Hyperacuity and Navigation Testing with Haptic Belts

Julian Vallyeason

Submitted On: April 28, 2020

Submitted in partial fulfillment of the requirements of the degree of Bachelor of Science *with Honors* in Engineering

School of Engineering, Brown University

Prepared under the direction of:

Professor Benjamin Kimia, Advisor

Dr. Brian Free, Reader

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

____

Advisor's Signature

____

Reader's Signature

____

Honors Chair's Signature

BROWN

Table of Contents

Acknowledgements

I would like to acknowledge and thank Viktor Ladics for his support and help as we worked together in LEMS to build and test haptic belts, Hongyi Fan for the tremendous amount of time he put into training me in lab as my direct supervisor and for our weekly guidance meetings, Professor Benjamin Kimia for his guidance and support as my thesis advisor, and Dr. Brian Free for his help as my reader and for teaching me and giving me access to the VEN Lab for virtual reality tests. I would also like to thank all of the members of the LEMS group and the VEN lab for their help and resources throughout this project.

1. Abstract

Haptic belts are an emerging candidate as a navigational tool using vibrotactile communication. These belts use vibrating motors along the waist to communicate information to a user through variations in vibratory position and intensity. This thesis seeks to (1) investigate the effect of haptic belt motor density on vibratory perception of direction, (2) examine the efficiency of single-motor vibration vs. vibrating a distribution of motors at varying intensities, and (3) understand how vibratory perceptions are interpreted into a navigable direction.

Two belts, with eight and twelve vibrating motors equally spaced around its circumference, were tested with two different vibration schemes. The first scheme directly vibrates the motor most nearly corresponding to the intended direction to be communicated (single-motor vibration) ; the second scheme vibrates a “Gaussian blob” of motors at varying intensities, with the motor closest to the intended direction vibrating at the highest intensity, and adjacent motors vibrating at correspondingly lower intensities.

Vibrotactile perception tests demonstrated that increased motor density does not necessarily yield lower errors in perception but does allow for a greater range of directions to be specified under single-motor vibration. These tests also demonstrated acuity in spatial perception for the Gaussian scheme, with a mean angle error between intended and perceived vibrations of 13.7^{o}. Discrete control and continuous feedback tests were performed using both belts and both vibration schemes on a wayfinding task and a maze task. Continuous feedback for the Gaussian scheme allowed participants to successfully navigate both the wayfinding and maze task with a mean deviation distance of 0.32 and 0.36 meters respectively. This demonstrates a high level of steerability and potential viability for the Gaussian scheme as a means of communicating directional information to the visually impaired.

2. Introduction

An estimated thirty-seven million people around the world are classified as legally blind and require the use of assistive navigational technologies [1]. An additional two-hundred million people suffer from some form of significant visual impairment, which inhibits them from performing everyday tasks [1]. Although technologies do exist to help manage their mobility, there are no inexpensive and effective solutions that allow for independent mobility over a large variety of distances.

Most navigational technologies for the visually impaired focus on two tasks: obstacle detection and avoidance, and wayfinding. When we use our vision, we can view our own position with respect to the spatial configuration of surrounding objects. This external information, provided through visual cues, is critical to position-based navigation; we instinctively keep track of our orientation in our environment, and appropriately adjust to a changing environment [2]. However, this information can also be relayed through other sensory modes, including tactile, olfactory and auditory cues. Key issues in building systems to communicate this information in these ways include:

(1) possible intrusion into the existing capacity of a sensory mode
(2) difficulty in distilling visual feedback into low-complexity data without information loss
(3) developing an encoding scheme that can be reliably learned and continuously provide sensory feedback

A critical component of assistive technologies is finding a way to encode spatial positions and orientations through these other modes in a nonintrusive manner.

Widely used tools to aid in obstacle detection are the guide dog and the long (white) cane. The long cane combines tactile and auditory feedback to provide the user with low-resolution about the proximal environment [3]. While this provides specific information about nearby obstacles, it limits navigation to paths along an edge in unfamiliar environments. Guide dogs are generally viewed as more effective due to the added benefit of auditory feedback in obstacle detection and the ability to take direct routes between objects [3].

Modern technologies hope to combine wayfinding and obstacle detection capabilities by integrating multiple navigation and environment communication techniques into a single platform. Sonar and infrared systems can be combined with a GPS-based navigation system to guide users along a path with consistent tactile and auditory output. However, these systems are often bulky, difficult to use, and cost-prohibitive. A summary of commercially used navigational technology is provided in Table 1.

Designing and developing a system to help the visually impaired navigate distances from 10 to 500 meters still remains an open field of study.

Table 1: Summary of Navigational Technology by the Visually Impaired

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

Below is a literature review examining several pertinent fields of study relevant to the design and construction of a haptic navigation system. Section (2.1) examines several different methods of conveying positional information to a visually impaired user. Ultimately, this section focuses on recent experiments performed with vibrotactile technology. In Section (2.2), the underlying motion planning algorithms behind navigational technology are discussed. A brief summary of several of the key findings in the field are presented, along with several examples. In Section (2.3), findings from recent literature on human thresholds for vibration perception are discussed. Building on an understanding of how we perceive vibrations, Section (2.4) discusses possible methods of conveying information through vibrotactile encoding schemes. Finally, Section (2.5) provides a research overview comprising the goals and purpose of the current study.

2.1 Navigational Systems for the Visually Impaired

Recent studies have sought to expand upon existing technology by using novel ways to encode and communicate environmental obstacles to users. One study proposed the use of an enhanced white cane, with infrared scanning of nearby objects [4]. They proposed a mechanism through which users can understand the distance and shape of nearby objects through an encoding of vibratory and auditory cues. The general structure of the system they used (see *Fig. 1*) is common among many tools for the visually impaired.

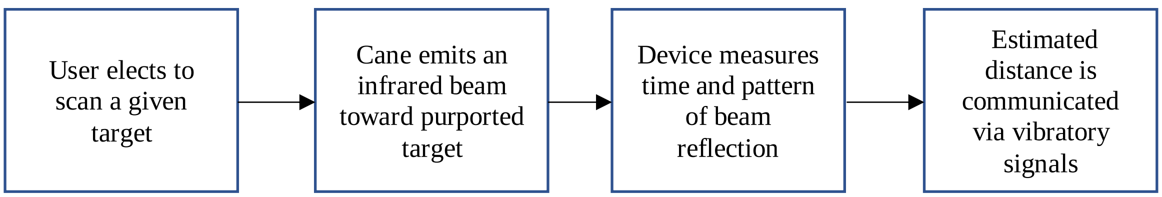


Figure 1: Schematic depiction of sensing and encoding of nearby obstacle with infrared technology. (Adapted from [4]: The 'EyeCane' a new electronic travel aid for the blind)

They observed that vibratory cues from the cane can successfully be used to communicate an object's position to a user; after five minutes of training, 84.3% of visually impaired participants could accurately estimate an object's distance to the nearest 0.5 meters [4]. While this was promising, the authors noted that this device did not solve the possible cultural stigma associated with a cane and was meant to be used within an array of different tools to assist with obstacle detection. Auditory cues were generally disfavored for vibratory cues due to their potential to disrupt participants' hearing ability; in especially crowded or unfamiliar environments, auditory cues are a primary source of positional information for the visually impaired [2,3]. Furthermore, when compared to navigation without any aids, the tool did not significantly prevent more collisions.

Another study built upon these findings by studying methods to integrate this technology into walking aids for the mobility-impaired; over 80% of blind people worldwide are over the age of 50 and are likely to need this type of assistance [5]. The smart walker presented in this paper by Wachaja *et al.* demonstrates a proof-of-concept of two key paradigms in the paradigm of navigation: (a) vibratory patterns on the handle of a walker can serve as a form of feedback to guide a user along a specified path and (b) systems can be built to provide an adjustable level of autonomy in mobility.

Wachaja's study used two vibration motors to encode four different directions (straight, left, right, goal) through differential vibration of motors at the same intensity. Although they observed a fast reaction time, they had significant variability in both reaction time and rotational radius (r) across all participants studied; this makes it difficult to build a navigational controller, since frequent corrections to a user's path may be needed. They proposed a controller model that continuously calculated waypoints and turning positions by experimentally calculating the turning angle (α) and turning distance thresholds (d_{max}) as:

$$\alpha_{thresh} = \arctan\left(\frac{d_{max}}{r}\right) \qquad \text{(Eqn. 1)}$$

$$L = \frac{r}{\cos(\alpha_{thresh})} \qquad \text{(Eqn. 2)}$$

Graphically, these two variables can be experimentally determined from experiments as shown in Figure 2 below.

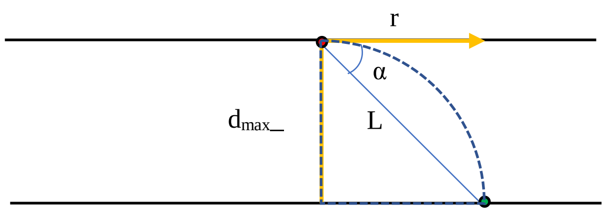


Figure 2: Calculation of turning angle and distance to initiate turning sequence based on individual experimental data from Wachaja et al. [5]. *The red and green dot represent the user and destination respectively. The r-vector and d-max represent the horizontal and vertical distance from the destination.*

Although this suggests that vibration feedback devices will need to be user-customizable due to variations in r and α across different people, it shows that vibrational encoding can be effectively interpreted into directional information on a fundamental level. This idea was expanded upon in a study by *Katzschmann et al.*, where they developed an array of lidars and vibrotactile units (ALVU), which sought to provide haptic feedback on nearby obstacles [6].

