Design and Testing of a Haptic Belt Navigation System

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By signing below, I attest that the undergraduate thesis listed above meets the criteria for Honors.

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1. Abstract

Haptic technologies have developed substantially over the past decades with developments in a wide range of applications. Support for the visually impaired is one of these avenues which is partial reason for developing popularity of haptic belt systems. These systems integrate vibration motors along a user's waist to transmit information through haptic feedback based on vibration location and intensity. This study investigates the effect of motor density along with two vibration schemes – a single-motor and Gaussian scheme - on direction perception and haptic navigation in a laboratory environment.

Three different belts were tested. These were nearly identical in design with only the number of motors varying between 8, 12, and 16 motors, respectively. These motors were evenly distributed around the belt and vibrated in the direction that the user was supposed to move to reach their goal. The single-motor vibration scheme only activated the motor closest to the intended direction. In contrast, the Gaussian scheme mapped the intensity of each motor based on a normal distribution centered at the intended direction of motion.

Two perception tests and one extended navigation task tested the performance of the belts and vibration schemes. The relative intensity discrimination task required subjects to specify which of two adjacent, vibrating motors was vibrating at a higher intensity. A threshold intensity difference of approximately 25% was observed. The second perception test investigated direction perception. Subjects were provided with vibrational cues and were required to record the angle at which they felt the vibration through a visual display. Results suggested that there is no significant correlation between the motor density or vibration scheme on accuracy. Lastly, the final navigation task had subjects walking around a virtual environment limited to a 10m x 10m area following randomly generated paths of invisible waypoints. Results in this task also suggested that there was no significant correlation between motor density and path error or path time. A minor discrepancy was found in favor of the Gaussian vibration scheme with regard to path time. However, even this discrepancy was minimal. Overall, the study revealed that both the single-motor and Gaussian vibration schemes are viable methods of navigation. However, more data needs to be collected to determine the reliability of these conclusions especially with subjects who experience visual impairments themselves.

2. Introduction

This thesis is a summary of the Laboratory of Engineering Man-Machine Systems' research into haptic feedback navigation for the visually impaired. Specifically, it focuses on the design, implementation, and testing of the haptic belt system that has been developed during the past years. Some of the work here has been explored previously in Julian Vallyeason's thesis [1] though there have been many developments in the year since, especially regarding the experimental procedures and the associated communication and software infrastructure. This paper will summarize previous works related to the project and discuss how it has evolved over the last year.

While Vallyeason approached the challenge from a navigation standpoint, this introduction approaches it from a haptics perspective. First, an alternate investigation is provided which delves into haptic perception and the history of haptic technologies to complement previous work. Then, a summary is provided of Vallyeason's research into vibration perception and navigational systems for the visually impaired.

2.1 Applications of Haptic Technologies

Haptics have proven to be an important area of development as they combine engineering, computer science, psychology, neurology, and biomechanics in a vast range of applications. These technologies utilize our sense of touch to develop new systems in myriad different areas. This section investigates some of these applications to emphasize the vast potential for haptics. There are multiple categories of implementations including force feedback, ultrasound, and vibrations. Fields that implement these include interactive learning, aids for disabilities, aircraft, virtual reality, and robotics.

2.1.1 Early Applications

Initial applications were in large aircraft that used servomechanism systems [2]. Such systems prevented external aerodynamic forces from being felt through the pilot's controls. In smaller aircraft that lacked such a sytem, these forces could be felt directly. This was helpful especially in instances where a critical stall point was reached. The strong resulting vibrations were felt by the pilot informing them of the potential danger. In larger aircraft this feeling was lost through the servomechanism systems, so pilots had minimal information of such potentially deadly situations. To make up for this, a combination of springs and masses were implemented to simulate such resistance in the control mechanism. This way pilots were aware of dangers and had a better feel for the aircraft despite the feedback forces being synthetic.

In a separate field, a tactile telephone was patented by Thomas D. Shannon and a tactile man-machine communication system was patented by A. Michael Noll in the early 1970s [3]. The latter was a system which enabled the user to 'feel' a three-dimensional object stored in the computer's memory. The goal of the system was to depict objects or surfaces that were difficult to display visually. Noll noted the power of such a device for conveying computer graphics to the blind and emphasized the value of such a system as an educational tool. Using the system to better understand the basics of electromagnetic forces was an example of this.

Applications in interactive media started in 1994 with the Interactor Vest [4]. This wearable, force-feedback vest had inbuilt electromagnetic actuators to convert low frequency sound from an audio source into vibrations across the vest. Plugging the system into a source such as a television or stereo allowed the system to filter out high-frequencies and utilize the remaining bass to create a unique experience for the user. Modern applications in video games use a similar mechanism by embedding vibration motors in controllers to convey in-game events.

Related to this project, Ertan et al. developed a haptic wearable haptic navigation guidance system in 1998 [5]. The aim was to build a system for the visually impaired. It stored a 4-by-4 array of vibration motors embedded in the back of a vest that the user wore which, in conjunction with an infrared-based input, allowed the system to detect the user's location and orientation in their environment. A wearable computer accounted for route planning. While this system was helpful for navigating an unfamiliar environment when testing with sighted individuals, the authors noted the limitation in position and orientation tracking which required further improvement for the user to walk freely through space. More examples of applications in navigation are explored section 2.2.

Lastly, a suitable transition from older technologies to more modern ones is the haptic wristwatch developed by Geir Jansen in 1995 [6]. Much like modern smart watches, the device connected via Bluetooth to a mobile phone. When receiving a call, the watch alerted the user of the caller's identity using preconfigured skin taps. Analogous to ringtones, different tap patterns corresponded to different caller ID's. Jansen believes this innovation was more applicable then than it is now since mobile phones used to be much bulkier and less discrete when they rang. The wristwatch also included programmed texts or voice messages which could easily be sent through the watch directly.

2.1.2 Improvements in Psychophysical Understanding

Since these initial ideations 50 years ago, haptic technologies have developed substantially. A large factor has been psychophysical research which has shed light on the effectiveness of haptic cues in humans. Hale and Stanney provide an overview of haptics literature and outline some important findings [7]. They begin by mentioning how haptic interactions provide "an independent sensory channel that the brain can process to further enhance a user's experience in a multimodal environment." This is especially valuable in today's environment as it can both reduce coordination errors and improve reaction time when interacting with computers. They discuss the different receptors that exist in both hairless and hairy skin. The latter have low spatial resolution suggesting that they are poor at perceiving two-dimensional form or texture compared to the former. In general, perceptual threshold depends on the stimulus type, timing, and stimulus location which are important factors to consider when designing haptic feedback systems.

Sherrick and Cholwiak investigated stimulus location by varying actuator placement for a set of stimuli [8]. For both single-point vibrations and two-point discrimination, they found that the nose, mouth, and finger-pad were the most sensitive loci. The back was the least sensitive. They also found discrepancies in pressure thresholds between genders.

Another factor to consider is force feedback and kinesthetic receptors. These receptors which include joints, tendons, and muscles make us aware of our limb movement. They allow us to determine the direction and speed with which our limbs are moving and lets us determine if motion is external or voluntary [7]. This plays an important role in perceiving haptic objects or surface textures through force feedback [9, 10]. This is particularly useful for virtual environments in which users can interact with virtual objects. Limb motion, in conjunction with visual stimuli, contributes to conveying an objects location, stiffness, and to a lesser degree texture. Such multi-modal interactions have been investigated thoroughly with the dawn of virtual reality and remote interactions. Examples of this are discussed below.

2.1.3 Modern Applications

Haptics for navigation has been an area with multiple developments. These are discussed in more detail in Vallyeason's thesis which is summarized in the following section. Here, some alternate developments are discussed.

Education and computer interactions were important considerations since the dawn of such technology. This goal has continued to develop through the power of virtual reality and spatial learning. Skulmowski et al. studied tangible user interfaces (TUIs) as a tool for learning. They found that the TUI resulted in better learning in college students studying the anatomy of the human heart when compared with a traditional mouse interface. Students in the TUI group outscored those in the mouse interface group 26 to 19. The task tested retention of labels for corresponding components of the heart with a maximum score of 30 [11]. This was also supported by the reduction in germane load for subjects in the TUI group which suggested they had less difficulty with the learning task.

Pan et al. looked into existing virtual learning environments to explore how these architectures improve collaborative learning. One system aimed to help 7- to 10-year-old children improve their storytelling abilities [12]. The environment allows students to interact with 3D models of characters with unique qualities. Students can assign emotions to these characters along with reasons for these emotions to foster sociability and adaptability. Other systems enable similar leaning mechanisms. While not all implement haptics, many applications have begun to implement haptics alongside virtual environments to create a holistic experience.

Another different application is in robotics. Developments in robot-assisted surgery have proven to be an important step in the future of medicine. Van der Meijden and Schijven provided an overview of the literature to reveal that there is still uncertainty and ambivalence regarding haptic feedback for minimally invasive surgeries. Nevertheless, they explain how the absence of such feedback for robotic surgeries is a major setback. A lack of force feedback makes it challenging for the surgeon to apply the correct amount of pressure through the robotic system. This can result in slippage or tissue damage in the patient. However, they also note that sensory stimuli are best felt through bare hands. While it is likely impossible to replicate such sensations completely, instruments can be used as levers to amplify the experienced forces as they are transferred to the surgeon. This amplification could range from a factor of 0.2 to 4.5 to enhance sensitivity [13]. Even still, this is a hard feat to achieve for such delicate applications. During teleoperated robotic surgery, this ability is lost completely since the surgeon does not directly interact with the instruments. Alternative mechanisms that could develop viable technologies for clinic trials are being investigated, but there is still much work before they become commonplace [14].

2.2 Overview of Previous Research

Now that haptic technologies have been explored, a summary of previous research is provided. Here, Vallyeason's research into vibratory perception, encoding schemes, and navigational systems for the visual impaired are summarized and elaborated on.

2.2.1 Navigational Systems for the Visually Impaired

Vallyeason's begins his work by providing an overview of existing navigational technologies that assist those with visual impairments. These challenges effect a large portion of the population with approximately two-hundred-forty million people globally having significant visual impairment that affects their daily lives. Within this group, there are approximately thirty-seven million who are classified as legally blind [15].

These individuals often utilize assistive technologies for wayfinding and both detecting and avoiding obstacles. For those with traditional sight, these challenges are handled through visual cues which allows for awareness of surroundings [16]. Assistive technologies aim to relay this information through alternate sensory modes including auditory, olfactory, and tactile cues. Oftentimes auditory cues are disfavored since hearing ability is crucial for the visually impaired. Particularly in crowded environments, it can be both difficult and overwhelming to transmit such cues clearly to the user. Regardless of the type of cue, this proves to be challenging due to potential information loss and intrusion into the existing capacity of the sensory mode being used. A summary of existing technologies is presented below.

