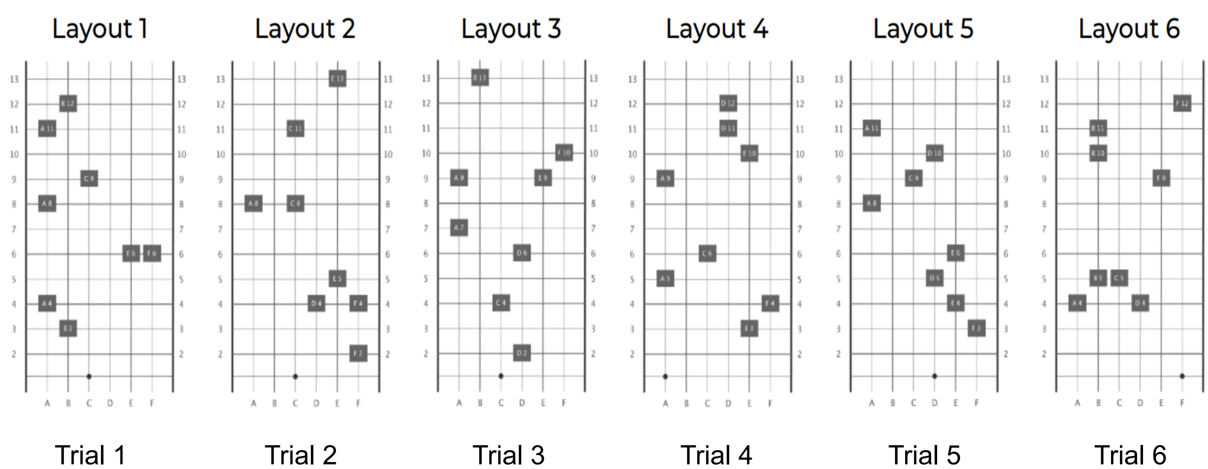


Figure 8. The 6 layouts/trials of the maze.

4.2.7 Statistical analysis

All statistical analysis of results will be performed using JASP. A Paired-Samples T-Test will be used on The two groups of haptic condition BC or MC across all trials of the study. An Independent Samples T-Test will be performed on each of the trials for BC vs MC. An Independent Samples T-Test will be performed for Gender and handedness. A Linear Regression Test will be performed for time of day, age and trial order.

5) Results

This section includes a table(Table D) of statistical analysis results from the main study, graphical representations of those results as well as a summary of only the statistically significant results from the main study.

Table C. Maze results showing effects of various independent variables on TTC and NOC.

Indep. Variables	**Stat. Analysis Test**	***n***	**Dependent Variables**		**Notes**
			Time to Complete (TTC)	**Number of Collisions (NOC)**	
Haptic condition (BC/MC)	Paired Samples T-Test	*n*=42	p=0.198	p=0.03*	The average TTC with BC (61.96 s) was larger than the average TTC with MC (58.381 s) over trials 1-6, but was not significant. The average NOC with BC (1.167) was significantly smaller than the average NOC for MC (1.563) over trials 1-6.
Haptic condition (BC/MC)	Indep. Samples T-Test	BC: *n*=21 MC: *n*=21	p=0.944	p=0.41	The average TTC with BC (68.762 s) was larger than the average TTC with MC (67.905 s) in trial 1, but was not significant. The average NOC with BC (1.429) was smaller than the average NOC for MC (1.714) in trial 1, but was not significant.
Haptic condition (BC/MC)	Indep. Samples T-Test	BC: *n*=21 MC: *n*=21	p=0.853	p=0.379	The average TTC with BC (56.524 s) was smaller than the average TTC with MC (58.381 s) in trial 2, but was not significant. The average NOC with BC (1.905) was larger than the average NOC for MC (1.571) in trial 2, but was not significant.
Haptic condition (BC/MC)	Indep. Samples T-Test	BC: *n*=21 MC: *n*=21	p=0.209	p=0.794	The average TTC with BC (50.048 s) was smaller than the average TTC with MC (63.048 s) in trial 3, but was not significant. The average NOC with BC (1.19) was larger than the average NOC for MC (1.095) in trial 3, but was not significant.
Haptic condition (BC/MC)	Indep. Samples T-Test	BC: *n*=21 MC: *n*=21	p=0.246	p=0.03*	The average TTC with BC (64.381 s) was larger than the average TTC with MC (52.857 s) in trial 4, but was not significant. The average NOC with BC (0.619) was significantly smaller than the average NOC for

					MC (1.429) in trial 4.
Haptic condition (BC/MC)	Indep. Samples T-Test	BC: *n*=21 MC: *n*=21	p=0.056	p=0.086	The average TTC with BC (62.667 s) was larger than the average TTC with MC (44.524 s) in trial 5, but was not significant. The average NOC with BC (0.619) was smaller than the average NOC for MC (1.095) in trial 5, but was not significant.
Haptic condition (BC/MC)	Indep. Samples T-Test	BC: *n*=21 MC: *n*=21	p=0.559	<u>p=0.028*</u>	The average TTC with BC (69.381 s) was larger than the average TTC with MC (63.571 s) in trial 6, but was not significant. The average NOC with BC (1.238) was significantly smaller than the average NOC for MC (2.476) in trial 6.
Trial (T6/T1-5 averaged)	Paired Samples T-Test	*n*=42	<u>p=0.015*</u>	<u>p=0.039*</u>	The average TTC in trial 6 (66.476 s) was significantly larger than the average TTC in trials 1-5(58.91 s). The average NOC in trial 6(1.857) was significantly larger than the average NOC in MC(1.267).
Trial (T1-5)	Linear simple Reg.	*n*=210	p=0.083 r^2 =0.014	<u>p<0.001*</u> <u>r^2 =0.068</u>	The average TTC decreased on average by 2.831 s with every increase in trial over trials 1-5, but was not significant. The average NOC highly significantly decreased by 0.214 with every increase in trial over trials 1-5. This effect was small (r^2 = 0.068).
Gender (M/F)	Indep. Samples T-Test	M: *n*=126 F: *n*=126	p=0.831	<u>p=0.027*</u>	The average TTC of female participants (60.619 s) was larger than the average TTC of male participants (59.722) over trials 1-6, but was not significant. The average NOC of females(1.548) was significantly larger than male participants(1.183) over trials 1-6.
Handedness (L/R)	Indep. Samples T-Test	L: *n*=24 R: *n*=228	p=0.873	p=0.153	The average TTC of left handed participants (61.208 s) was larger than the average TTC for right handed participants (60.061 s), but this was not significant. The average NOC for left handed participants(1.0) was smaller than the average NOC for right handed participants(1.404), but this was not significant.
Age	Linear simple Reg.	*n*=252	<u>p=0.006*</u> <u>r^2 = 0.03</u>	p=0.973 r^2 = 0.0	The average TTC very significantly increased by 1.022 seconds for each year older a participant was over trials 1-6.This effect was small (r^2 = 0.03). The average NOC increased by 4.822e-4 for each year older a participant was over trials 1-6, but was not significant.
Time of Day	Linear simple Reg.	*n*=252	p=0.545 r^2 = 0.001	p=0.625 r^2 = 0.001	The average TTC increased by 0.651 s per hour, but this was not significant. The average NOC increased by 0.021 per hour, but this was not significant.