This device builds upon existing ActiveBelt technology, which used directional information from a GPS receiver to provide an indicator on a user's orientation relative to a goal node [7]. However, a key issue noted in that paper was a lack of encoding of local obstacles, which are more relevant to the immediate wayfinding ability of visually impaired users. Katzschmann's paper seeks to address this by using a sensor array mounted separately from the vibrotactile unit, which measures distances to nearby obstacles in a pre-built experimental map. Results suggested that it is possible to provide navigational information to users without requiring any physical contact with the environment. However, the ability of users to sense their relative distance from obstacles due to vibrational intensity and the ability of the obstacle-detection system to accurately relay information on a variety of different obstacles remained a question for future exploration.

Shown below in Figure 3 is a schematic of the systems involved in encoding sensor measurements into vibrations. This forms the basis of vibrotactile belt structure for future work.

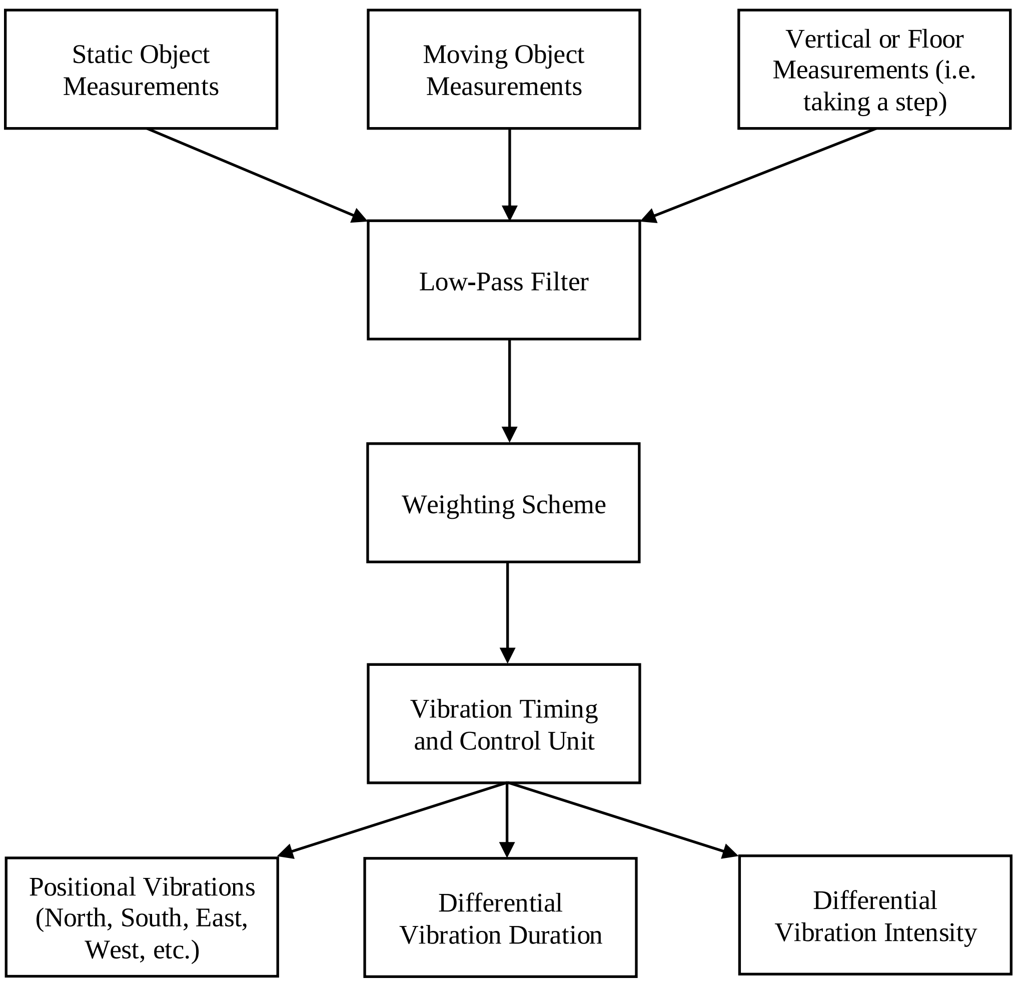


Figure 3: High-level schematic for processing of environmental measurements into vibrational encoding patterns. (Adapted and Modified from [6]: Safe Local Navigation for Visually Impaired Users).

2.2 Wayfinding and Motion Planning

The core component of most navigational devices is an underlying algorithm to guide people between two points. Given the infrastructure to communicate directional information to a user, a critical step is to be able to generate a path within an environment and ensure the path is followed. Two common world representations that are often used in testing are a "Grid World" and a "Polygonal World" (see Figure 4) [9]. Several of the methodologies that have been developed to efficiently navigate these worlds are briefly outlined below.

In a grid world, each square can be considered a node, with obstacles encompassing a certain configuration of squares. Here, A* informed search is an effective tool in pathfinding toward a goal. A* search generates two sets, a "frontier" and an "explored" set of nodes. It moves nodes from the frontier in order to optimize a given consistent and admissible heuristic. Commonly used heuristics include the Manhattan distance and Euclidean distance. However, while useful in preliminary testing, this often fails to encapsulate real-world navigation. A modification to A* is Jump Point Search (JPS), which handles asymmetries in grid worlds by jumping between nodes adjacent to obstacles [10].

A polygonal world is often used to more accurately reflect navigational principles of constrained visibility. Due to an infinite number of valid positions and possible directions, visibility graphs are used as a tool to prune the number of possibilities. Only protruding corners (convex) which can be seen from one another are included in a visibility graph, and A* can then be used to build an efficient path [9]. However, these algorithms are not well-suited for dynamic maps with moving obstacles.

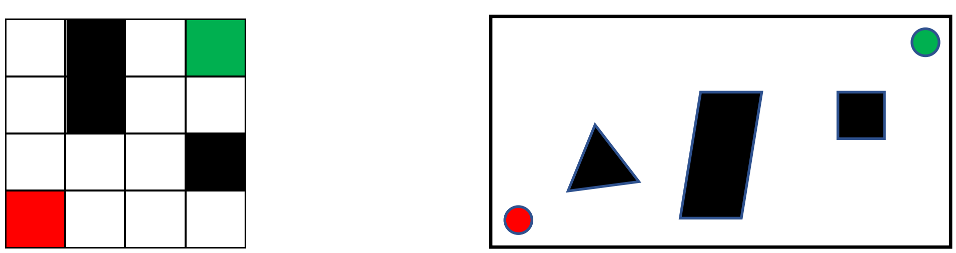


Figure 4: Schematic representation of a 'grid world' and 'polygonal world'. Similar encoding is used when building these environments in virtual reality. Red and green circles represent start and end nodes respectively, while black objects encode obstacles in the environment.

A recent study by *Wang et al.* built upon these assumptions and used a vision and vibratory-feedback system with a haptic vibration pad attached at the abdomen [11]. In this study, they had participants navigate until they reached an obstacle, at which point the system would guide them away from the obstacle in the direction that maximized free space; they used the Manhattan distance under the Grid World assumption to calculate free space.

Although this study did not actively provide navigational information to the participants, it did show that a grid world assumption was compatible with simple navigational and obstacle avoidance tasks. Participants were able to navigate a “shore-lining” task where they walked along a curved wall and could navigate to a chair placed among other items. However, in both tasks, vibrational cues served to either, (1) detect nearby obstacles, or (2) point toward the direction of a desired object; they failed to encode both pieces of information at the same time. Building a system that both detects and informs users of obstacles, while providing pathfinding capability toward a goal remains an active area of research.

2.3 Vibratory Perceptions

Vibratory perceptions are important as a means to understand how quickly and how accurately we infer directions from a set of vibratory cues. This serves as an important metric in assessing the efficacy of any given vibrational scheme. Position and intensity of motor-firing sequences should be engineered in such a way as to minimize subject response time while ensuring that subjects can accurately discriminate between where the source of vibrations is coming from. This section examines variations in subject responses to different vibrations in order to understand how we perceive and interpret motor vibrations.

A previous study examined vibrotactile pattern recognition using various motor arrangements to study the way we perceive different vibrational cues [12]. Subjects were given 1D and 2D tactile arrays (see Figure 5), which then vibrated in several circumferential patterns. Across all trials, they found high (> 90%) accuracy in both 1D and 2D arrays for individual motor identification, direction identification, and clockwise/counterclockwise pattern recognition. The strong performance observed in detecting these patterns indicate that they demonstrate potential in being used to encode information on the environment. In particular, there was little difference between the accuracy between the 1D and 2D arrays in detecting vibratory patterns, suggesting that vibratory cues on the torso can be easily identified. However, subjects performed slightly better in recognizing patterns where a group of motors vibrated in a certain region vs. identifying a single motor that was vibrating within an array. This suggests that while we do have haptic sensitivity, we might be better tuned toward recognizing groups of motors vibrating toward a general direction, rather than a single motor vibrating in a specific direction.

(A) (B)

Figure 5: (A) For circular tactile arrays on the waist, subjects better identified regions of motor activity (yellow -> orange -> red) than a single motor being turned on (green). (B) For two-dimensional tactile arrays on the torso, subjects performed best in identifying directional patterns (motors being turned on in sequential clockwise fashion). (Adapter from [12])

This is supported by a study conducted by Dura *et al.*, where they found that visually impaired participants preferred direct vibrational cues (Figure 5A), rather than guiding motion patterns (Figure 5B) when asked to walk around a circular track [13]. In order to provide direct vibrational cues, it is important to have enough motors to be able to specify directions with accuracy. However, there is a concern that people may be unable to discern between two motors vibrating within close proximity of one another.

Johannesson et al. published a paper that sought to address these concerns. Over three experiments, they showed that subjects retained spatial tactile acuity for motors that vibrated at distances as close as 13 mm apart [14]. When given two vibrations and asked whether the second vibration was to the left, right, or the same as the first vibration, participants had an accuracy of 64% for a 13 mm motor separation, which increased to 92% for separations of 30 mm. This spatial acuity suggests that an array of vibrational motors spanning the waist might be highly effective in communicating directions to a user with a high degree of specificity.