Device	Description	Range	Capacity
Long (white) cane	Mobility tool to detect objects within close proximity	< 10 meters	Tactile Input -> Tactile Feedback
Guide Dog	Assists with navigation in public spaces; often trained to recognize traffic signals and assist in public transport.	10 meters – 500 meters	Complete Sensory Animal Input -> Navigation Output (through tactile / auditory cues)
Braille-Note GPS	Voice assistant to direct users to a destination by triangulating the user's position	>100 meters	Location Input -> Audio Output
Laser and Sonar Canes	Maps obstacles from wave reflection to warn users	< 10 meters	Visual Input -> Tactile Feedback
Brain Port	Sensory information is sent to an electrode array on the tongue	< 10 meters	Visual Input -> Tactile Output

Table 1: Summary of navigational technologies for the visually impaired [1]

Multiple studies have explored improvements to some of these technologies. Vallyeason discusses some of these including the EyeCane, a smart walker, and a system using an array of lidar and vibrotactile units. The EyeCane combines a traditional white cane with infrared scanners. User's can active the scanning mechanism manually to scan in the direction of a suspected nearby object. Results of the scan then communicate the distance of the object through vibratory cues. The smart walker targets elderly people who have visual impairments. It has built-in vibratory feedback through its handles to guide users along their intended path. Motors inside the handles conveyed cues to move forward and to turn right or left. They also informed the user once they arrived at their goal. Lastly, the system with an array of lidar and vibrotactile units used a global positioning system to determine user's location and orientation compared to a predetermined goal position. The system also accounted for nearby obstacles using a separate, mounted sensor array which measured distances to nearby objects.

These technologies all showcase possible avenues for improving navigation for the visually impaired. These systems first convey information to the user and then guide them accordingly based on wayfinding algorithms. Such algorithms determine the path the user must take to reach their target destination while accounting for both static and dynamic obstacles. Although these considerations are not discussed in this paper, they are an active field of study and will become a point of importance for this project as it develops.

2.2.2 Vibratory Perception and Encoding Schemes

Effective haptic feedback systems require an understanding how such cues are perceived by the user. The location and vibration intensity of vibrational motors proves to be an important design decision when developing such systems since users must be able to sense changes in vibration intensity while also discriminating the location that the vibration occurs (assuming multiple vibration motors are implemented at vary locations).

Vallyeason discusses the high accuracy (over 90%) in a variety of circumferential vibration patterns. Subjects in the study [17] were able to accurately identify single motor vibrations in particular directions and vibration patterns such as clockwise and counterclockwise rotations along their torso. This shows that vibratory perception is an effective method of communication in general. It is important to note that subjects were slightly better at identifying vibratory patterns than single motor vibrations. This suggests that vibration schemes which utilize multiple motors to form a gesture may be more effective than simpler, single-motor vibration schemes for conveying information.

Other studies not only support this claim, but they also highlight other important consideration [18, 19, 20]. When conveying directional information, it is crucial to have enough vibration motors to accurately specify the direction of interest. Simultaneously, there is a threshold vibration separation below which humans are unable to discern two vibrations. Johannsen et al. [19] found this to 13mm. Though even at 13mm accuracy is at only 64% compared to 92% for 30mm separation. It is also important to consider how the location of the vibration affects perception. Cholewiak et al. [20] investigated vibrations distributed at twelve locations around the abdomen. They found that subjects perceive vibrations relative their front and back – corresponding to their navel and spine. This suggests that subjects are better at discerning vibrations close to these locations and are worse at discerning vibrations located on their sides.

Such factors are important to consider when choosing how to encode information into vibrational cues for directional navigation. Currently, no standard, universal mechanism exists but some research has been conducted in the field. Some considerations include the number of vibrating motors, the frequency at which cues are provided (continuous feedback versus selective feedback) and the type of selective feedback (on-course versus off-course). Vallyeason highlights some helpful studies which found that subjects with visual impairments preferred consistent vibratory feedback over selective feedback. Furthermore, during selective feedback, participants preferred receiving cues when they deviated from their path (off-course feedback) rather than receiving cues when they were following their path (on-course feedback). For single-motor vibrations, a study noted the limitation of such encodings since they are limited to the directions that correspond to the motor locations. Regardless of how many motors there are, this mechanism cannot account for all direction the user may need to move in and thus adds a discretization to directional movement. Navigation is then also limited by the hardware in question since two systems with a different number of motors are not equally effective.

2.4 Research Objectives

This project aims to design, assemble, and test a belt system for haptic navigation. An initial belt prototype was created and tested in Vallyeason's thesis and more developments have followed since. The custom belt uses vibration motors evenly distributed around the wearer's waist which communicate directional cues to help guide them to their destination. While testing the system, three key questions are asked.

Firstly, the effect of motor density is considered for accuracy of vibration direction perception. Three separate prototypes were built with 8, 12, and 16 vibration motors, respectively. Higher belt density is suspected to improve accuracy during navigation as the user has more sources of information.

Secondly, two separate vibration modes are compared for vibration perception. The first is standard single-motor vibration where one of the motors – the one closest to the desired orientation of the target – vibrates at full intensity while the others are off. The second mode uses a wrapped, non-normalized Gaussian distribution. Here, multiple motors vibrate at different intensities according to the chosen standard deviation. The exact direction of the goal corresponds to maximum intensity vibration while nearby motors vibrate at lower intensities. This is discussed in greater detail in section 3.3. With multiple motors active, it is also important to consider how accurately differences in vibration intensity can be perceived. As a result, both direction perception and intensity perception are tested.

Lastly, this study tests how perceptions of these vibratory cues are translated into motion inside a controlled laboratory environment. Different motor densities are tested with both vibration modes to help evaluate the system holistically. As an underlying requirement, both hardware and software infrastructures are established to build a flexible system that can easily be integrated with a variety of programs and environments. Building a robust communication mechanism to interface with the belt is a crucial consideration.

3. Materials: Belt Design

This section discusses the initial design of the haptic belt system and outlines the changes that have occurred since the initial ideation. The first subsection is an overview of the system. It describes the various components and discusses future expansions to incorporate camera glasses to make a completely self-sustained navigation system. The following two subsections go over the design decisions for the belt hardware, software, and communication mechanism to elaborate on how the system arrived at its current state. These include the motor mounting mechanisms, belt material choice, microcontroller choice, microcontroller wireless communication, and supporting software infrastructure.

3.1 System Overview

The haptic navigation belt system consists of two main components. As outline in section 1, the first component handles odometry and localization to locate the user in their environment. The second conveys information about the user's environment through the haptic cues. In this instance, the former is handled by a Samsung Odyssey VR headset and the latter is handled by the haptic belt.

3.1.1 Headset for Localization and Mapping

It should be noted that, as the project progresses, the VR headset (left-most component in Figure ***x***) will be replaced by separately produced head-mounted hardware that is designed specifically for this system. This will avoid dependencies on previously developed hardware which is usually expensive and often has more involved functionality than is required. Although development of this system has been in progress, there are still many challenges that need to be overcome before this step is achieved. Furthermore, the final hardware must handle mapping since visually impaired users will use the system outside of established environments. This is a crucial step before localization can occur.

In the meantime, the Samsung Odyssey VR headset is a perfect place holder. A laboratory environment is already established with this headset integrated with a back-mounted MSI computer. The headset's location and orientation are directly accessible through the integrated Vizard virtual reality software. No mapping is required since the environment boundaries are hardcoded into the system. Therefore, this platform provides an excellent mechanism for testing the belt in a virtual environment.

3.1.2 Communication

With the localization taken care of, this information is processed, and cues are sent to the belt system using both serial and wireless communication. For experimental purposes, processing and some communication are handled locally on a computer. Figure ***x*** below summarizes the aggregate system including the communication mechanism between the headset and belt systems.

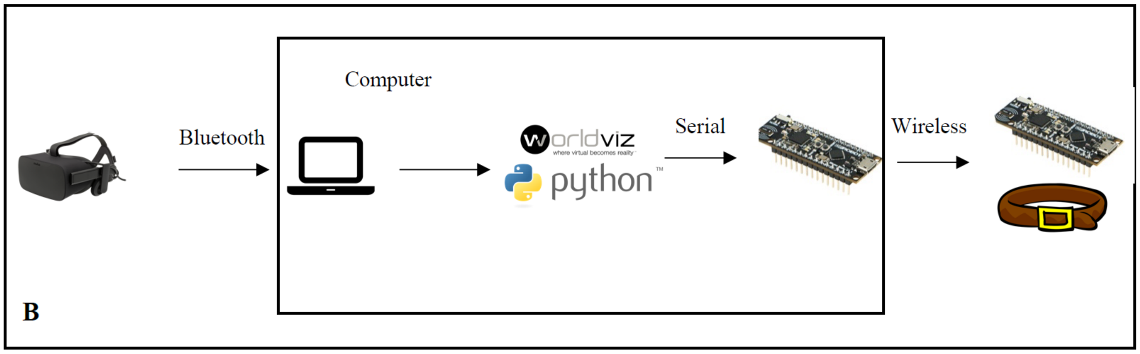


Figure 1: Schematic of communication mechanism between the headset (left) and the microcontroller on the belt (right)

The VR headset communicates via Bluetooth to the computer where Vizard software can extract the location and orientation of the headset. This information is then compared to the user's desired destination and appropriate cues are synthesized to send to the belt. This is handled via a Python script which sends cue data via a serial USB port to a microcontroller. This microcontroller then transmits these cues wirelessly to a second microcontroller which is connected directly to the belt system.

3.2 Belt Hardware

The belt system had a simple consideration in mind. As discussed in the section 1, the goal was to build a design which distributed vibration motors around the user's waist. Various haptic cues can then be conveyed to the user by altering the intensities of the motors as desired. To control the motors, the Arduino Bluno Nano BLE was selected. This is a small, 48mm by 19mm board that has low-power Bluetooth functionality built in. Its small size was a crucial factor to minimize the bulkiness of the mounted hardware.

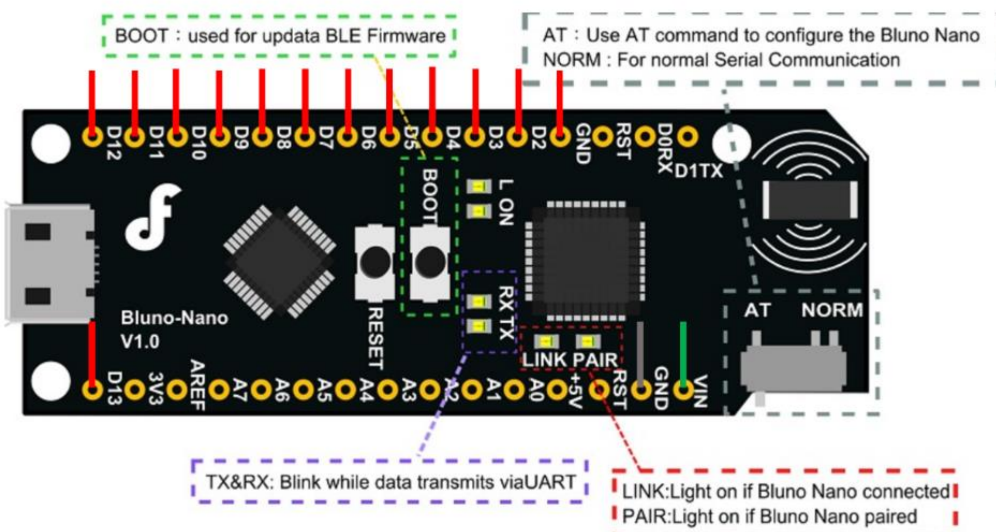


Figure 2: Arduino Bluno Nano BLE schematic [21]

The belt was made from a 2-inch wide, knit elastic band and a basic plastic belt buckle. Acrylic supports mount the motors onto the belt while a larger acrylic box stores the Arduino and excess wires. Lastly, a 9V battery powers the Arduino and is encased in a small battery pack which has an in-built switch to turn the power on and off. Three different belts were made, with 8, 12, and 16 motors, respectively. These motors were evenly dispersed with motors located directly at the front, back, and two sides of the user's waist. Remaining motors were distributed evenly in in between the four main directions. Each motor was connected to ground and their respective digital pin on the Arduino.