Descriptive Plots of Participants Age,Gender,Handedness & Time of day of Participation in Study(*n*=42).

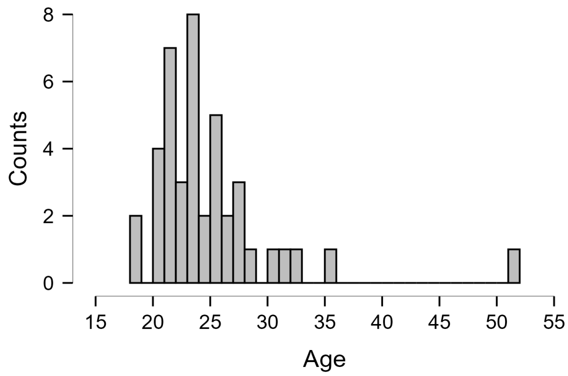


Figure 9. Age (years) counts across study (*n*=42).

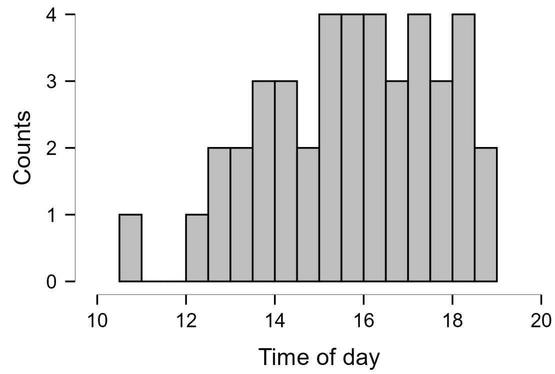


Figure 10. Time of day(24h) counts across study (*n*=42).

Figure 11. Gender counts across study (*n*=21 for males, *n*=21 for females).

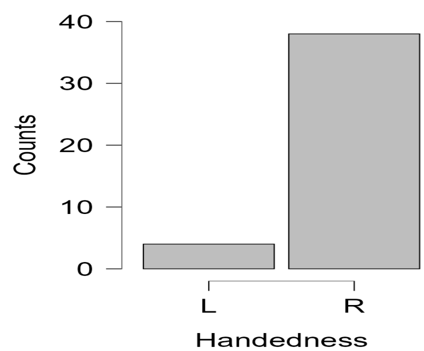


Figure 12. Handedness counts across study (*n*=4 for left handed, *n*=38 for right handed).

Descriptive Plots of TTC and NOC across study and over all trials (n=252).

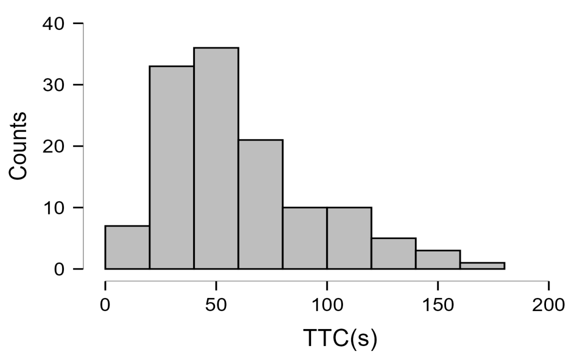


Figure 13. Time to Complete(TTC) counts across study for all trials under Bihaptic condition(BC) (*n*=126).

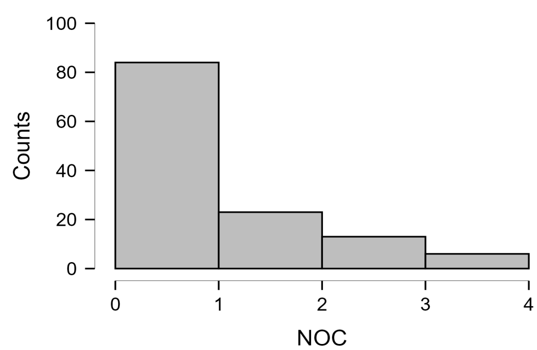
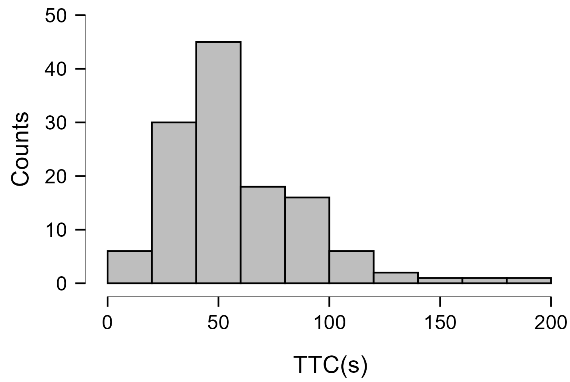


Figure 14. Number of Collisions(NOC) counts across study for all trials under Bihaptic condition(BC) (*n*=126).