Johannesson's findings are confirmed in a similar paper by *Cholewiak et al.* [21], which found that the ability to localize vibratory stimuli is a function of separation between each vibratory locus. In their experiments, they examined detection thresholds for vibration on twelve sites around the abdomen. There, they found that people tend to interpret vibrations relative to specific loci around the body (generally the spine and the navel). Thus, performance for detection thresholds were best around the spine and navel and became poorer at interpolated positions between the reference loci.

2.4 Vibrotactile Encoding Schemes

Despite evidence that vibrotactile stimulation can encode spatial and directional information, no standardized scheme or methodology exists to represent a proximal environment through vibrations. This section examines several key considerations in vibrotactile encoding schemes: single-motor vibration vs. vibration of nearest motors, on-course vs. off-course vibratory feedback, and frequency of vibratory feedback.

In one study by *Heuten et al.*, participants were asked to indicate which direction they felt was represented based on two different vibration schemes: direct single-motor vibration, and vibration of the two nearest motors [15]. Although single-motor vibration was effectively recognized, it failed to capture the wide variety of possible directions one might have to use in an unfamiliar environment; the range of possibilities was constrained by the number of motors. However, when two adjacent motors were activated, there was a high degree of deviation among participants between the expressed and perceived direction.

These results can be combined with those from another study by *Marston et al.*, which found that among the visually impaired, consistent vibratory feedback was preferred (when on-course and when off-course) to selective feedback [16]. Participants preferred to receive a vibration signal when off-course and no signal when on-course as compared to receiving no signal when off-course and an indicator signal when on-course. This suggests that encoding schemes should seek to provide consistent feedback to the user that is more focused on detecting deviations from a path, as opposed to reinforcing motion along a path.

Results from both studies were finally integrated into a preliminary navigational planning device, which combined a low-cost microcontroller, vibrational motors, and an elastic, concealable haptic belt [8]. Directional and rotational instructions were encoded using four different schemes:

I: Solo Once. II: Solo Twice III: Solo Continuous IV: Dual Continuous

The first and second scheme involved individually activating a motor once or twice, while the third and fourth scheme involved continuously activate either a single motor, or multiple motors at the same time. The solo continuous (III) scheme had the smallest directional error (8.4^{o}) and among the fastest reaction times, while the single vibration (I) and a continuous wave (IV) had among the highest directional errors [8]. All of the patterns were recognized within 2 seconds of vibration, indicating that there is a slight processing time between vibrational input and response. Overall, it is clear that although vibrational encoding schemes are an effective way to represent a surrounding environment, more work needs to be done to develop a standardized methodology that best reflects human navigational principles.

2.5 Research Objectives

The goal of this study is to examine navigational technologies for the visually impaired through the lens of navigation based on a haptic belt containing vibrotactile motors. The motors are uniformly distributed along the belt and their vibration is intended to convey a specific direction. Specifically, this study seeks to design, engineer, and build a suite of tools to test haptic belts as a means of wayfinding. Three questions are posed in this study.

The first question investigates the effect of haptic belt motor density and vibration strength on vibratory perception of direction. To that end, two haptic belts were created of varying numbers of motors to determine whether tighter spacing of motors leads to more accurate directional perception and whether we possess the acuity to parse specific directions in belts with higher motor density. Further testing was conducted to understand human interpretation of differential vibrational intensities, and whether an acuity to different vibration strengths can be used to encode different environmental characteristics. A better understanding of this can be used to target and better focus future research on haptics.

The second question examines the efficiency of single-motor vibration vs. vibrating a distribution of motors at varying intensities in conveying a vibratory perception of direction.

Several previous studies looking at tactile vibrations have chosen different encoding schemes to represent and communicate the surrounding environment and obstacles to users. Here, we seek to examine the efficacy of the single-motor vibration scheme, and a new, independently developed “Gaussian scheme” (3.3), to determine what environmental representation elicits the fastest and most accurate response times.

The third question concerns how vibratory perceptions are translated into directions and navigation. While individuals may correctly interpret the direction of a given vibrational cue, it is also important they are able to move in that direction. Tests for both haptic belt motor density and the two different encoding schemes will be done in several environments with different tasks to ensure that each encoding scheme is measured and examined across a breadth of possible scenarios that may be encountered.

Finally, this study aims to develop software and hardware tools that can be used as an interface for future testing and potential deployment of vibrotactile belts. Such tools include a customizable vibration intensity diagnostic, a haptic gesture designer, and an interface for user testing. This will allow for increased access to haptic belt designs to ensure a better product in the future.

3. Materials: Design of the Haptic Belt

In this chapter, the experimental design, tools, and software used in the research process are discussed. In Section (3.1), the three core experiments to assess the haptic belts are summarized. The process of construction and electronic components used in haptic belts are outlined in Section (3.2). Section (3.3) provides a technical specification of the single-motor and Gaussian scheme, as well as a pseudocode specification for discrete control and continuous feedback. Next, the Bluetooth libraries and Lightweight Communications Marshalling (LCM) package, used to send information between two programs, are discussed in Section (3.4). Finally, a description of the software interfaces and tools built to aid in future testing are mentioned in Section (3.5).

3.1 Study Overview

This study comprises three stages of experimentation to examine the efficacy of vibrotactile feedback as a navigational tool. The first stage seeks to study the phenomenon of perception in sensing various vibrational intensities and positions. Haptic gestures rely on differential motor intensity through pulse-width modulation (PWM), and the ability for humans to distinguish between motor vibrations in adjacent regions of the waist, in order to communicate directional cues to a user. Two belts of 8 and 12 motors are used to communicate haptic gestures. Understanding what vibrations can be easily understood can inform the types of haptic gestures that can be used to provide navigational guidance.

The second stage of this study seeks to examine individual performance in navigating certain tasks while wearing haptic belts of differing motor density with a discrete control system. This is shown schematically in Figure 6A below. Discrete control trials determine how individuals interpret and move based on a single vibrational cue. They also shed light into the mechanics of navigating unfamiliar environments using only haptic cues. These factors include our response time to signals, error accumulation, and error persistence. This will provide a baseline set of data that can inform future research into ways in which navigational data can be communicated at-scale.

The third stage of this study seeks to use a continuous feedback system to provide navigational information to users through the haptic belts. Here, signals are continuously being updated with new user orientations and positions (Figure 6B). Thus, corrective haptic gestures are sent to users who do not adhere to the navigational path. This study seeks to determine the effectiveness of a haptic belt as a navigational aid in environments with accurate positional tracking.

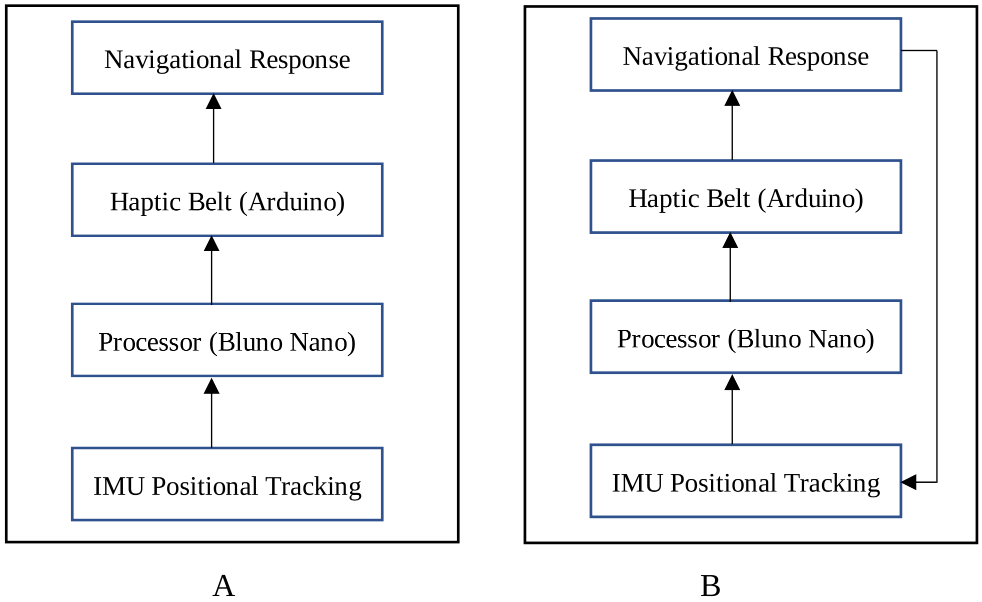


Figure 6(A-B): System architecture schematic for (A) Discrete Control Systems and (B) Continuous Feedback Systems.

Across all stages, two separate encoding schemes will be examined. The first scheme, single-motor vibrations, consists of a signal that directly corresponds to the intended direction of motion. For example, if a user needs to turn right, the motor corresponding to 90^{o} clockwise of the user's orientation will vibrate. However, certain directional cues may be more intricate (like an 80^{o} turn) and cannot be conveyed using this scheme. The second scheme relies on a "Gaussian" distribution of motor vibrations. For example, if a user needs to turn right, a series of three motors will vibrate, with the motor corresponding to 90 degrees clockwise of the user's orientation vibrating at a higher intensity than the two adjacent motors. This technique may be more effective at conveying directional signals not clearly specified by a motor's position through vibrational interpolation.

Finally, this study is concerned with the engineering and implementation of various software tools to supplement research and development of haptic belts. Specifically, software interfaces and visualizations will be developed that allow researchers to easily create custom haptic gestures, cue motors with a specified direction and intensity, adjust motor intensities based on user preferences, and visualize haptic belt signals in real-time while navigating an environment.