Figure 3: Images of the assebmled 8 (top), 12 (middle), and 16 (bottom) motor belts

The acrylic supports are designed such that their position can be adjusted by sliding them up or down the belt. This, along with the elastic fabric, were important considerations to make the belt flexible and easy to fit on people with different waist sizes. To account for potential stretching a motor shifting, excess wiring is present between motors as shown in the images above. The base of the acrylic piece is a simple rectangle with narrow slits on either end to allow the elastic fabric to to fit around the acrylic. These slits are narrow enough to ensure that the support pieces are not too loose on the belt that they would shift while wearing the system. However, they are loose enough to allow for easy assembly and readjustment if necessary.

Figure 4: Images of the base motor support piece (left) and the Arduino compartment with the sliding lid removed (right)

The motors are mounted onto the center of these pieces such that the fabric looped behind the acrylic. This ensures that motors make direct contact with the user's waist rather than having fabric between the user and the motor. To ensure good contact, an additional piece of acrylic is mounted to these base pieces to raise the motor. During initial testing, this substantially improved the ability for the wearer to sense the vibrations. Furthermore, two additional support pieces are mounted at the top of the base acrylic piece to help thread the wires through each support. By mounting these at the top of the acrylic base, it allows for efficient space use as wires can be looped as shown in the figure above without them hanging too low below the elastic fabric.

Another important factor was the location of the battery and Arduino along the belt. For symmetry sake, the Arduino is mounted at the center of the user's back in an acrylic box which is mounted onto the back of the motor support piece. This makes wiring simpler since the wire distribution going down either side of the belt is almost identical. The box has holes at the top to allow all wires to discretely feed into it and connect to the Arduino that is housed inside. For testing purposes, a simple sliding door provides easy access to the Arduino. The battery pack is similarly mounted to the outside of the motor support piece located on the left side of the user's waist. This allows the user to easily turn the system on or off while wearing it.

Since the initial design there have been minor changes. The base acrylic support pieces are now narrower to allow for more motors to be fit onto a single belt. Similarly, the size of the Arduino casing has decreased to minimize the bulkiness on the user's back. Lastly, the motors have been raised even further off from the base acrylic supports to further strengthen the user's perception of vibrations. Most updates since the initial design relate to the Arduino code and the communication protocol between the computer and belt system. These are outlined in the following subsection.

3.3 Belt Communication and Software Infrastructure

The core communication mechanism for the system is Bluetooth. One Arduino wired via USB to the computer transmits data that it receives from the Python program directly to the Arduino in the belt. This wireless communication worked sufficiently in the lab environment with no connectivity issues. For a final product, this communication would come directly from the headset that the user is wearing with no computer in between. In this case, a wired connection would also be possible to directly connect the headpiece to the belt. The more important concern is the communication protocol that establishes how the cues are communicated from the program handling the orientation processing to the belt hardware.

The Arduino on the belt requires information about the intensity of each motor. Based on these values, it can them drive each motor at the desired intensity using pulse width modulation (PWM). The current mechanism uses code in the Arduino which specifies the number of motors and their respective pins. The program works like a state machine. At each time step it receives a byte of data from the Arduino connected to the computer. Two values are chosen to represent the start and end of the data stream. Once the data stream starts, the program collects the following *n* bytes where *n* is the number of motors. It then expects the signal to specify that the data stream is complete, and all motor intensities were transmitted. If this is the case, the program drives each motor at the specified intensity with the help of an Arduino library which implements the PWM. (Originally the PWM was hardcoded too, but the library proved to be more effective as it allowed higher data transfer rates thus reducing latency.) It then goes back to a standby state where it waits for the beginning of the next data stream. If the length of the message is not the expected length, the system also returns to standby mode since the data stream was either too short or too long.

This effectively allows any motor to be driven at 253 different intensity levels. 8 bytes of data corresponds to a total of 255 different values, but two of these are assigned to be the message start and end markers. However, at very low intensities there are two considerations. Firstly, the motors do not vibrate at all since the signal they receive is not high enough to overcome factors such as friction inside their chamber. Secondly, even if the motors do vibrate, at low intensities the subject cannot sense them. Because of this, it makes sense to use low-intensity values as the message start and end markers as this will not affect the functionality of the belt. Regardless of what these markers are, this needs to be accounted for in the Python program to ensure that these values are not transmitted as intensities since the belt would misinterpret these values as being message markers. A simple solution is to use the values 1 and 2 to represent the start and end of a message. This leaves room for the motors to be completely off (intensity 0) and all other values below some threshold (e.g. 10) can be rounded down to 0 by the Python program before transmission.

In the program, the angle between the user’s location and the target waypoint is calculated. Subtracting this angle from the user’s current orientation provides the angle that the user should turn such that they can walk straight to their waypoint. For single-motor vibrations, the motor closest to this direction is activated at full intensity and all other motors are turned off. For Gaussian vibrations, a distribution is generated with the preset standard deviation centered around the desired angle. The distribution has a horizontal axis that corresponds to degrees and a vertical axis which corresponds to vibration intensity. The peak of the Gaussian always has a value of 1

(100% intensity) regardless of the standard deviation. These values are then directly mapped to the motors based on the angle that each motor corresponds to around the user's waist. Before the result intensities are transmitted, all values below a chosen threshold are rounded down to 0 as discussed in the previous paragraph. From this, it is expected that the single-motor vibration mode is less accurate than the Gaussian mode since a rounding error is introduced that is directly proportional to the number of motors in the belt.

This mechanism has proven to be effective since the 253 different intensity levels are large enough that the discrepancy between consecutive intensity levels is low enough that users likely cannot feel it. (This will be explored in an experiment later in section 4). The result is a near continuous spectrum of intensities from the user's perspective. This is an improvement on the original design which limited the intensity brackets to only 5 ranging from 0% to 100% in linear 20% increments. Previously, it was the motor number that was transmitted in correspondence to each of the five intensity levels. Flipping this so that it is the intensity of each motor that is transmitted has proven to be more robust as it is a more flexible communication mechanism with less complexity.

4. Experimental Procedure

This section outlines the procedure developed over the last year for testing and evaluating the haptic belt system. Although the fundamental questions that are asked have not changed, the method for conducting these experiments has changed in both major and minor ways. These experiments test the user's ability to perceive haptic cues and navigate their environment accordingly. Two vibration schemes were used: a single-motor scheme and a Gaussian distribution scheme and the experiments are broken into two parts: perception and locomotion.

The first subsection explains the methodology used to investigate the user's ability to perceive vibrational cues through the belt. Two experiments tested the ability to perceive direction and relative intensity, respectively. The first aimed to determine the accuracy with which the user can interpret the haptic cues at different points around their waist. The second aimed to determine the just-noticeable-difference (JND) between the intensities of two adjacent motors. In previous work, a third test was also included to test absolute intensity perception where the user is asked to specify the intensity with which a single motor is vibrating. However, after much deliberation this test was removed as it has large dependencies on the hardware and other specifics of this project. Furthermore, it contributes minimal value to this project since absolute intensity is not considered for current navigation schemes.

The second subsection explains the methodology used to investigate the user's ability to perceive these haptic cues and utilize them for navigating an environment. This was achieved by continually tracking the user's location and orientation. The belt guided the user while navigating various paths in the room. Originally, two separate feedback schemes were considered. The continuous feedback scheme has the belt vibrating constantly. The discrete feedback scheme specifies a period and a duty cycle for which the belt is on and off, respectively. In the current experiments, only the discrete feedback system was removed due to the added complexity and time requirements that came with testing it. However, there are some additional factors related to this which are discussed further below.

4.1 Perceptual Experiments

The first two tests examined vibrotactile performance. For these tests, the subjects were asked to wear the belt slightly above their waist while standing. They were then presented with haptic cues and asked to mark responses accordingly on a computer screen.

4.1.1 Direction Perception

This test had the subject wearing the belt rotated 90 degrees counterclockwise orientation with the buckle on the left side of the subject. They were then provided with cues of identical intensity but at different locations around their waist. Throughout the experiment, subjects had the following display.

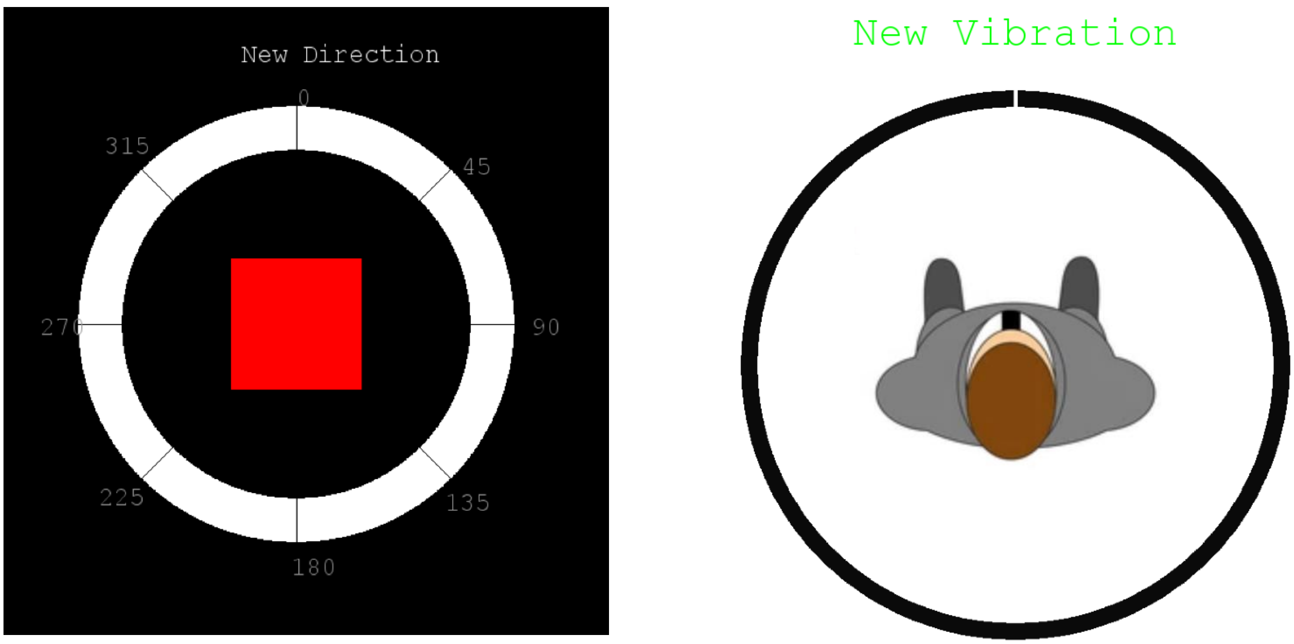


Figure 5: Original (left) and current (right) display for the direction perception task

The ring represented the belt with a full 360° range of possible cues. The top of the ring represents the front of the subject as shown by the central, top-down view of a human. Participants were given a mixture of both Gaussian and single-motor vibrations randomly distributed around their waist for each of the three belts. They then had to record the location of the vibration around their waist by clicking on the corresponding location in the ring.