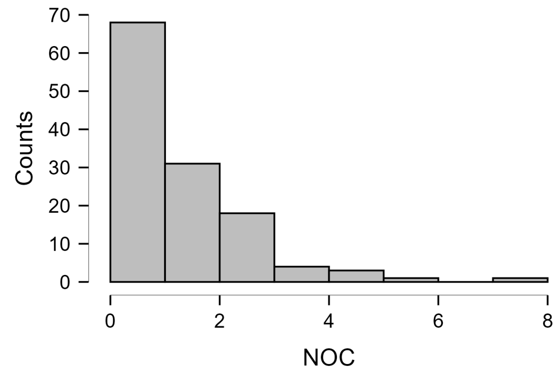


Figure 15. Time to Complete (TTC) counts across study for all trials under Monohaptic condition(MC) (*n*=126).

Figure 16. Number of Collisions(NOC) counts across study for all trials under Monohaptic condition(MC) (*n*=126).

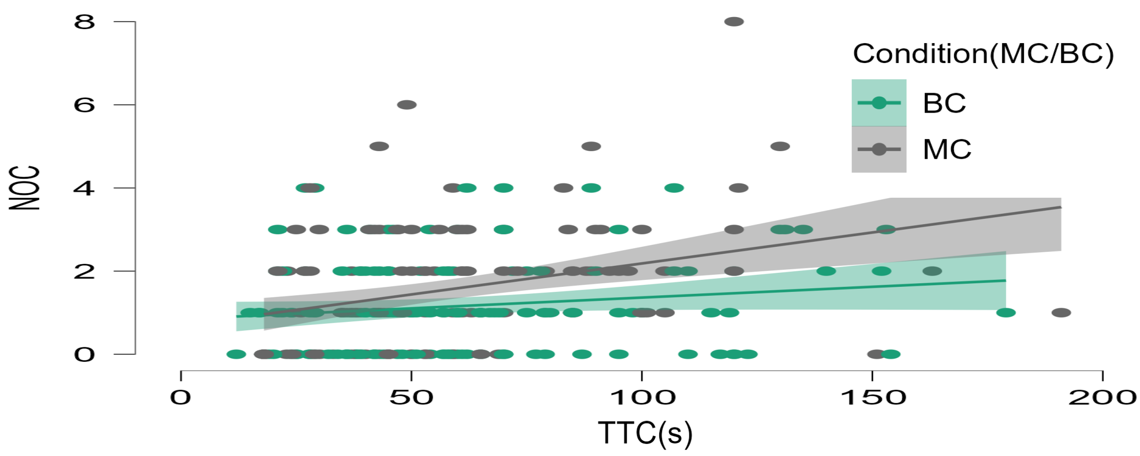
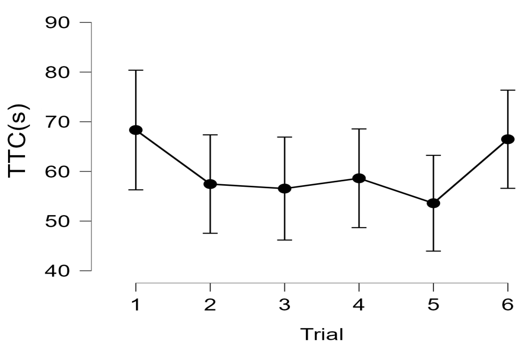


Figure 17: Scatter plot of Time to complete (TTC) vs Number of Collisions(NOC) across study for all trials for both Bihaptic condition(BC, *n*=126) and Monohaptic condition(MC, *n*=126).



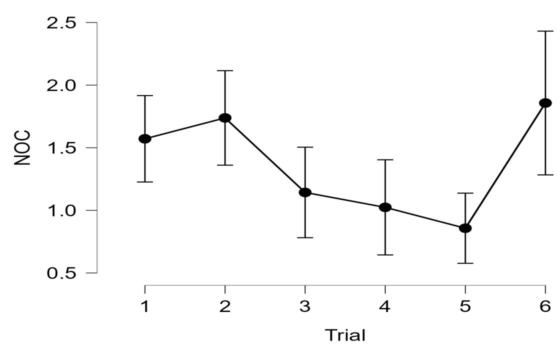


Figure 18. Average Time to Complete (TTC) per trial, regardless of haptic condition (n=42 per trial).

Figure 19. Average Number of Collisions(NOC) per trial, regardless of haptic condition (n=42 per trial).

Bihaptic(BC) vs Monohaptic(MC) plots of average TTC and average NOC across study and for each trial.

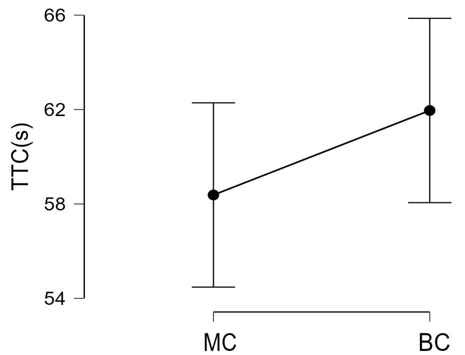


Figure 20. Average Time to complete (TTC) over all trials for Monohaptic condition(MC, *n*=126) and Bihaptic condition(BC, *n*=126).

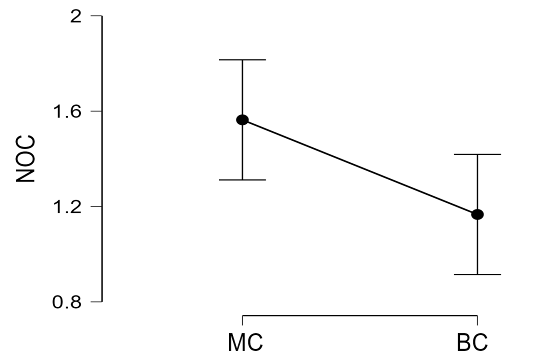


Figure 21. Average Number of Collisions(NOC) over all trials for Monohaptic condition(MC, *n*=126) and Bihaptic condition(BC, *n*=126).