3.2 Haptic Belt Hardware

Two haptic belts of eight and twelve motors were built. Each belt comprises an adjustable black elastic strap, a plastic buckle, a battery pack, and a laser-cut acrylic holding case. Each 10 mm x 3 mm mini-vibration motor (DC: 3V, 12000 RPM) is attached to laser-cut acrylic buckles embedded within the belt's elastic strap. The acrylic holding case contains a Bluno Nano (SKU DFR0296) for Bluetooth connections, that serves as the belt's mobile processing unit, translating input signals into motor vibrations. Power and ground cables are soldered from each motor and the 9V battery to corresponding output pins on the Bluno device. Wires were interweaved between each acrylic buckle on the belt for structural stability as the belt is stretched, and to minimize exterior exposure. Motors were similarly placed on the interior of the acrylic buckles to ensure haptic vibrations could be felt by the user.

Shown below are the two haptic belts built.

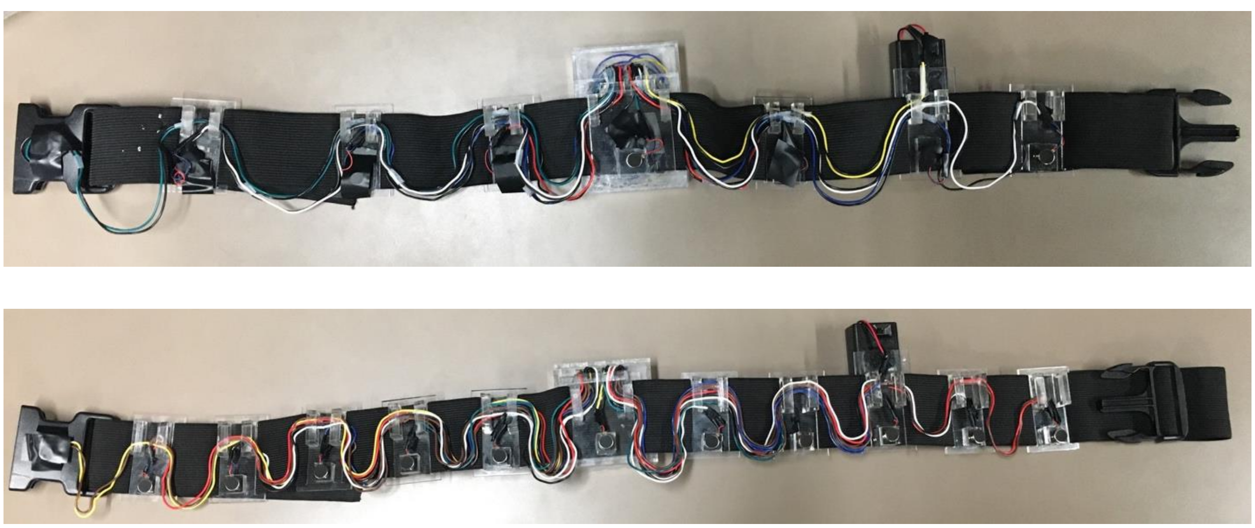


Figure. 7: Images of the haptic belts constructed. Top: 8-Motor Belt. Bottom: 12-Motor Belt.

All motors are connected to output pins on the Bluno that are controlled by an Arduino program loaded onto the Bluno. This script receives wireless signals via two distinct options:

either from a second Bluno unit, or from a Bluetooth radio on a host computer. The Bluno unit then responds with the appropriate motor output.

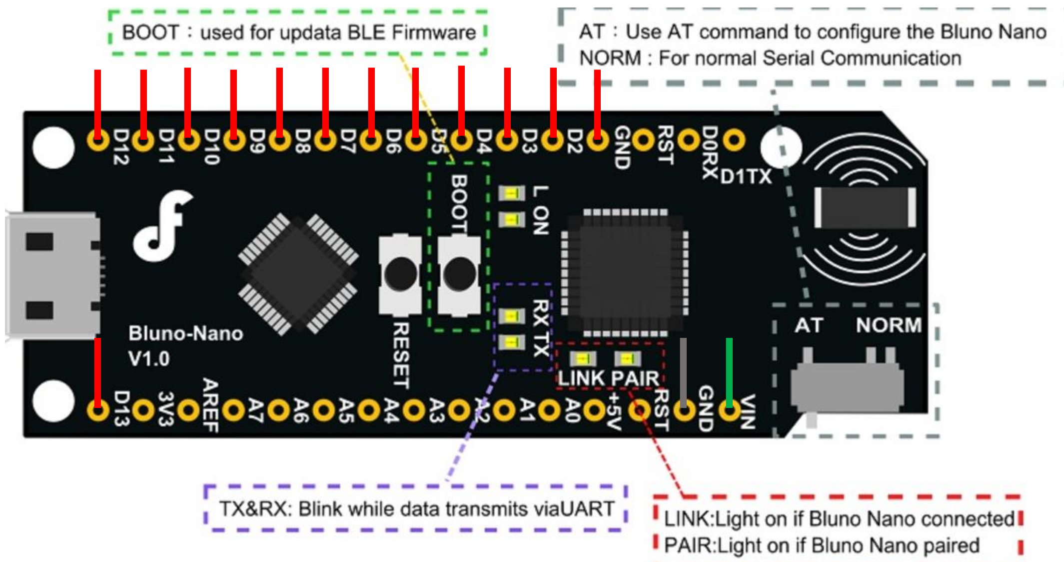


Figure 8: Schematic of the Bluno Nano board. Red wires represent power out to belt motors, while green and grey lines represent power out to the battery and a common ground respectively (Adapted from DF Robot: Specification) [17].

3.3 Software Infrastructure

In order to assess the navigational capability of the haptic belts, several virtual environments were built that represent wayfinding and pathfinding tasks. These environments were created in Vizard, a virtual reality development platform for research. Each environment consists of several obstacles blocking a user's path, along with several waypoints ending in a goal point. Subjects are assessed on their performance in navigating these environments using a keyboard and mouse, with only feedback from the haptic belts.

Two types of feedback schemes were tested: discrete control and continuous feedback. Discrete control consists of giving a set of vibration commands that are temporally or spatially spaced apart. When a user reaches a certain time milestone or reaches their destination, as determined by the headset's IMU and timer, a vibrational cue will be given. Thus, paths and haptic gestures in the discrete control paradigm are pre-programmed into the trial and do not change dynamically given a user's position. No continuous feedback loop exists within this scheme, implying that deviations from an intended course will not be corrected through further vibrational feedback (see Fig. 9A).

Continuous feedback sends directions to the belt by interpreting the user's orientation and the desired orientation needed to reach the goal. Given a user's orientation, motors on the belt are characterized based on how accurately they spatially correspond to the desired direction, and a resulting signal composed of motors-to-fire and strengths at which to fire is formed (see Fig. 9B for more information). These signals are continuously delivered to the belt to ensure that course-correction is possible.

```
Algorithm 1: Discrete Control Navigation
  Result: Motors to Vibrate at a Given Time
  Initialization: Belt motors and I/O stream
   gestures[t] ← haptic gesture to publish at each time interval ;
  while time < timeLimit do
  |  sendCommandToVibrate(gestures[time])
  end
```

```
Algorithm 2: Continuous Feedback Navigation
  Result: Motors with Vibration Intensities
  Initialization: Belt motors and I/O stream
   motorVectorList[i] ← unitVector in direction
   motorVibrationList ← int(vibrationIntensity) ;
  while distToDest < threshold do
     define currentOrientation ; define desiredOrientation ;
     for motor in motorVectorList do
        strengths[motor] = strength = dotProduct(motor, desiredOrientation)
         if strengths[motor] > strengthThreshold then
           intensity = interpolate(strengths[motor]) ;
           sendCommandToVibrate(motor, intensity)
        end
     end
  end
```

Figure 9(A-B): Pseudocode for discrete control (A) and continuous feedback (B) for the haptic belt navigation system.

Schematically, continuous feedback can be viewed through the perspective of correcting a user's current orientation to a desired orientation (Fig. 10). Orientations and positions within the environment are used to compute a desired path and form an instantaneous directional cue. Consistent corrective feedback is delivered from the headset via Bluetooth connection. The set of equations being solved by the navigational script is shown below in Equations 3 and 4 below.

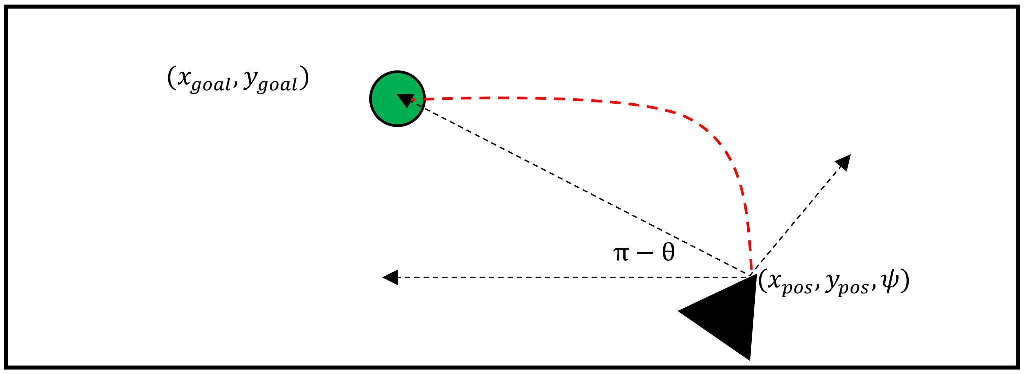


Figure 10: Sample schematic of parameters fed into the navigation algorithm at a given time.

$$\begin{pmatrix} dx \\ dy \\ \theta \end{pmatrix} = \begin{pmatrix} x_{goal} - x_{pos} \\ y_{goal} - y_{pos} \\ \tan^{-1}(\frac{dx}{dy}) \end{pmatrix} \qquad \text{(Eqn .3)}$$

$$d\psi = \psi - \theta \qquad \text{(Eqn. 4)}$$

After the desired turning orientation is calculated, the motors-to-fire are calculated by taking the dot product between the unit vector of the desired orientation and the unit vectors of each motor to be fired. The magnitude of the dot product determines the intensity at which each motor is fired. In a single-motor vibration scheme, only the closest motor to the desired direction is fired. In the Gaussian vibration scheme, the three largest positive dot products are normalized with respect to one another and vibrate with a linearly interpolated intensity; all other motors don't vibrate. The intensities of the motor vibration are classified on a five-point scale, with 1 being the weakest vibration and 5 being the strongest. This methodology is supported by previous literature, which has suggested that there are between 4-5 different levels of vibration that should be used between the detection threshold and the comfort threshold [18].