Rather than giving a 5 second time limit for each response as was done previously, subjects could take as much time as needed to specify their response. Similarly, the divisions on the circle were removed and a picture of a human from a top-down view was added. These changes minimized the cognitive load during the experiment while providing a more intuitive reference for the subject. In addition, the circle radius was expanded, and its thickness was reduced to improve the accuracy of the responses at the pixel level.

The discrepancy between the actual angle of vibration and the perceived angle of vibration was measured for each trial. It is predicted that the Gaussian vibration scheme would result in better accuracy than the single-motor vibration scheme for all three belts for the same reasons that were discussed in section 2.4. Similarly, it is expected that the perception of vibration cues located at the back of the subject are less accurate than other angles. This is due to the mounting of the corresponding vibration motor as outlined in section 3.

4.1.2 Relative Intensity Perception

This test had the subject wearing the 12-motor belt rotated 45^{o} counterclockwise from the standard orientation. Only the two motors closest to their front vibrated throughout the test. With each trial, the two motors fired at different intensities and the subject was asked to identify whether the left or right motor had a higher vibration intensity. Subjects had to press either the left or right arrow keys on the keyboard to specify their choice of the stronger motor. The 5-second time limit was removed for this experiment too.

The goal of this test is test is to determine the threshold intensity difference below which subjects cannot reliably determine which motor has a higher intensity. Previous experiments used 5 intensity levels for each motor – 0% to 100% in 20% increments – and compare all possible combinations. The current methodology is substantially different as it uses the QUEST+ algorithm [22]. This is an iteration of the original QUEST procedure and is a Bayesian adaptive psychometric testing method that allows for multiple stimulus dimensions. In this case, only two dimensions exist which are the intensities of the two motors. This method iteratively provides the subject with new pairs of vibrations and accounts for statistical randomness in responses. One axis, in this case the vibration of one of the motors, is set at a constant value - 50% intensity. The intensity of the second motor is then adjusted iteratively until a sufficient certainty is reached. For each trial, the intensity of the first motor is fixed at 50%, and the side that it appears on (left or right) is randomized. The algorithm then determines the intensity of the second motor based on the previous trials. This technique results in a more accurate result and it quickly focuses trials to vibration differences that are close to the threshold, rather than wasting trials at combinations that the user can easily distinguish. Once sufficient certainty is reached the experiment is complete and the threshold intensity difference is reported.

4.2 Locomotion Experiment

This final test examined navigation with the haptic belt. Subjects wore the belt just above their waist rotated 90 degrees counterclockwise with the buckle on their left side. They were then asked to navigate multiple paths using haptic cues. This test was conducted in an empty, 12x12 meter lab environment with the aid of a MSI backpack computer and a virtual reality headset. The subjects wore these in addition to the belt placing them in an empty virtual environment. This basic environment consisted of a blue sky and flat, textured ground using Vizard software as shown below. The headset tracked the position and orientation of subject which was used in processing to determine and send haptic cues to the belt.

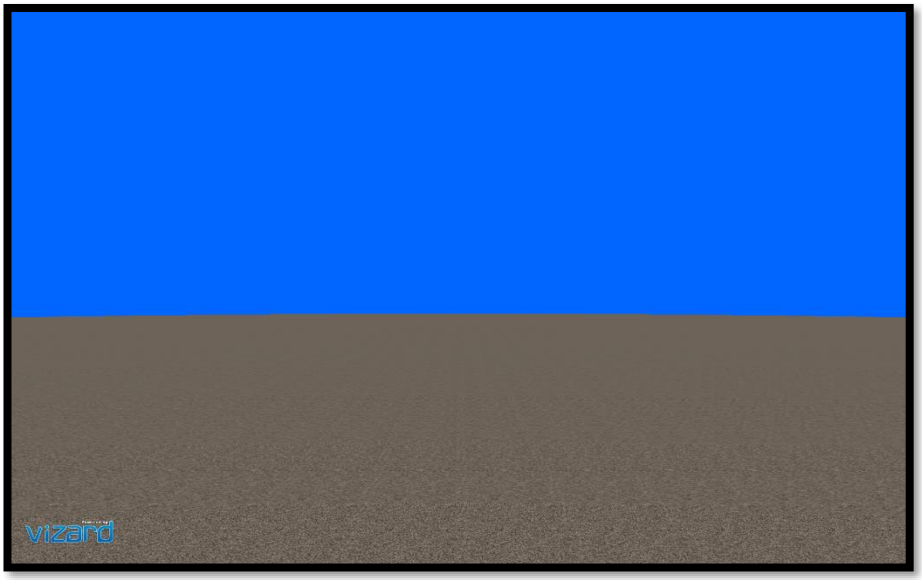


Figure 6: View of the virtual environment during navigation

With the environment and navigation mechanism established, subjects were asked to navigate through a variety of paths. These consisted of sets of waypoints which were generated randomly for each subject such that the path started at the origin (the center of the room) and ended at an arbitrary point such that the total straight-line path length was 45m. To prevent risk of collision with the laboratory walls, the waypoint boundaries were limited to a 10x10m area. Between trials, two pillars appeared in the environment. Subjects navigated to the yellow pillar which was located at the center of the room. They then faced the red pillar corresponding to the center of the room's back wall for 3 seconds before their next trial commenced. During the trials, these two orientation pillars were removed from the virtual environment.

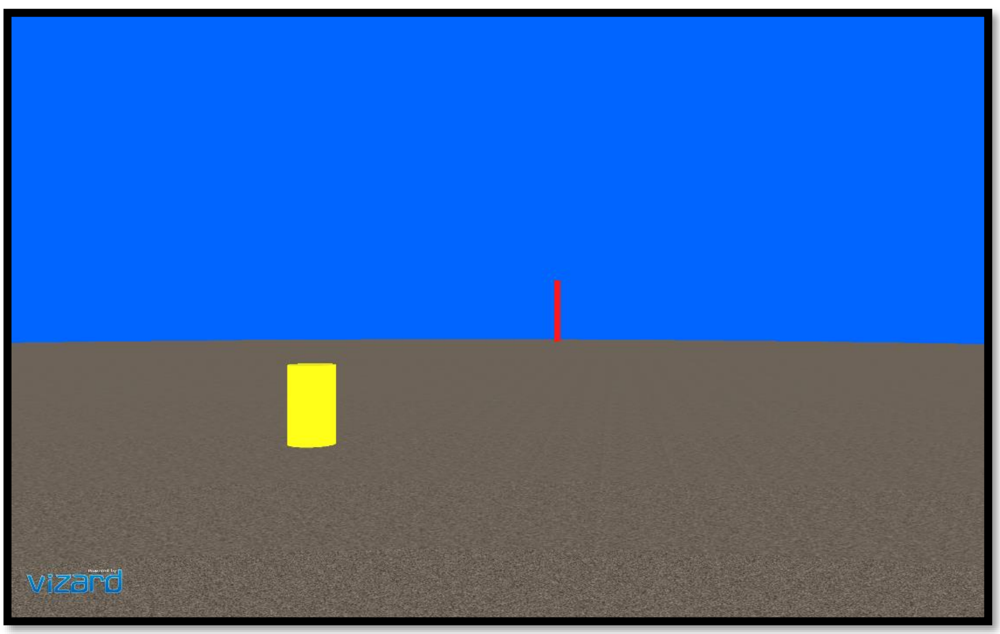


Figure 7: View of the virtual environment with the destination pole (yellow) and the reorientation pole (red) visible

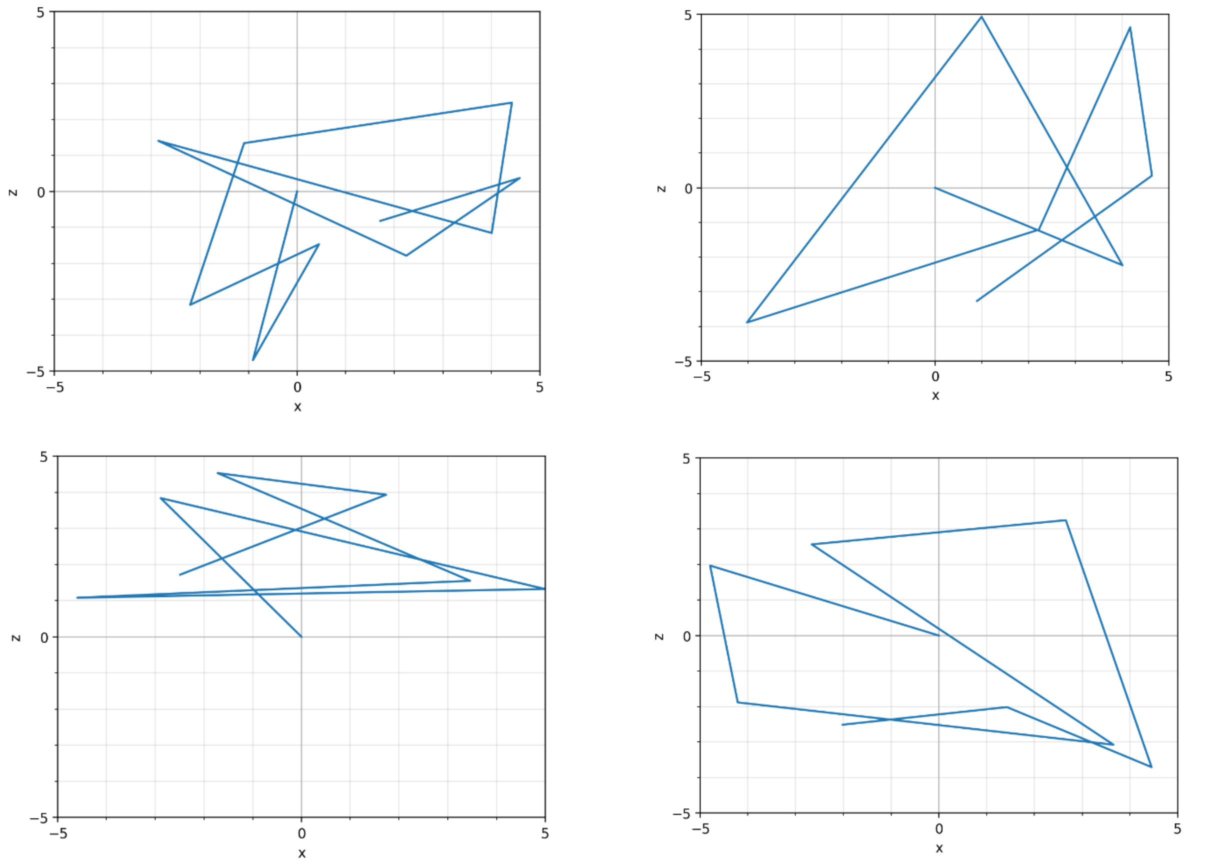


Figure 8: Examples of randomly generated paths within the 10mx10m space

To begin the test, the researcher guided the subject to the center of the room to calibrate the headset's position and orientation. Trials then commenced starting with controls in which the subject could see the next waypoint in their path and received no haptic feedback. Next, the main trials started where the subject could not see their next waypoint and did receive haptic feedback. Specifically, subjects received either single-motor or Gaussian vibrations and were required to move in the direction that they felt the vibration. They received a one second long 'stop' cue which activated all motors across their waist at full intensity to notify them that they had successfully reached the current waypoint. After this they continue receive regular cues to direct them to the next waypoint.