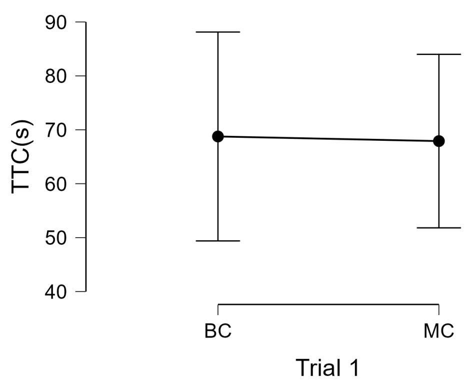


Figure 22. Average Time to Complete (TTC) in Trial 1 for Bihaptic condition(BC, *n*=21) and Monohaptic condition(MC, *n*=21).

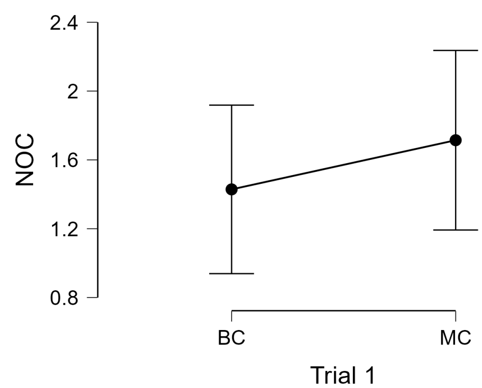


Figure 23. Average Number of Collisions(NOC) in Trial 1 for Bihaptic condition(BC, *n*=21) and Monohaptic condition(MC, *n*=21).

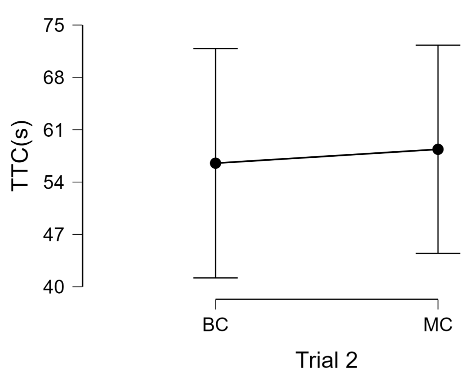


Figure 24. Average Time to Complete (TTC) in Trial 2 for Bihaptic condition(BC, *n*=21) and Monohaptic condition(MC, *n*=21).

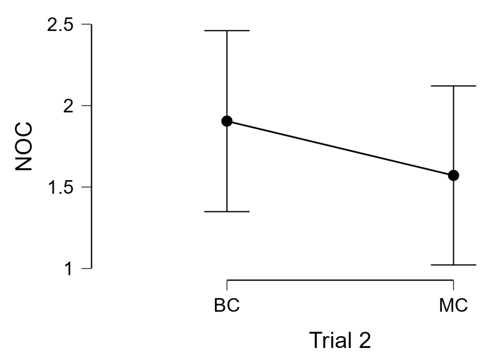


Figure 25. Average Number of Collisions(NOC) in Trial 2 for Bihaptic condition(BC, *n*=21) and Monohaptic condition(MC, *n*=21).

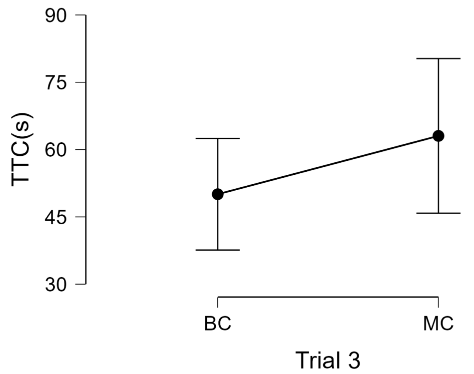


Figure 26. Average Time to Complete (TTC) in Trial 3 for Bihaptic condition(BC, *n*=21) and Monohaptic condition(MC, *n*=21).

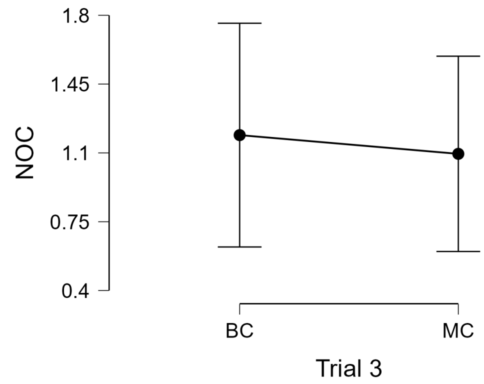


Figure 27. Average Number of Collisions(NOC) in Trial 3 for Bihaptic condition(BC, *n*=21) and Monohaptic condition(MC, *n*=21).

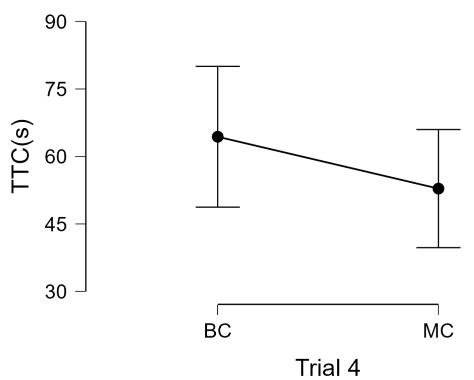


Figure 28. Average Time to complete (TTC) in Trial 4 for Bihaptic condition(BC, *n*=21) and Monohaptic condition(MC, *n*=21).

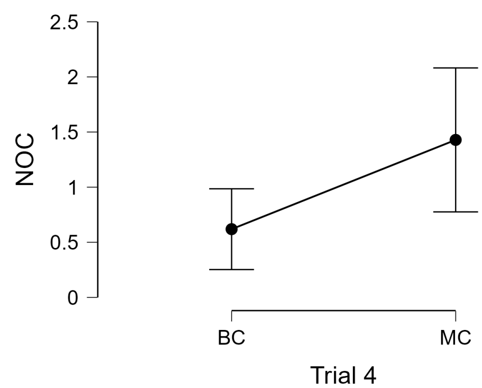


Figure 29. Average Number of Collisions(NOC) in Trial 4 for Bihaptic condition(BC, *n*=21) and Monohaptic condition(MC, *n*=21).