Different levels of intensity are manifested physically by controlling the signals sent to the motors from the Arduino using pulse-width modulation (PWM). Thus, each level of vibration has a separate duty cycle. Recent studies have indicated that the temporal resolution for sensing vibrations on the skin is ~ 10 milliseconds [19]. The temporal difference between each vibration level using PWM was set to 4 milliseconds, which falls significantly below this threshold. Shown below in Table 2 are the specifications for each vibration level. Further conformational tests were done to ensure that differences between levels are detectable.

Table 2: Vibration Levels in the Gaussian encoding scheme

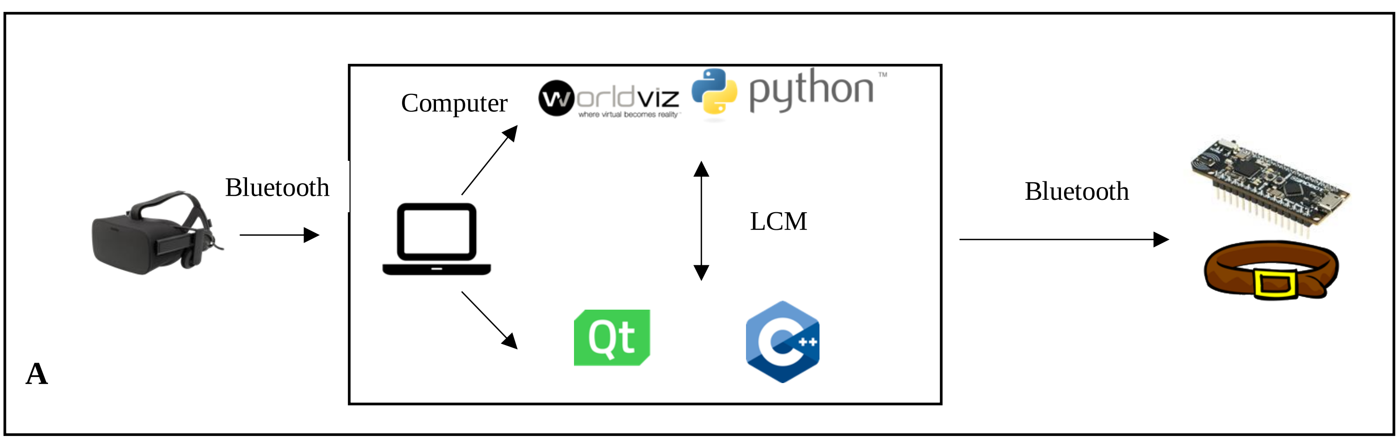
Gaussian Vibration	HIGH (milliseconds)	LOW (milliseconds)	DUTY CYCLE
1	20	0	100%
2	16	4	80%
3	12	8	60%
4	8	12	40%
5	4	16	20%

3.4 Communication Mechanisms

Two methods for laptop-to-belt communication were developed. Both are shown schematically in Figure 11 below. While both of these systems work, they have different hardware and software requirements, and are used for different testing purposes.

The first communication system relies on C++ for the underlying motor connectivity and navigational processing. Location and orientation information is communicated via "Lightweight Communication Marshalling" (LCM) between concurrently running Python and C++ scripts (see Fig. 11A). Motor vibration output and intensity is sent via Bluetooth from the C++ script on the host computer to the Bluno Nano receiver and haptic belt.

The second communication system relies on built-in wireless pairing between two separate Bluno Nano devices. Processing of location and orientation information is performed in the same Python script that communicates with Vizard (virtual reality software) and the Samsung Odyssey VR headset. Motor vibration output and intensity is written via Serial from the host laptop to the Bluno through a wired connection (see Fig. 11B). This information is then relayed to the Bluno on the belt through the paired wireless connection.



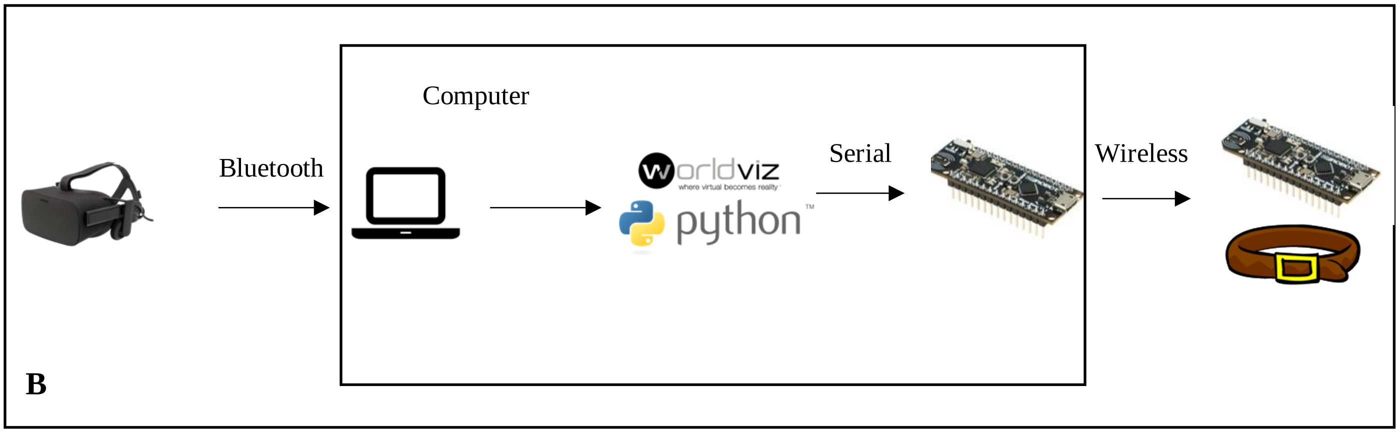
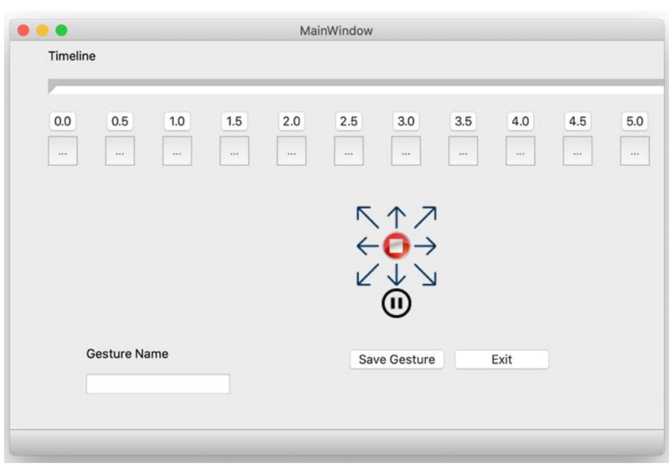


Figure 11(A-B): Communication schemes between the Samsung Odyssey VR Headset (left) and the Bluno Nano on the haptic belt (right).

3.5 Gesture Designer and User Interface

To develop standardized testing procedures for both examinations of hyperacuity and discrete control, a haptic gesture designer featuring an interactive user interface was developed to allow rapid prototyping of gestures for the system. The haptic gesture designer allows for the creation of custom gestures over a 5-second interval; discretion is given over which motors to vibrate on 0.5 second intervals and at what intensity to vibrate at. These gestures can be saved and pre-loaded into an interactive user interface which also allows researchers to send live commands to the belt for certain vibrational cues. Shown below in Figures 12 – 13 are samples of the tools built.



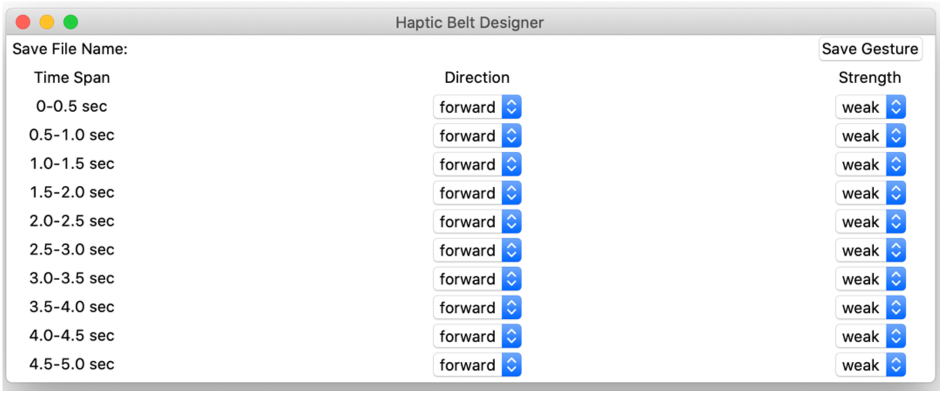


Figure 12(A-B): (A) - Drag-and-Drop gesture designer for building custom gestures. Gestures can be saved and pre-loaded into the belt as needed. (B) – Strength customization designer for haptic gestures. Gestures can be specified through a direction, time, and intensity before being saved to a haptic belt.