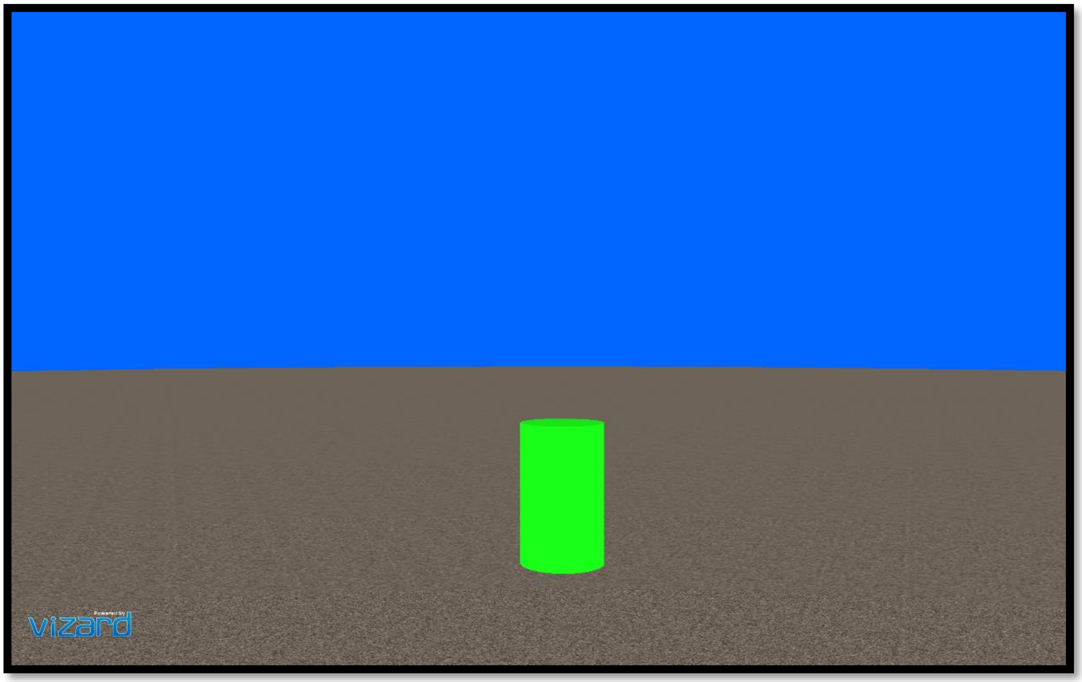


Figure 9: View of the virtual environment with the visible waypoints (green) during control trials where subjects received no haptic feedback

Due to potential nausea resulting from prolonged movement with the virtual reality headset, subjects had a brief break after completing all trials for each belt. The belt order for each subject was randomized as well as the order of the vibration schemes with each belt. However, all single-motor vibration trials were conducted separately from all the Gaussian vibration trials. This allowed subjects to become acquainted with each vibration scheme which would have not occurred had these trials been mixed.

Another consideration was the rate at which the haptic cues were provided. A cognitively loading task such as this makes it easy for the subject to become both tired and desensitized to the vibrational cues over the course of the data collection session. By virtue of human navigation, most subjects orient themselves to face their waypoint and then move forward until they reach it. Therefore, most of the time the vibration cues are concentrated at the front of the subject's waist. This expedites the desensitization process, especially with the single-motor vibration scheme since the vibration is always at 100% intensity meaning no pulse width module is occurring. To minimize these effects, a click rate was introduced to constantly change the stimulus received from the belt. This was done by firing the belt at a frequency that was sufficiently high to prevent latency in the communication between the belt and the subject.

To measure performance, the total time per path was recorded along with the location and orientation of the subject throughout each trial. The subject's path was then compared with the ideal straight-line path to measure the subject's accuracy. These details are outline further in the following section, but it was predicted that, as with the direction perception task, the Gaussian vibration scheme would result in higher accuracy than the single-motor vibration scheme. However, neither scheme is expected to have a better accuracy than sighted navigation represented by the control trials.

5. Results and Discussion

First, it needs to be noted that these are initial results and more data still needs to be collected to provide further insight. Regardless, this section outlines the results for each of the three different experiments to evaluate the different belts and vibration schemes.

5.1 Perceptual Experiment Results

5.1.1 Direction Perception

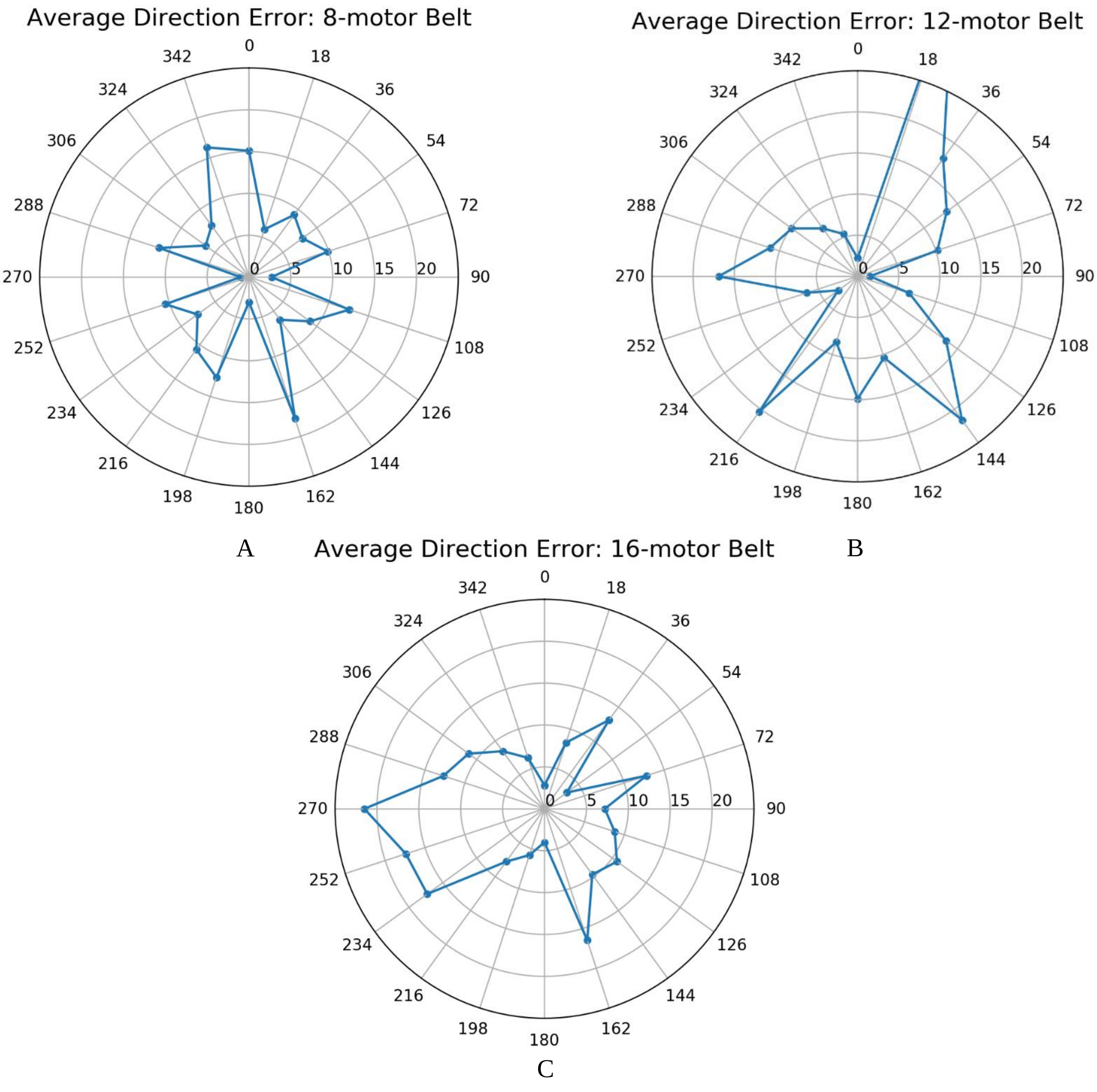
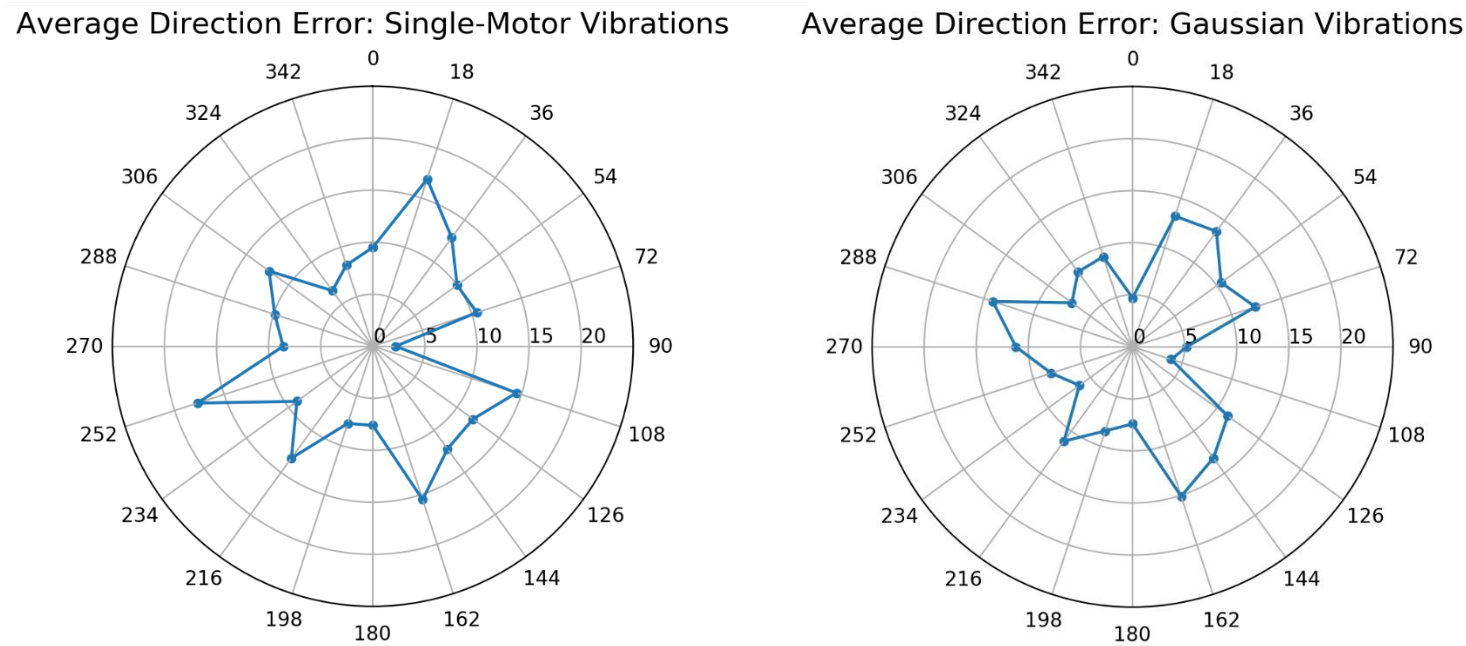