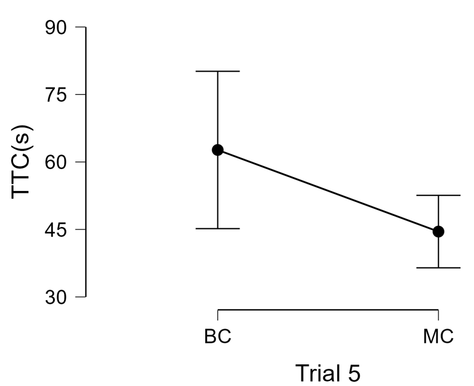


Figure 30. Average Time to Complete (TTC) in Trial 5 for Bihaptic condition(BC, *n*=21) and Monohaptic condition(MC, *n*=21).

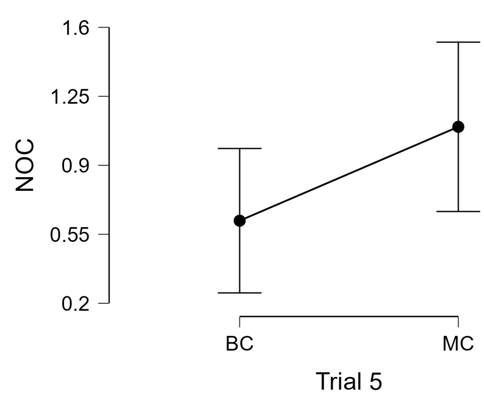


Figure 31. Average Number of Collisions(NOC) in Trial 5 for Bihaptic condition(BC, *n*=21) and Monohaptic condition(MC, *n*=21).

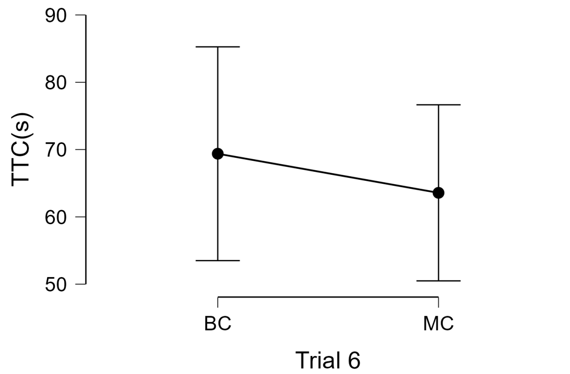


Figure 32. Average Time to complete (TTC) in Trial 6 for Bihaptic condition(BC, *n*=21) and Monohaptic condition(MC, *n*=21).

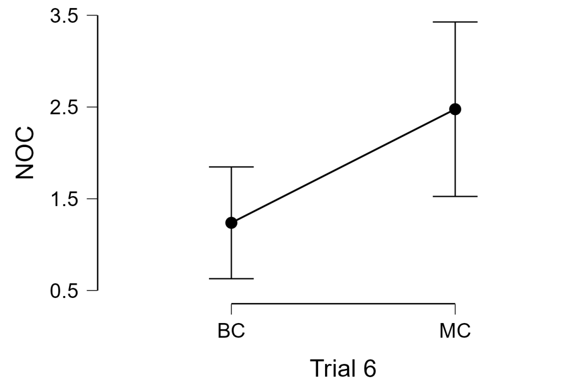


Figure 33. Average Number of Collisions(NOC) in Trial 6 for Bihaptic condition(BC, *n*=21) and Monohaptic condition(MC, *n*=21).

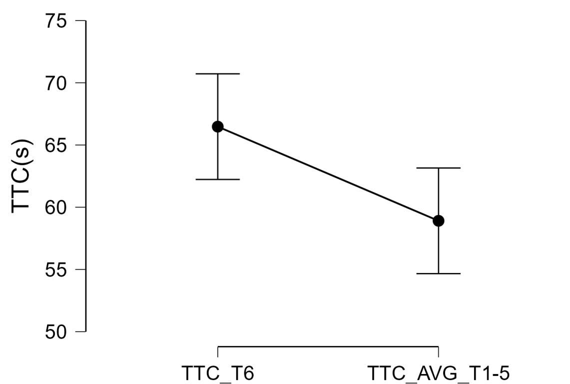


Figure 34. Average Time to Complete (TTC) under both haptic conditions for Trials 1-5 (*n*=210) and Trial 6 (*n*=42).

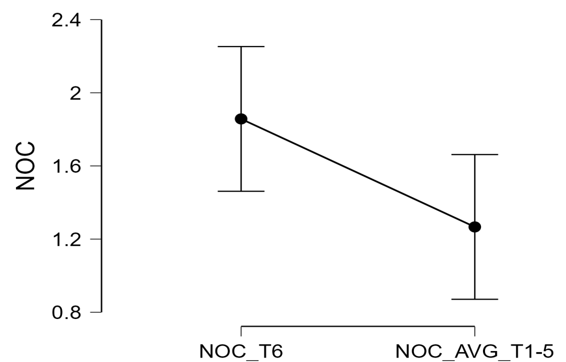


Figure 35. Average Number of Collisions(NOC) under both haptic conditions for Trials 1-5 (*n*=210) and Trial 6 (*n*=42).

Plots of other variables effect on TTC and NOC, regardless of haptic condition

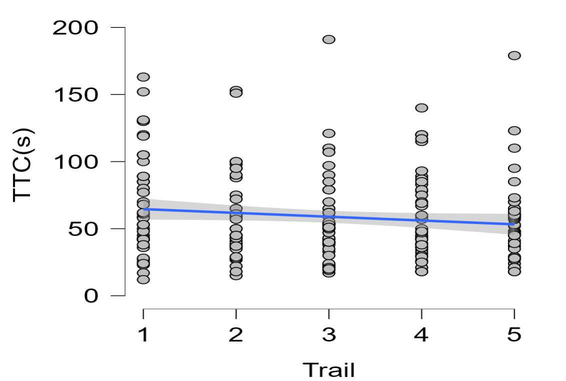


Figure 36. Scatter plot of Time to Complete (TTC) under both haptic conditions for Trials 1-5 (*n*=210).