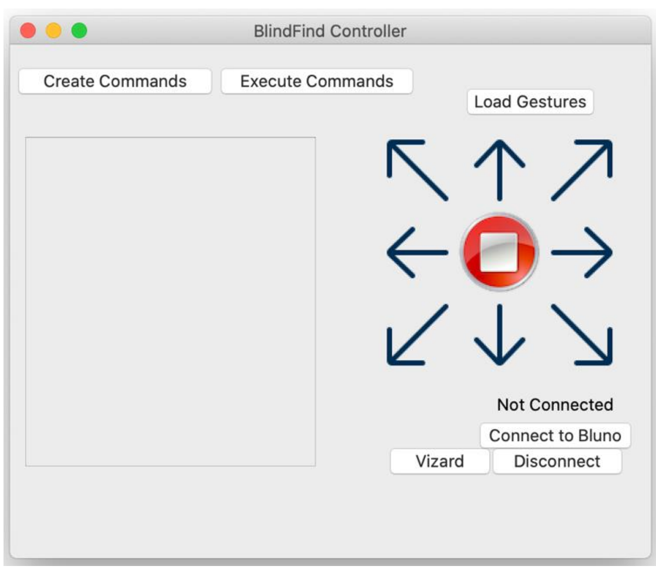


Figure 13: Central belt controller which facilitates interactive, real-time belt communication via Bluetooth. The controller also allows for Vizard input, and execution of custom gestures pre-loaded from the gesture designer.

4. Experimental Procedure and Results

This chapter presents the research findings of three experiments that examine haptic belt performance. In Section (4.1), perception of the vibrations of the eight and twelve-motor haptic belts are presented. Individual perception was studied under a “single-motor vibration scheme” and a “Gaussian vibration scheme.” Since vibration intensity plays a crucial role in these encoding schemes, tests for individual perception of vibration intensity are also presented.

Section (4.2) seeks to translate the stationary tests of perception in (4.1), to real navigation. Here, navigation with the belts is assessed under a system of partial “discrete control” where individuals navigate between several waypoints with no vibratory feedback. A vibratory signal is cued whenever a waypoint is reached; however, participants receive no vibratory signals as they traverse between waypoints. These findings seek to examine how individuals translate their vibratory perceptions into motion.

Finally, Section (4.3) extends upon the methodology in (4.2) by testing the belts under a “continuous feedback” system. In this paradigm, individuals navigate tasks and receive continuous vibratory feedback, guiding them along a desired path. In an environment where a user’s position can be continuously tracked as they move, this series of tests examines the efficacy of the haptic belt system and the Gaussian vibration scheme as a means of navigation. Two different tasks are tested. The first has frequent turns with sharp angles to test the navigational efficacy of the Gaussian vibrations. The second only has 90 and 180 degree turns; this map tests the general efficacy of haptic belts as a navigational tool.

4.1 Experiment 1: Vibrotactile Perception

Vibrotactile performance was assessed by sending different vibrational cues to the haptic belt. Subjects then clicked on the direction they felt was best represented by the vibration on a representative circle. A single-motor (one motor vibrates directly in the desired direction) vibration scheme was examined for both the 8-motor and 12-motor belt. A Gaussian scheme was also examined for the 12-motor belt; the 8-motor belt does not provide enough spatial resolution to generate meaningful gaussian cues. Shown below in Fig. 14 is the interface (built in Python) used for subjects to indicate their perceived vibrational direction. Subjects were told to click their guessed direction within the white subsection of the circle at the earliest time during the 5-second vibration period when they felt confident of their vibration perception. 5 seconds was believed to be an upper threshold on the amount of time it would take for a subject to perceive a direction given a vibrational cue. This trial was run with three participants. Each participant had three sessions, each of which consisted of ten different randomized vibrational cues being given. The first session was a trial session to allow participants to familiarize themselves with the software and with the procedure; results from this session were not recorded.

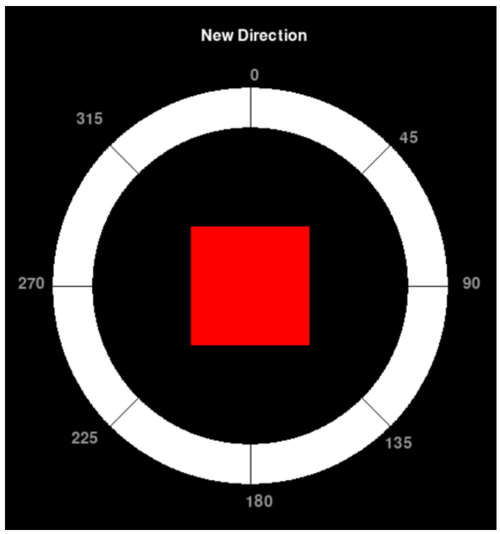


Figure 14: Interface used by subjects to click on their perceived direction following a vibrational cue. 0^o indicates the direction the subject is facing.

Results for the perceived versus intended vibration results for the direct vibrational cues on the eight-motor belt over two separate trials are shown in Figure 15. The results in Figure 15 represent the aggregated perceived directions of the three subjects across all trials. Overall, there was a high degree of correlation between the intended and perceived directions. This was especially pronounced for cues at 90 and 270 degrees. Higher variance was observed in perceived angle for cues ranging from 45 - 135 degrees and from 135 – 225 degrees. These results are similar to those observed in a recent study by *Cholewiak et al.,* [21] which suggested that humans interpret vibrations relative to certain stationary points along the body, most notably the spine and the navel. The 'STOP' cue, which was indicated by vibration of all motors along the belt, was consistently recognizable in all trials.

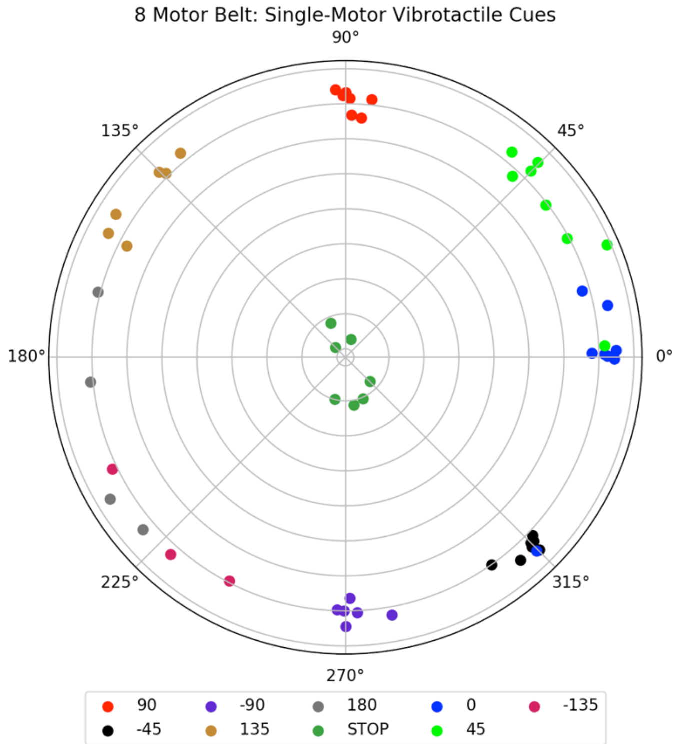


Table 3: Positional Data [8-Motor]

Direction	Mean Angle Error	Max Angle Error
0°	7.69° (7.69)	45.43°
45°	12.21° (13.5)	42.44°
90°	2.10° (1.88)	5.77°
135°	9.23° (7.32)	17.98°
180°	22.91° (13.6)	40.36°
225°	13.44° (7.19)	19.44°
270°	2.69° (3.47)	10.19°
315°	2.37° (3.29)	9.77°
ALL	8.03° (11.26)	45.43°
Cue	**Percent Accuracy**	
STOP	100%	

Figure 15: (A): Map of spatial perceptions of direct motor vibrations on the 8-motor belt. (B): Mean angle error between perceived and intended motor vibration directions.

A similar experimental methodology was followed to assess single-motor vibrations for the 12-motor belt. However, due to experimental constraints, only two participants were tested; each participant received two sessions, with fifteen vibrational cues in each session.

Single-motor vibrations on the 12-motor belt were found to slightly improve mean angle error in most directions, but increased uncertainty between 90° and 150° (Figure 16). One possible explanation for this decrease in spatial accuracy with more motors in the 90 – 150 ° arc may be possible asymmetries in the way in which participants wore the belts. However, it is important to note that since only two separate trials were run with two participants, these findings are not necessarily conclusive, but rather provide a baseline set of data.

For the 8-motor belt, the longest response times were seen for 180° and 225°, which were coincidentally the directions with the highest mean angle error (Table 5). For the 12-motor belt, this finding is less robust, although the arc between 90° and 150° did have slightly elevated response times.