Figure 10(A-C): Plots of mean direction error for each of the 20 experimental bins for all three belts

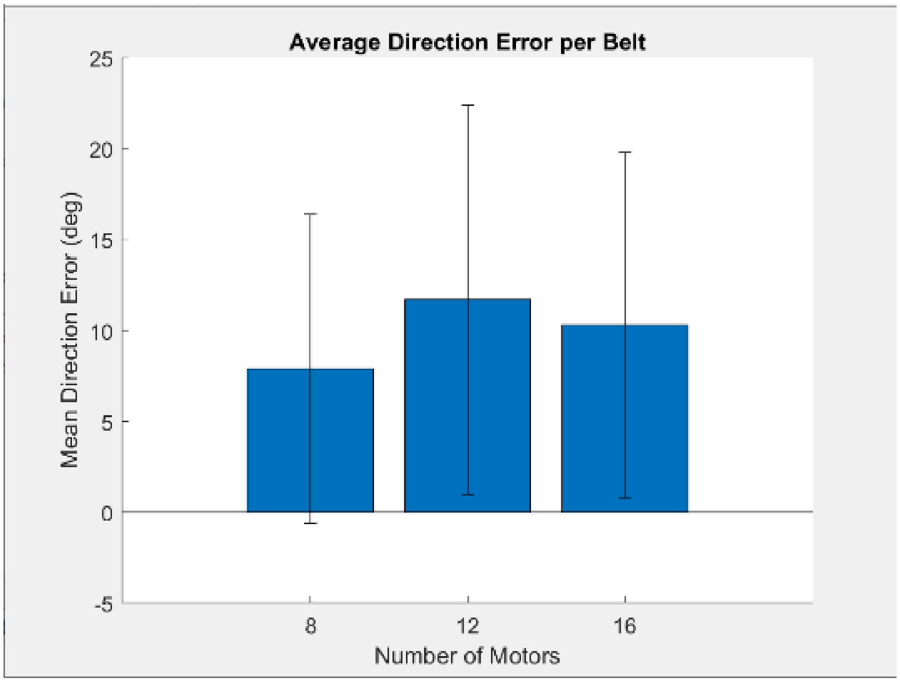


A B

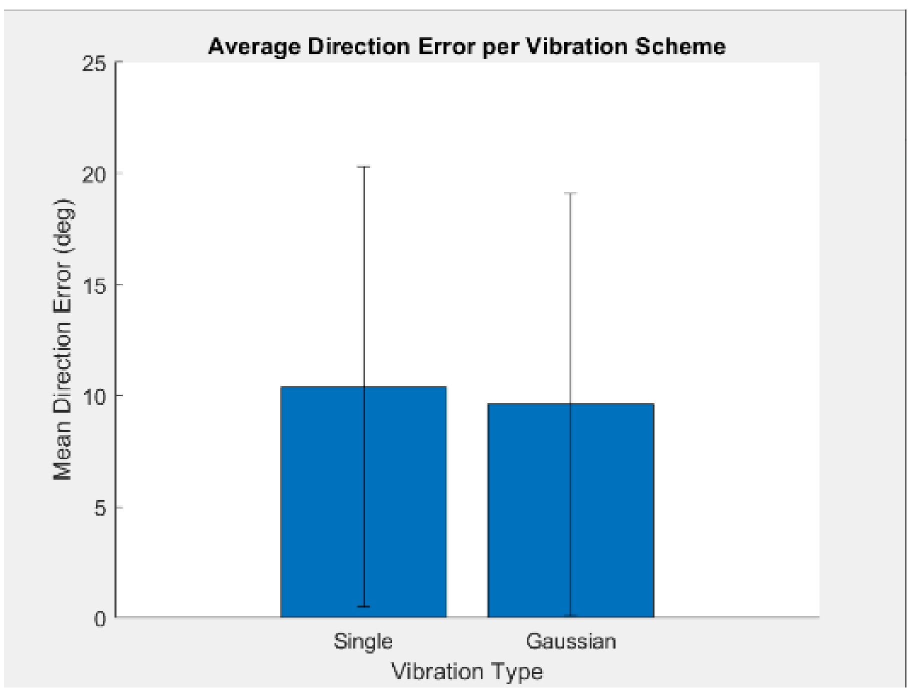
Figure 11(A-B): Plots of mean direction error for each of the 20 experimental bins for both vibration schemes.

The polar plots shown in figures 9 and 10 have a radial axis which ranges from 0 to 25 and represents the mean direction error in degrees. Their angular axis represents the actual angle of vibration that the subjects received also in degrees. One data point at 18 degrees for the 12-motor belt was abnormally large with a value of 37.6. For visual purposes, the scale was set below this threshold, so the data point goes beyond the scale of the radial axis.

These figures suggest that subjects are more accurate when given signals that correspond to the cardinal directions relative to the subject. However, cues at 270 degree had a high error on average. This likely due to the belt hardware since this corresponds to the belt's buckle. The motor mounting is different here since it is just attached to the buckle as opposed to being mounted on the acrylic supports. The 8-motor belt results show higher accuracies for the cues that correspond to bins which directly align with motor locations. On the other hand, the 12- and 16-motor results do not show an explicit favor towards these collocated cues. This suggests that the number of motors does not have a large effect on the accuracy of direction perception.



A



B

Figure 12(A-B): Plots of mean direction error for all angles for the three belts (A) and for the two vibration schemes (B)

Figure 11 supports the previous implication that the number of motors does not directly correlate with direction accuracy. The same can be said for the two vibration schemes. In both cases, the aggregate errors are very similar relative to the large variance meaning there is no significant relationship for either variable group.

5.1.2 Relative Intensity Perception

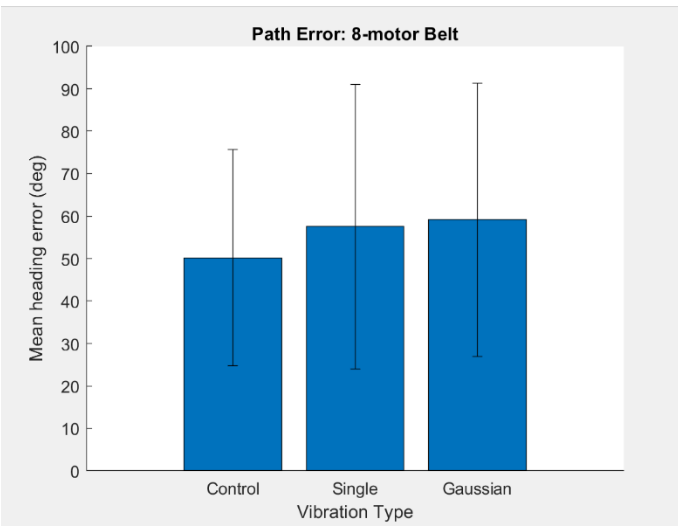
Test Number	Number of Trials	Intensity Difference Threshold (%)
1	76	14.09
2	95	26.54
3	82	25.06

Table 2: Results for each of the three initial relative intensity tests

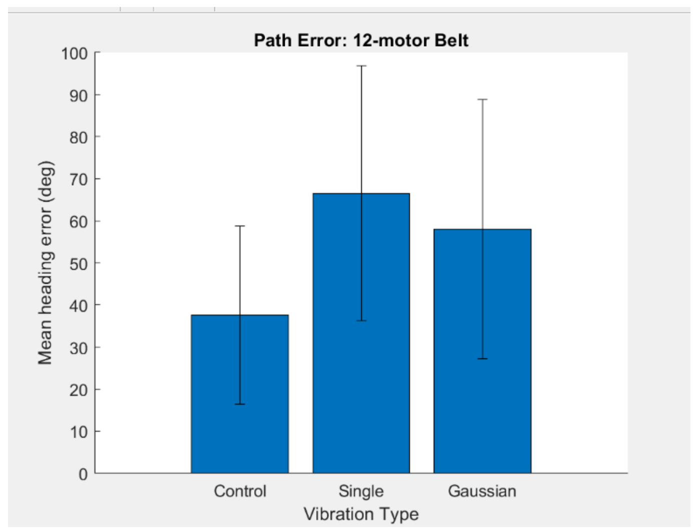
Initial testing from three separate experiments with the QUEST+ algorithm resulted in threshold intensity differences shown in Table 2. The number of trials here refers to the number of vibration pairs the subject received before the trial completed. The three trials were done sequentially on a single subject. The large discrepancy between the first test and the next two suggests that the subject may have experience some level of desensitization to the stimulus. The threshold intensities are relative to the full intensity scale ranging from 0% (motor off) to 100% (motor firing at maximal intensity). This suggests that there needs to be an approximately 25% intensity difference between two adjacent motors for a subject to reliably discern which motor is vibrating stronger.

5.2 Locomotion Experiment Results

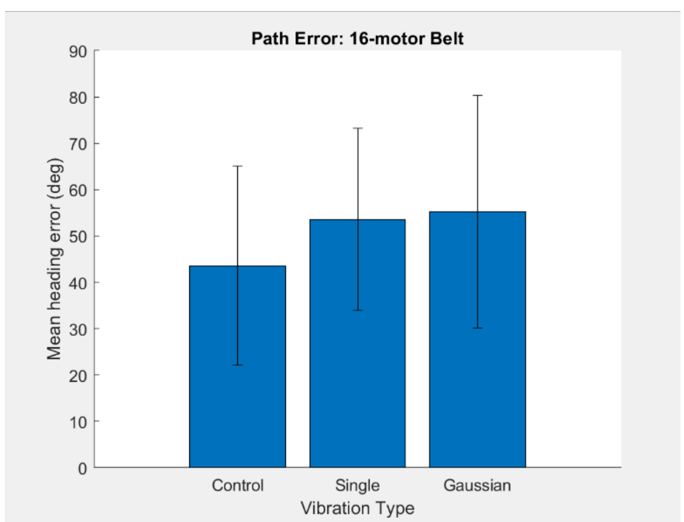
The data was processed for each belt consisting of 12 total paths with 2 controls, 5 single-motor, and 5 Gaussian vibrations per belt. The average path time, path error (with respect to orientation in degrees), and path length are plotted below for each belt. These are split between the three experimental groups: control, single-motor vibration, and Gaussian vibration. In addition, path time is plotted against path number to observe how subjects adjusted, if at all, to each belt as they completed sequential trials. The first 2 control trials are not included in these plots since they do not utilize the belt system. Hence, the x-axis starts at path 3.