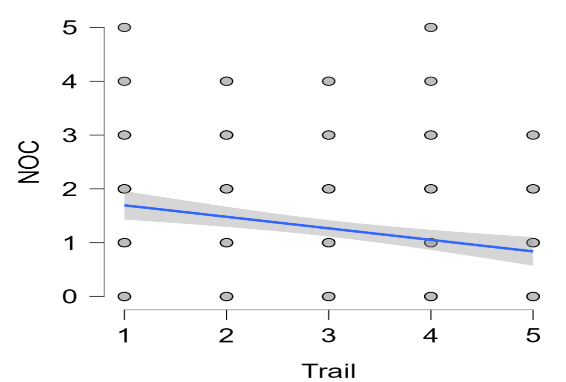


Figure 37. Scatter plot of Number of Collisions(NOC) under both haptic conditions for Trials 1-5 (*n*=210).

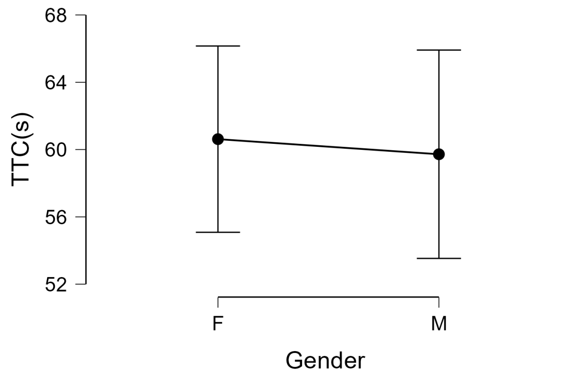


Figure 38. Average Time to Complete (TTC), regardless of haptic condition, for females(F: *n*=126) and males(M: *n*=126).

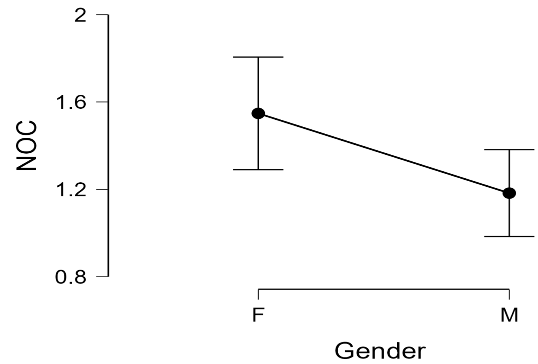


Figure 39. Average Number of Collisions(NOC), regardless of haptic condition, for females(F: *n*=126) and males(M: *n*=126).

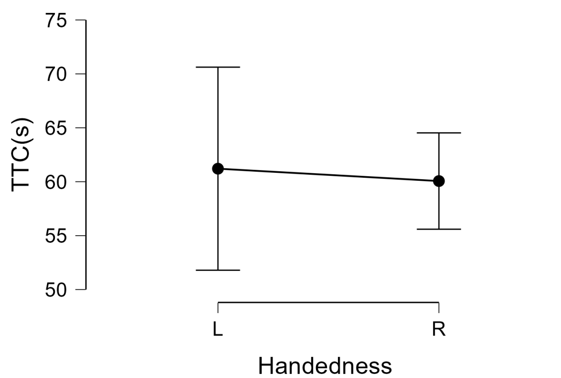


Figure 40. Average Time to Complete (TTC),regardless of haptic condition, for left handed participants(L: *n*=24) and right handed participants(R: *n*=228).

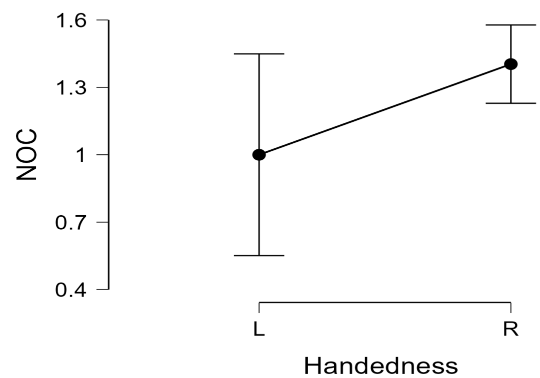


Figure 41. Average Number of Collisions(NOC) ,regardless of haptic condition, for left handed participants(L: *n*=24) and right handed participants(R: *n*=228).

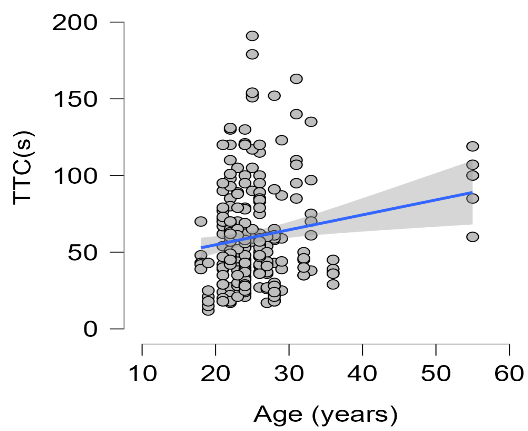


Figure 42. Scatter plot of Time to Complete (TTC) vs Age (years), under both haptic conditions for all trials across study (*n*=252).

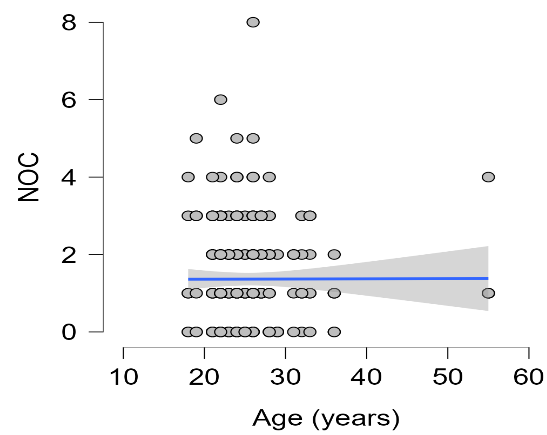


Figure 43. Scatter plot of Number of Collisions(NOC) vs Age (years), under both haptic conditions for all trials across study (*n*=252).