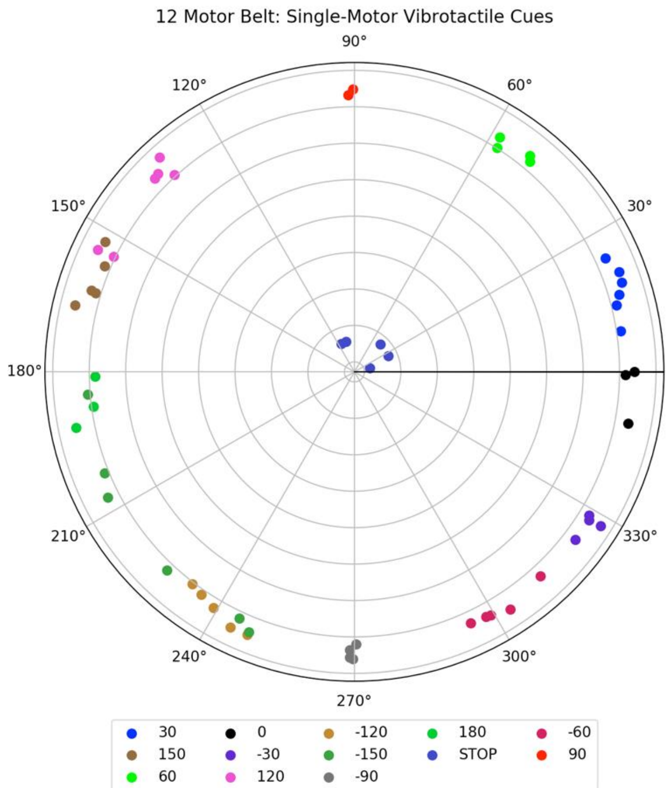


Table 4: Positional Data [12-Motor]

Direction	Mean Angle Error	Max Angle Error
0°	3.76° (4.87)	10.64°
30°	12.89° (4.92)	21.28°
60°	5.78° (3.69)	9.85°
90°	0.78° (0.47)	1.25°
120°	20.72° (9.81)	34.52°
150°	10.39° (5.02)	16.62°
180°	6.66° (4.28)	11.37°
210°	20.91° (12.99)	37.85°
240°	4.92° (2.54)	7.80°
270°	0.62° (0.31)	0.93°
300°	4.66° (4.11)	12.34°
330°	3.27° (2.31)	7.24°
ALL	9.41° (9.53)	37.85°
Cue	**Percent Accuracy**	
STOP	100%	

Figure 16: (A) Map of spatial perceptions of direct motor vibrations on the 12-motor belt. (B): Mean angle error between perceived and intended motor vibration directions.

Table 5: Response Time in seconds for Direct Vibrational Cues

Direction	8-Motor [Mean Response Time (sec)]
0°	2.70
45°	2.04
90°	2.06
135°	2.00
180°	3.18
225°	3.20
270°	2.76
315°	2.42

Direction	12-Motor [Mean Response Time (sec)]
0°	2.89
30°	3.69
60°	3.49
90°	2.11
120°	3.76
150°	3.36
180°	3.25
210°	3.24
240°	3.13
270°	2.13
300°	2.80
330°	3.06

The Gaussian vibration scheme contrasts with the single-motor vibration scheme, in that the Gaussian vibration scheme vibrates a series of three motors at different intensities (see 3.3 for more details). To ensure that differences in vibration intensities can be readily detected, participants were asked to distinguish between five different levels of vibration intensities. Participants wore the twelve-motor belt, and were told to feel the vibrations of two motors at the front of the belt, which vibrated at different intensities for five seconds; they were then asked which motor (left or right) vibrated at a higher intensity as a test for both spatial and vibrotactile acuity. Each participant had two separate sessions; a single session comprised all 20 different combinations between the left-hand-side (LHS) and right-hand-side (RHS) motor vibration levels. Three participants took part in this experiment.

Shown below in Table 6 are results indicating the percentage of correct responses participants gave when prompted with different paired motor vibration combinations. Participants could discern motor vibration intensity greater than one level apart with 100% accuracy. However, for intensities that were exactly one level apart, results were slightly mixed. This was especially the case between levels 3, 4, and 5; accuracy was as low as 50% between levels 4 and 5 for a single trial. Overall however, these results suggest that differing levels of motor intensity can be felt, lending credibility to the methodology of interpolating directional cues via motor intensity through a Gaussian.

Table 6: Motor Intensity Discrimination Accuracy

		RHS Motor Intensities				
		1	2	3	4	5
LHS Motor Intensities	1		100%	100%	100%	100%
	2	100%		100%	100%	100%
	3	100%	100%		100%	100%
	4	100%	100%	83.33%		100%
	5	100%	100%	100%	50%	

Shown below in Figure 17 are the results for perceived versus intended directions, communicated to participants through Gaussian vibrations on a twelve-motor haptic belt. The procedure for this experiment was similar to the one in Figures 15 and 16. However, rather than being constrained to directions specified by the number of motors, random directions were generated and cued using Gaussian vibrations in this trial. Three participants took part in two separate sessions, with each session comprising 10 random vibrational directions, cued sequentially after one another. All participants were given a trial session to familiarize themselves with the Gaussian system of vibrations and the software interface.

Overall, the error between intended and perceived direction was low, and was evenly distributed across the waist, suggesting that errors weren't skewed toward any particular direction. Several individual points did have a high level of error (> 30°); however, these points were not clustered in a specific arc. Based on the mean error of 13.77° (Table 7), this suggests that a reasonable estimate for the number of motors to achieve optimal spatial resolution would be one motor for every 25° along the waist. For a full belt, approximately 15 motors would be needed to encompass all possible directions to a discernible level.

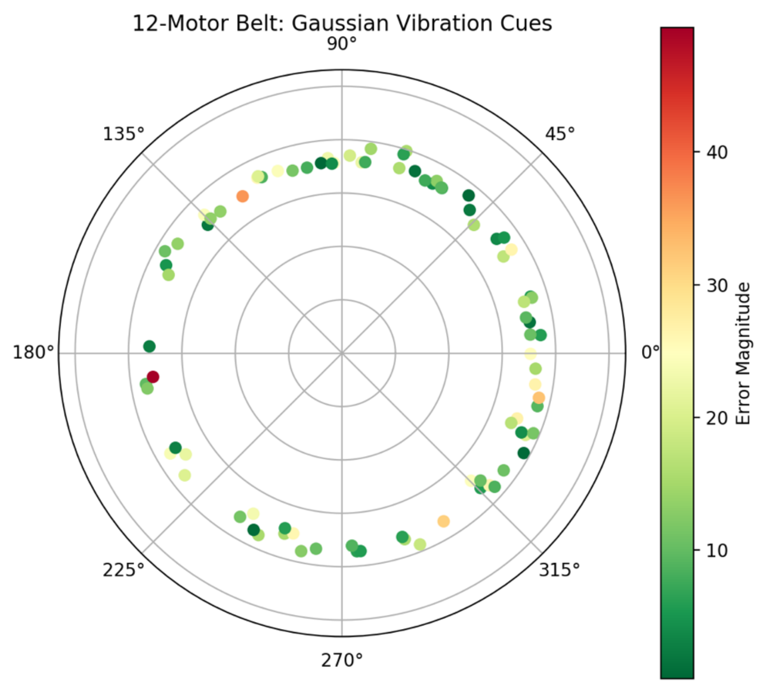


Figure 17: Distribution of perceived directions given by Gaussian cues on a 12-motor belt. The color of each point represents the absolute value of the error between the perceived and intended direction, with green indicating minimal error and red indicating a large error.

Table 7: Summary Statistics for Gaussian Vibration Trial

Error Statistic	12-Motor Gaussian (º)	12-Motor Single Vibration (º)	8-Motor Single Vibration (º)
Mean Error	13.77 (9.31)	9.41º (9.53)	8.03º (11.26)

4.2 Experiment 2: Discrete Control Navigation

Performance of the 8-motor and 12-motor belts was assessed using a discrete control system with single-motor vibrational cues for the 8-motor belt and 12-motor belt and with a Gaussian cue for the 12-motor belt. Participants were first asked to navigate a trial task on a test map using the Vizard virtual reality software to prompt familiarity with the controls and the Vizard environment. After this, the primary discrete control navigation task was explained to them as a series of seven waypoints, to which they were to navigate using only vibratory cues from the belt. Participants were not blindfolded as the environment was blanked out on the screen as they attempted to navigate the task. The mode for navigation was use of the W-A-S-D keys to move and change orientation. The ‘W’ and ‘S’ key allowed the participant to move forward and backward respectively. The ‘A’ and ‘D’ key allowed the participant to turn clockwise and counterclockwise respectively; turning using those keys was smooth, which allows for a continuous range of angles to which they could turn to. Thus, this form of navigation can be thought of as navigation with ‘finger-sensing’. Three trials were run with different participants.

To achieve discrete control, a single direction was communicated to the participant for three seconds at the start of the task through a vibrational cue. Follow-up directions were communicated either after a certain time interval, or if the participant successfully navigated to a waypoint or the edge of the map; vibration length was consistently three seconds for each new cue. Shown below in Figure 18 is a sample solution path to the wayfinding task. Participants are initially facing forward and have to navigate to each waypoint before finally returning to the starting point. A 0.5-meter threshold surrounded each waypoint; if a participant navigated to within 0.5 meters of a waypoint, they would be directed to the next waypoint in the sequence.

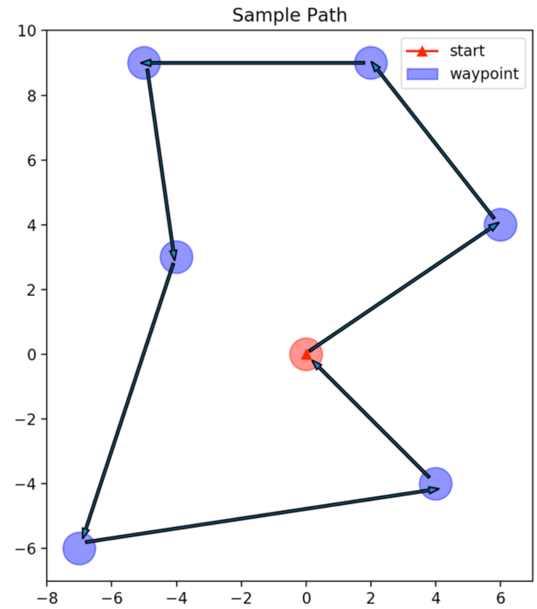


Figure 18: Sample path to complete the wayfinding task. The red arrow indicates the starting orientation, while the blue circles indicate the radius around the waypoint at which a participant is considered to have reached the given point.

Three trials were run on each vibration scheme and the paths taken by the participants are plotted below in Figure 19. As expected, without consistent directional feedback, there was a relatively high level of error among the paths taken, as all trials failed to successfully reach all waypoints through the discrete control task; participants found themselves changing their orientation as a result of new cues being sent after a given period of time or after hitting the edge of the map, rather than new cues being sent upon reaching the desired waypoint. The 8-motor belt with direct vibrational cues led to the fastest completion time of the discrete control task, although it also yielded the highest mean angle deviation and the lowest accuracy (Table 8). The 12-motor belt with Gaussian vibrational cues had the largest accuracy fraction, while the 12-motor belt with direct vibrational cues had the lowest mean angle deviation.