A



B



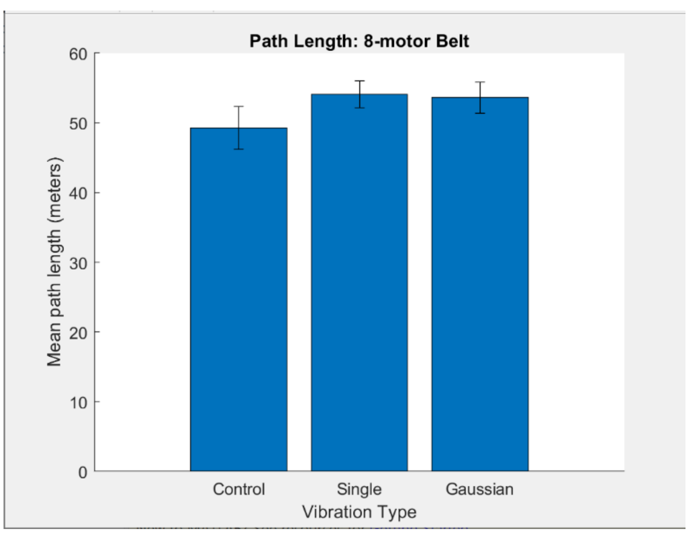
C

Figure 13(A-C): Plots of average heading error in degrees for the three different vibration categories. Plot A through C correspond to the 8, 12, and 16 motor belts respectively

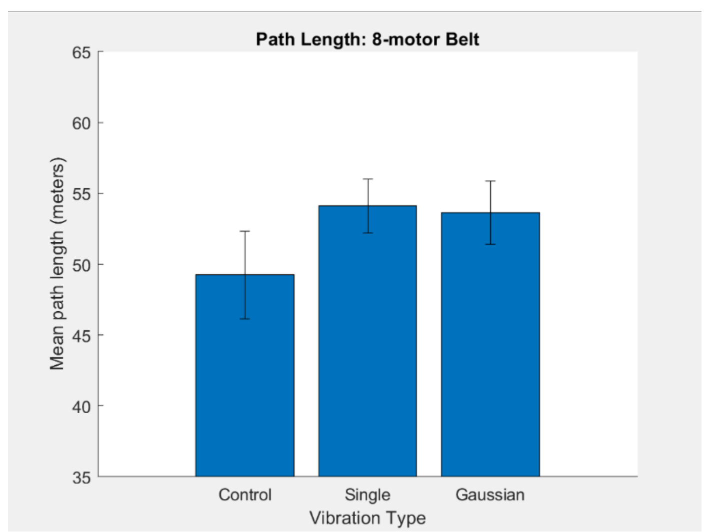
From these figures, it is evident that there is a large variation in heading when compared with an ideal, straight line path between waypoints. Walking generally does not follow ideal straight line paths and the transfer of weight between feet adds some oscillation to the movement. Therefore, some deviation is expected. Furthermore, once a waypoint is reached there is sudden change in the ideal path's orientation but it takes the subject some time to adjust their orientation to the correct direction in both the control and vibration cases. This is likely a large contributer since orientation error could be as high as 180 degrees immediately after the subject reaches their current waypoint and the new one is queued.

Furthermore, it is expected that the control would have the least heading error since subjects can see their waypoint. Both single and Gaussian vibration schemes had similar averages although the large variance suggests that these differences are not significant. The same can be said for the differences between the three belts. This large variance suggests that path error is strongly dependent on the paths. This also makes sense since the paths are fixed in length only and can therefore have a varying number of waypoints with different sharp turns. Certain paths may have fewer segments with relatively small turns compared to others. This is likely a larger factor than the effect caused by the different belts or the vibration scheme.

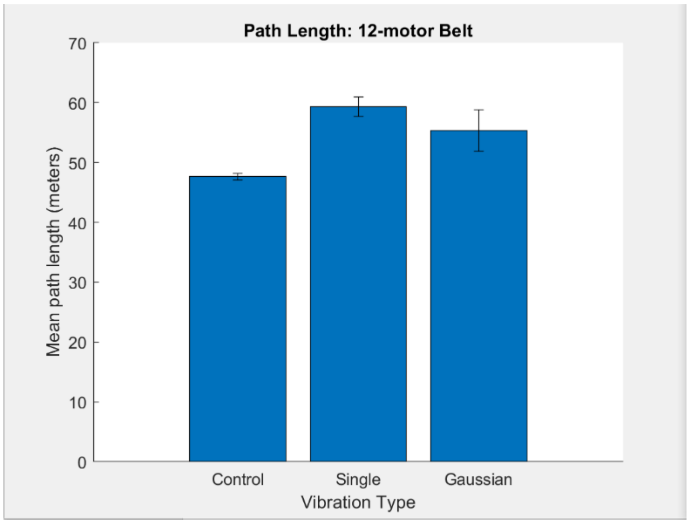
Another important consideration with this measure is that an error in orientation (or location) is not necessarily suggestive of poor communication between the belt and the subject. If a subject deviates at all from the ideal path between two waypoints, their new ideal path has changed. However, even if they are perfectly following this new ideal path, it will still register an error in orientiation or location.



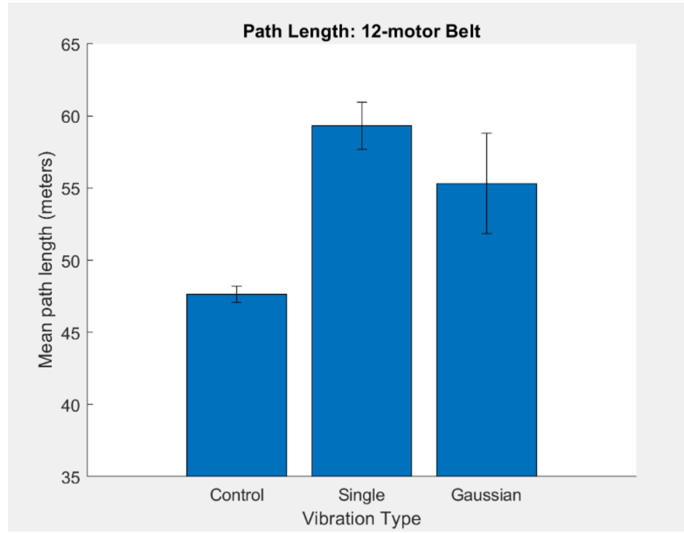
A_1



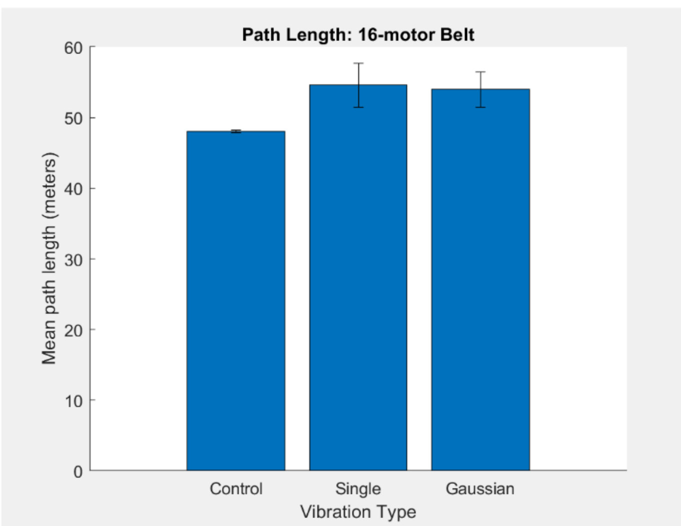
A_2



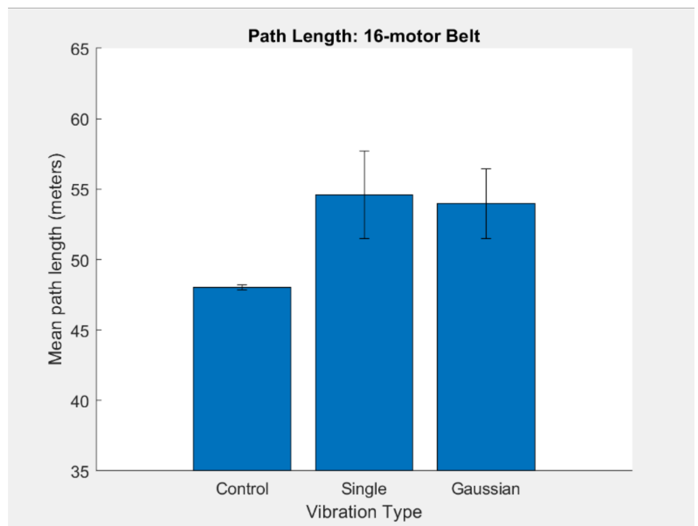
B$_1$



B$_2$



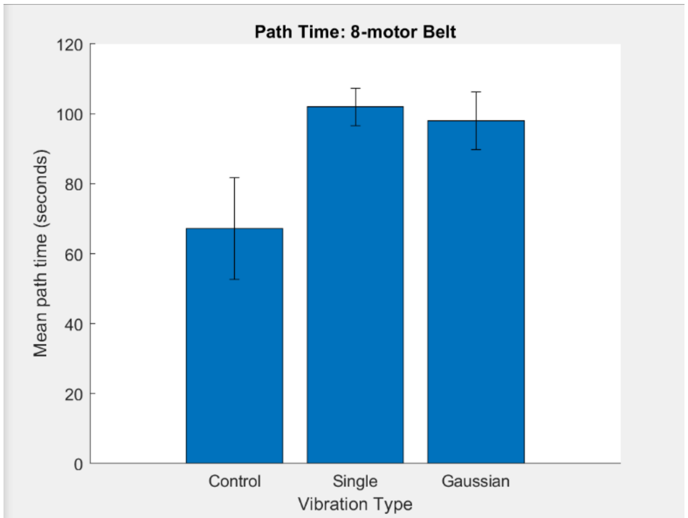
C$_1$



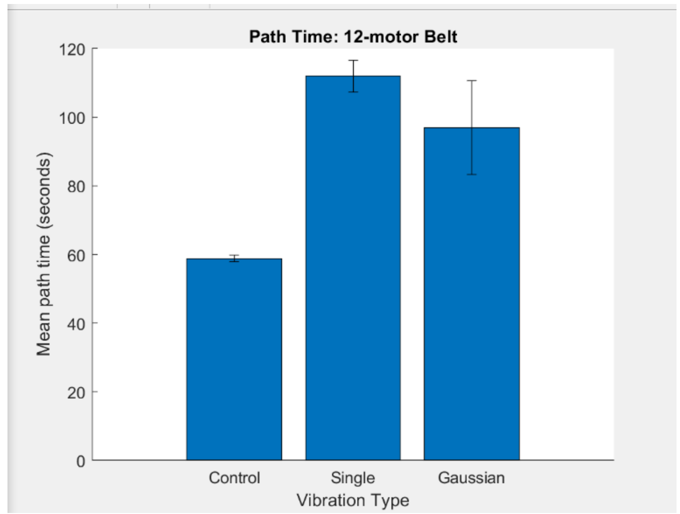
C$_2$

Figure 14(A-C): Plots of the subjects' path length for the three different vibration categories. Plot A through C correspond to the 8, 12, and 16 motor belts, respectively. Plots x_1 and x_2 are identical except the later has an altered y-axis scale.