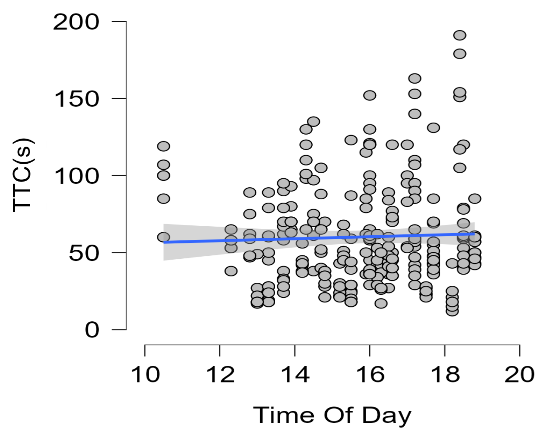


Figure 44. Scatter plot of Time to complete (TTC) vs Time of day (24h), regardless of haptic condition, across study (*n*=252).

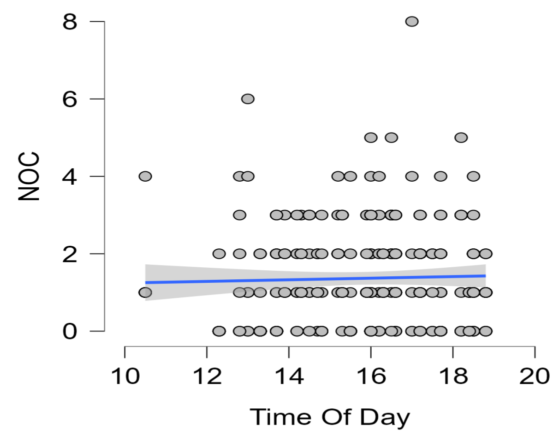


Figure 45. Scatter plot of Number of Collisions(NOC) vs Time of day (24h), regardless of haptic condition, across study (*n*=252).

Bihaptic(BC) vs Monohaptic(MC): The average NOC with BC (1.167) was significantly smaller than the average NOC for MC (1.563) over trials 1-6 (Figure 21). The average NOC with BC (0.619) was significantly smaller than the average NOC for MC (1.429) in trial 4 (Figure 29). The average NOC with BC (1.238) was significantly smaller than the average NOC for MC (2.476) in trial 6 (Figure 33).

Trials: The average TTC in trial 6 (66.476 s) was significantly larger than the average TTC in trials 1-5 (58.91 s) (Figure 34). The average NOC in trial 6 (1.857) was significantly larger than the average NOC in MC (1.267) (Figure 35). The average NOC significantly decreased by 0.214 with every increase in trial over trials 1-5, but this effect was small ($r^2 = 0.068$) (Figure 37).

Gender: The average NOC of female participants(1.548) was significantly larger than the average NOC of male participants(1.183) over trials 1-6 (Figure 39).

Age: The average TTC very significantly increased by 1.022 seconds for each year older a participant was over trials 1-6, this effect was small ($r^2 = 0.03$)(Figure 42).

Time of Day & Handedness: Time of day and Handedness showed no significant effects on TTC or NOC during the study.

6) Discussion

6.1 BC had lower NOC than MC

BC had significantly less NOC than MC, this may be due to a bigger zone of detection , which is typically the width of the participants shoulders. Some obstacles were next to each other with a small gap (~30 cm) between them and sometimes participants would, in MC, point towards the gap, detecting no obstacles and thus walk forward only to bump into an obstacle. This was far less likely with BC as the zone of detection was around shoulder width which would detect at least one of these obstacles, alerting the participant and causing them to scan the area more carefully, avoiding collisions.

When collisions occurred it was usually because participants turned and collided with their arm or shoulder and rarely with obstacles directly in front of them. This happened less with BC as the sides of the participant could be scanned by crossing their arms instead of turning around, reducing the need for turning motions to detect obstacles to the side.

The DV glove had difficulty detecting corners of obstacles and participants would sometimes not detect it or feel a ‘pulsing’ feedback. This was perhaps less of a problem with BC as both gloves would not be pointing at the same angle or position. For instance if detecting an object in BC , one device might be pointing towards the flat surface , giving a steady vibratory feedback, and the other the corner, giving a pulsing feedback or no feedback. Instead of this being a drawback, as such in MC, this is a positive benefit in BC as the user would not only detect the obstacle but know where the corner or edge was, giving general distance, size and orientation of the obstacle.

Feedback from some participants who preferred BC said that this was due to a larger range of detection. When participants changed from BC to MC they said that it felt as if they had lost perception on one side and that side was where collisions would happen most often.

6.2 MC had lower TTC than BC

MC had a lower TTC than BC, but not significantly. Feedback from the people who preferred MC was because they had to only focus on 1 stimulus and so didn't have to concentrate as much. It may be that the cognitive load was lower and they were able to process feedback faster. This is supported by the feedback from participants in the unfolding space glove study who had to focus on 9 separate vibrational stimuli on the back of the hand, commenting that it took alot of concentration when using the device. Another reason that MC had less TTC is that in MC there was significantly more NOC. For instance, during MC a participant would walk confidently forward, having not perceived the obstacle in front of them (due to a corner or gap perhaps) and collide with it, having collided with this obstacle they would know its location and simply walk around it, nullifying the need for the DV glove and thus completing the maze quickly but with more collisions.

6.3 Older participants had higher TTC

TTC would increase by around 1 second for each year older a participant was, although this effect was small it was still significant. Reaction times to vibrotactile stimuli is slower in old people than in young people (Bao et al., 2019). Although most of the participants in this study were rather young, most under 30 years old, this is likely the cause of the increased TTC in older participants.