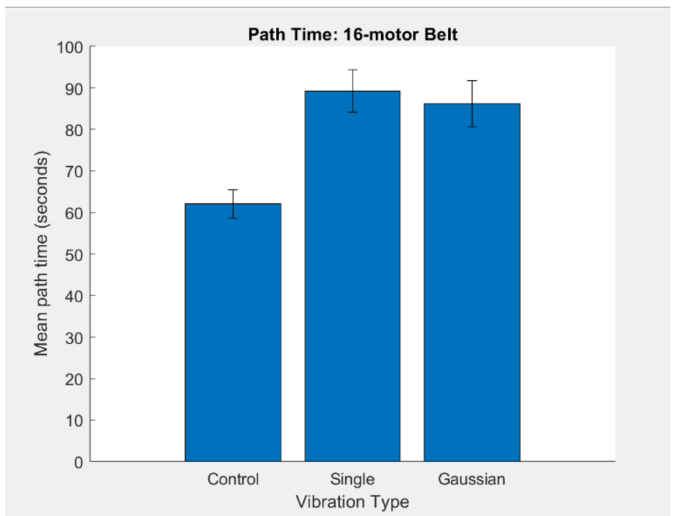
As expected, subjects completed the control paths with a shorter aggregate path when compared with both the experimental groups. These figures also reveal that there is minimal difference between the Gaussian and single-motor vibration schemes. However, the Gaussian vibration scheme results in slightly shorter path lengths than the single-motor scheme for each of the three belts. When accounting for the data spread these differences do not seem significant, but it is worth noting the trend. Again, the number of motors seems to be unimportant as the mean values for each belt are very similar. Collecting data from more subjects will prove helpful in determining a significant difference for both the vibration scheme and the number of motors if one exists.



A



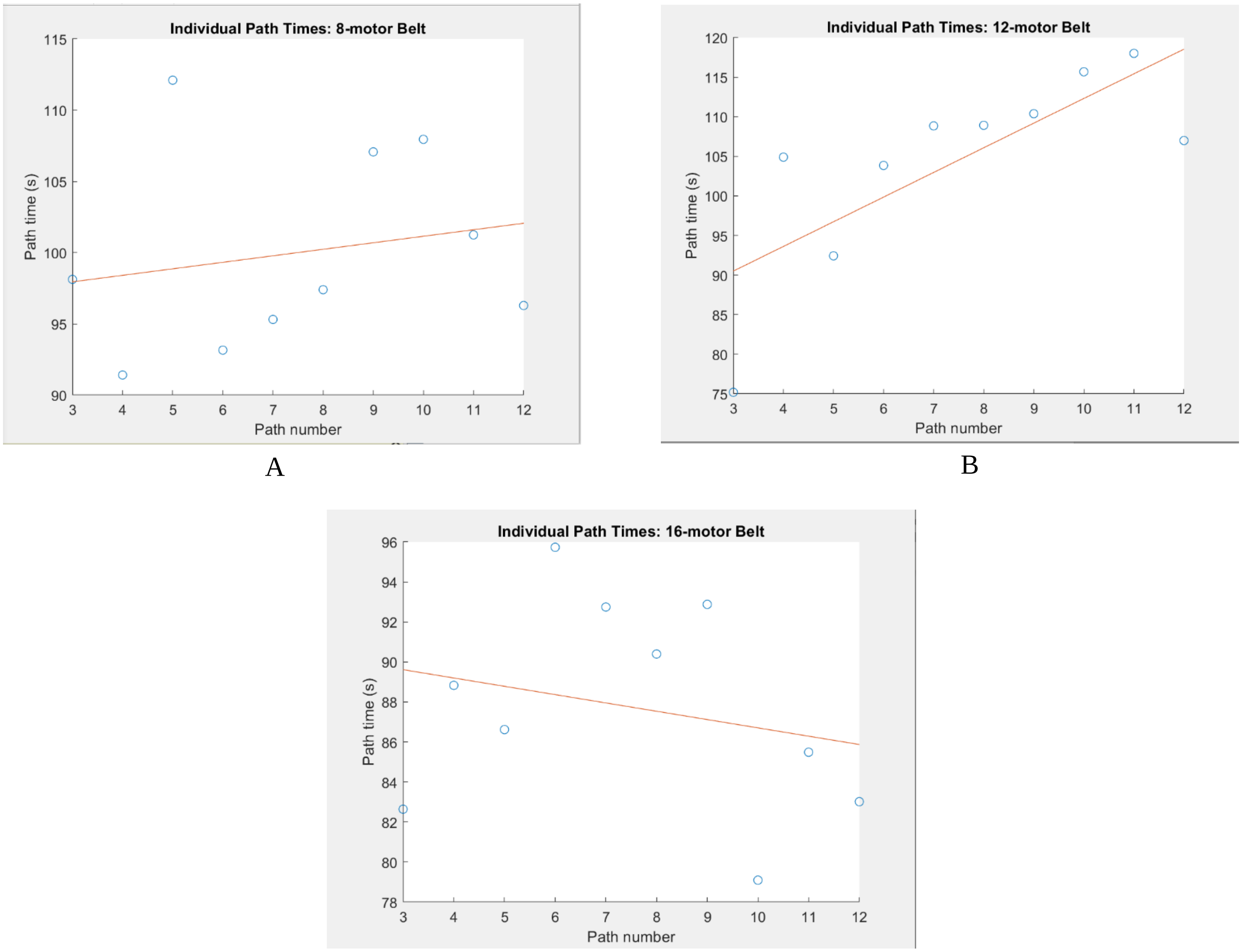
B



C

Figure 15(A-C): Plots of the average path time for the three different vibration categories. Plot A through C correspond to the 8, 12, and 16 motor belts respectively

The trend in path time matches that shown by the path lengths – that the Gaussian scheme results in slightly lower path times but is comparable to the single-motor scheme. Furthermore, the 16-motor belt resulted in lower average path times than the 8- and 12-motor belts. The discrepancy between the control trials and the experimental groups is more evident here. While the path length contributes to the difference times, the larger increase relative to the control trial suggests that subjects can mostly follow the correct path but they traverse it slower. This is again unsurprising since subjects have no information about the distance to their waypoint, they are only told the direction to move in. In control trials they can see the waypoint and are therefore also aware of their distance from the target. They can then modulate their speed accordingly which likely contributes substantially to the lower path times.



A

B

C

Figure 16(A-C): Plots of the path time for each path which used a vibration scheme. Plot A through C correspond to the 8, 12, and 16 motor belts respectively

Lastly, Figures 16A-16C show a variation in path time over the course of the trials with each belt. The distributions show a weak correlation with each belt. The 8- and 12- motor belts show an overal increase in path time as the path number increases while the 16-motor belt shows a decrease. This inconsistency between the three belts and the weak correlation suggests that there is not much difference in path time as path number increases. As more data is collected this uncertainty will likely be reduced.

6. Conclusion and Evaluation

The purpose of this study was to examine the effect of the number of motors on a haptic belt and the vibration scheme – single-motor vibrations or Gaussian vibrations - on perception and locomotion. The first two experiments focused purely on the perception of vibratory cues supplied by the belts. The first investigated direction perception to see if the number of motors on the belt or the vibration scheme affected subject accuracy when specifying the direction in which they sense a vibration. The latter focused on relative intensity perception where subjects had to specify which of two adjacent, vibrating motors vibrated at a higher intensity. Using the iterative QUEST+ algorithm, a threshold intensity difference was determined. The result of these experiments suggests that there needs to be an intensity difference of approximately 25% for subjects to reliably distinguish two vibrating motor intensities. Furthermore, the direction perception experiment revealed that there is no substantial relationship between the number of motors on the belt (the motor density) and the accuracy with which subjects can specify vibration directions. The same can be said for the two vibration schemes. However, it is important to note that these results are initial findings and acquiring more data is crucial before such conclusions are accepted.

The final experiment utilized the belt system in a more practical environment where subjects navigated invisible paths using each belt and vibration scheme. Again, initial results suggest that there is no correlation between the motor density and path accuracy. Although there was no significant difference between the two vibration schemes either, consistent reductions in path error and path time suggest that the Gaussian scheme may prove to have a slight edge over the single-motor vibration scheme as more data is collected. Path time over each trial also varied substantially suggesting that any desensitization over the course of the trials was less significant than the effect of the path shape. Another factor to consider is the short nature of the paths in question. The spatial limitation from the limited laboratory space means that waypoints can have at most a 14-meter separation. Most path segments are substantially shorter than this so there is limited distance over which errors in both location and orientation can occur. Frequent waypoints have a large contribution to these errors as subjects take time to reorient and face the direction of new cues. In a larger space with longer path segments, the discrepancies between the different belt densities and vibration schemes, if any, may become more apparent. For the Gaussian scheme, a whole alternate experiment can be run to determine the ideal standard deviation to implement for the vibrations. This is likely something that is dependent on motor density as suggested by the results from the relative intensity task. As motor density changes, the distance between motors also changes. If the subject is unable to discriminate between adjacent motor vibrations, then the benefit of increased motor density is lost. In theory, decreasing the variance of the distribution as the motor density increases provides a greater discrepancy between neighboring motor intensities. Whether this translates to improved accuracy is something worth testing.

Another important consideration is familiarity. Since the system is aimed to help those with visual impairments, it is important to test the system with members of this community going forward. A lack of visual information is quite jarring for subjects as is made evident by the large change in path time between the control paths and the belt-aided paths. Sensitization could also vary between visually impaired subjects and sighted subjects which could also alter results. Regardless, the effectiveness of the system suggests that such vibratory cues are effective for guiding users to desired waypoints. The current, simple cues are just an initial idea which can expanded to a whole variety of cue types. Rather than providing purely directional cues, subjects could receive signals which indicate the direction in which they should turn rather than specifying the exact angle to move in. Motor distribution could also be varied. Most subjects navigate by turning in the direction of their waypoint and then moving towards it in a straight line. Therefore, most of the time it is only the motor directly in front of the user that is vibrating. Reducing the number of motors concentrated around the users back could therefore be a cost-cutting mechanism which can provide higher acuity towards the users' front.

Adjustments to the belt hardware are also important to consider. As mentioned, the motor on the buckle showed to have a lower accuracy when compared with most other motors. Reducing the amount of solid material in contact with the motors will likely improve user sensation. Less vibrations would propagate through the belt to neighboring motor mounts – which is especially important for higher motor densities – and vibrations would likely be more focused on a smaller location. Contact with the wearer is also easily affected by minor changes in their posture or position so finding a tighter fit that does not jeopardize comfort is an important improvement. Generally reducing the amount of hardware in the belt design will likely improve results which is important to consider as the project moves forward. An example of an improvement may be sewing motors into the belt directly rather than having solid acrylic supports.

Overall, this study was helpful in determining the effectiveness of a haptic belt system for human navigation. Although it showed that such hardware, combined with simple vibration schemes, are effective for navigation, it is still important to consider how these results vary for the final user. Furthermore, it has raised the question of what alternate gestures and vibration cues can be utilized with such a system. Collecting more data for these tests is an important step to solidify the conclusions drawn here, but regardless there are many subsequent steps that can help improve navigation for people with visually impairments.

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