6.4 TTC and NOC decreased over time between trials 1-5

Participants would generally get better over time and throughout the study their TTC(not significantly) and NOC(significantly) would decrease. However, layout 6 was significantly harder, with higher TTC and NOC than the other trials and feedback from most of the participants stating trial 6’s difficulty in both MC and BC. This is why a linear regression analysis was performed on trials 1-5, which were comparable in difficulty, and found that people got better over time. It was not expected that participants would adapt so quickly to the devices and some participants were incredibly proficient with the DV gloves in both MC and BC.

6.5 NOC was significantly higher than males

Females NOC was significantly higher than males, but TTC was not significantly different.

6.6 Time of day and Handedness had no significant effect on TTC or NOC

Time of day and handedness did not show any significant effect on TTC or NOC. It was expected that participants' performance would get worse as it got later into the evening, but it seemed that this was not true and some participants did just as well at night as some participants in the early afternoon.

6.3 Other comments of the study

The device generally worked very well even though the device was quite cheap(~15 euros each). It is assumed that a higher quality device would produce even lower TTC and NOC but this was considered unnecessary for this study.

People generally enjoyed the experiment, every participant was asked between each trial how they felt and none reported any negative feelings throughout testing such as claustrophobia or dizziness, numbness of hands or tiredness and each participant completed all 6 trials in a short time (10-20 mins). In some long experiments some participants can lose concentration over time or become numb to feedback but with how short and enjoyable the study was I believe that this was not a significant factor during this study.

The sensors were ultrasonic sensors which had a slight perceivable lag as the emitted ultrasonic waves had to be waited on to return. This causes people who moved their arms too fast to detect an object slightly to the left or right of where it actually was, then the person would spend some time trying to ascertain the exact location. This is believed to have increased TTC, a different sensor such as a fast speed camera might reduce this effect. Although as mentioned before it was considered unnecessary to make a perfectly functional device for this study as the aim is to compare BC and MC and not to build the best device conceivable. In the end the device that was used in this study could have been better but worked sufficiently for this study. Results from this study are still valid as the devices were identical to each other and the test was the same for all participants.

7) Conclusion

The results from this paper's main study have demonstrated the benefits of BC over MC in a blindfolded maze study with sighted participants. BC had significantly lower NOC ($p=0.03$) without significantly affecting TTC. Older participants had a significantly higher TTC than younger participants ($p=0.006$), but the effect was small ($r^2 = 0.03$) and NOC was not affected by age. Participants NOC significantly decreased over time across trials 1-5 ($p<0.001$), showing that participants improved as they became more experienced with the DV gloves. Gender had no significant effect on TTC. NOC was significantly higher for females than males($p=0.027$). Handedness and time of day had no significant effect on either TTC or NOC. In conclusion, the results of this study supports the hypothesis that BC is better for obstacle detection than MC in navigation of an obstacle maze .

Referring back to the initial example of blind people who use both a white cane and guide dogs, of which 40% report head injuries at least once a year and as a result 34% only leave their normal routes only once or several times a month while 6% never do. The use of a bihaptic device like the one used in this study would allow them to sense objects at a farther distance and sense both grounded and above ground objects at the same time with a significantly better object detection rate than monohaptic devices. Although during the study collisions did still occur with a bihaptic device, most of these collisions were due to turning and touching an object with the hand and rarely from walking straight into objects. Participants also significantly reduced NOC over time and so I believe that if a bihaptic device was to be released on the market, with a short amount of training, it would allow the 34% of blind people who rarely leave their normal route to do so with confidence of not colliding with above ground objects, without significantly affecting the time to travel somewhere. There is no reason that a user could not use an assistive distance sensing cane as well as one DV glove as the same time, this would also be considered, by the definition of this paper, a Bihaptic condition, and would add to the benefits of a white cane, which is in itself a useful tool for blind people.

Acknowledgements

I would like to thank my family and friends for supporting me throughout this thesis project, my supervisor Maarten Lamers for all his help and advice, and all those who took part in both the pilot and main study.

8. Appendix

Table D. Pilot 1-4 Logistic Regression Analysis

Pilot Study #	Coefficients	Estimate	Standard Error	Odds Ratio	z	Wald Statistic	df	p
1	(Intercept)	1.267	0.179	3.55	7.078	50.095	1	< .001
1	Vib_PWM_Dif (7000)	-1.778	0.348	0.169	-5.112	26.135	1	< .001
1	Vib_PWM_Dif (14000)	-0.494	0.337	0.61	-1.467	2.153	1	0.142
1	Vib_PWM_Dif (21000)	0.317	0.427	1.373	0.742	0.551	1	0.458
1	Vib_PWM_Dif (28000)	1.753	0.746	5.775	2.351	5.527	1	0.019
2	(Intercept)	0.833	0.379	2.3	2.199	2.40E-29	1	0.028
2	Vib_AVG (40500)	-0.322	0.469	0.725	-0.687	1.68E-28	1	0.492
2	Vib_AVG (44000)	-0.496	0.479	0.609	-1.037	1.075	1	0.3
2	Vib_AVG (47500)	-0.571	0.482	0.565	-1.185	5.02E-28	1	0.236
2	Vib_AVG (51000)	-0.22	0.512	0.803	-0.429	0.185	1	0.668
2	Vib_AVG (54500)	-1.278	0.457	0.279	-2.794	2.11E-27	1	0.005
2	Vib_AVG (58000)	-0.322	0.5	0.725	-0.644	0.415	1	0.52
2	Vib_AVG (61500)	-1.046	0.479	0.351	-2.184	1.73E-27	1	0.029
2	Vib_AVG (65000)	0.489	0.549	1.63	0.89	0.792	1	0.374
3	(Intercept)	0.489	0.149	1.63	3.287	10.804	1	0.001
3	Same/ Diff Duration (sameD)	0.099	0.211	1.104	0.471	0.222	1	0.638
4	(Intercept)	1.431	0.181	4.184	7.927	62.833	1	< .001
4	Distance cm (1)	-0.357	0.358	0.7	-0.996	0.991	1	0.319
4	Distance cm (2)	-0.39	0.328	0.677	-1.188	1.41	1	0.235
4	Distance cm (3)	0.211	0.363	1.235	0.58	0.337	1	0.562

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