Plots of the actual orientation vs. orientation communicated through vibration are shown in Figure 20. There appears to be a roughly 5-second delay between when the direction was first cued and when we observe a shifting positional response. This delay was observed across all trials, suggesting the possible need to alter the timing methodology in which directions are given, in order to account for a delayed response.

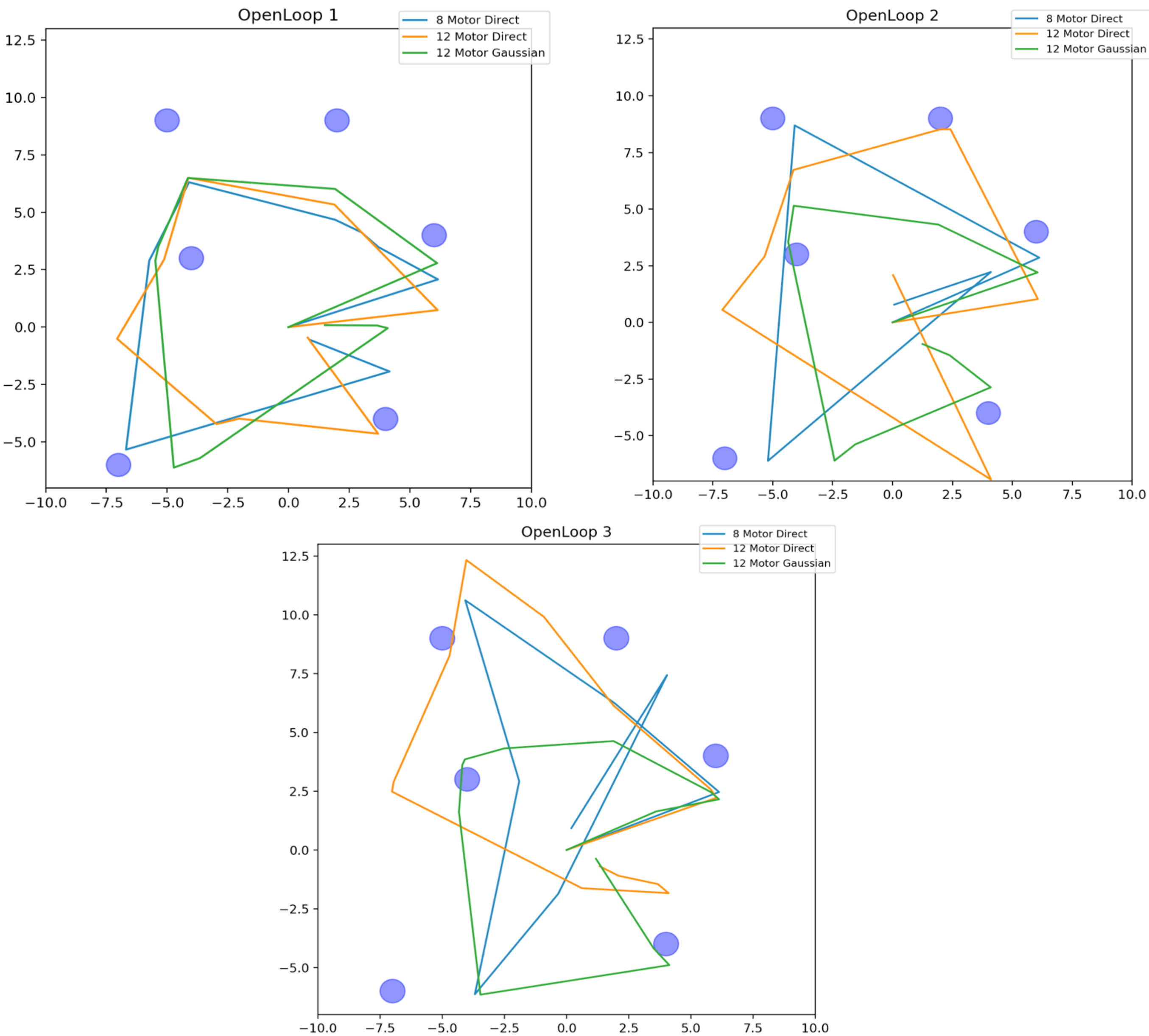


Figure 19: Discrete control paths for the wayfinding task. Blue circles represent a 0.5-meter threshold at which the participant is considered to have arrived at the point.

Table 8: Summary Orientation Results for Discrete Control Tests. Mean accuracy fraction is calculated as the fraction of time when the participant's orientation was within 15° of the intended accuracy.

	Time (s)	Mean Deviation (°)	Mean Accuracy Fraction
8-Motor Direct	103.33	37.65 (4.95)	0.55
12-Motor Direct	122.33	28.70 (4.80)	0.57
12-Motor Gaussian	121.33	33.03 (0.69)	0.56

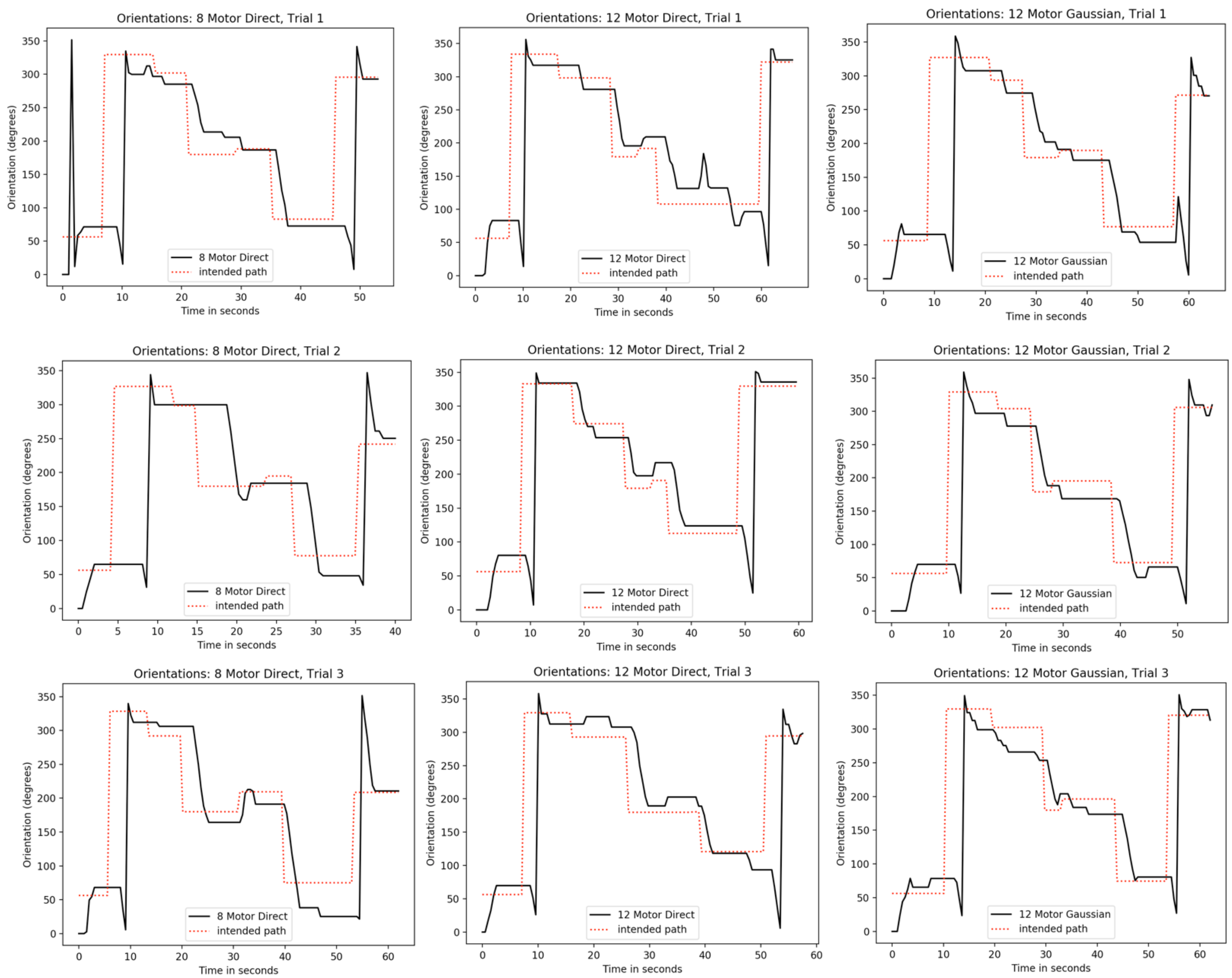


Figure 20: Plots of participant orientation (black) versus intended orientation (red) for the duration of the discrete control wayfinding task. Orientation is defined as degrees clockwise from due north. Since this was a computer-aided navigation trial, it was possible for participants to walk with zero-angle deviation if they chose; if a similar trial was run with live navigation, higher levels of noise would likely be observed.

4.3 Experiment 3: Continuous Feedback Navigation

The same wayfinding task used in discrete control trials was repeated using a continuous feedback system, where navigational data was communicated to the belt every 0.4 seconds based on the user's position. Users were blindfolded and navigated a virtual environment on a computer using the W-A-S-D navigational keys (finger-based navigation). All participants were given a trial environment which they successfully navigated without a blindfold to familiarize themselves with the navigational framework and software interface. Four participants were tested, and each navigated the task using the single-motor vibration scheme for the 8 and 12-motor belts, as well as the gaussian vibration scheme for the 12-motor belt. Results are shown in Fig. 21 and Fig 22 below.

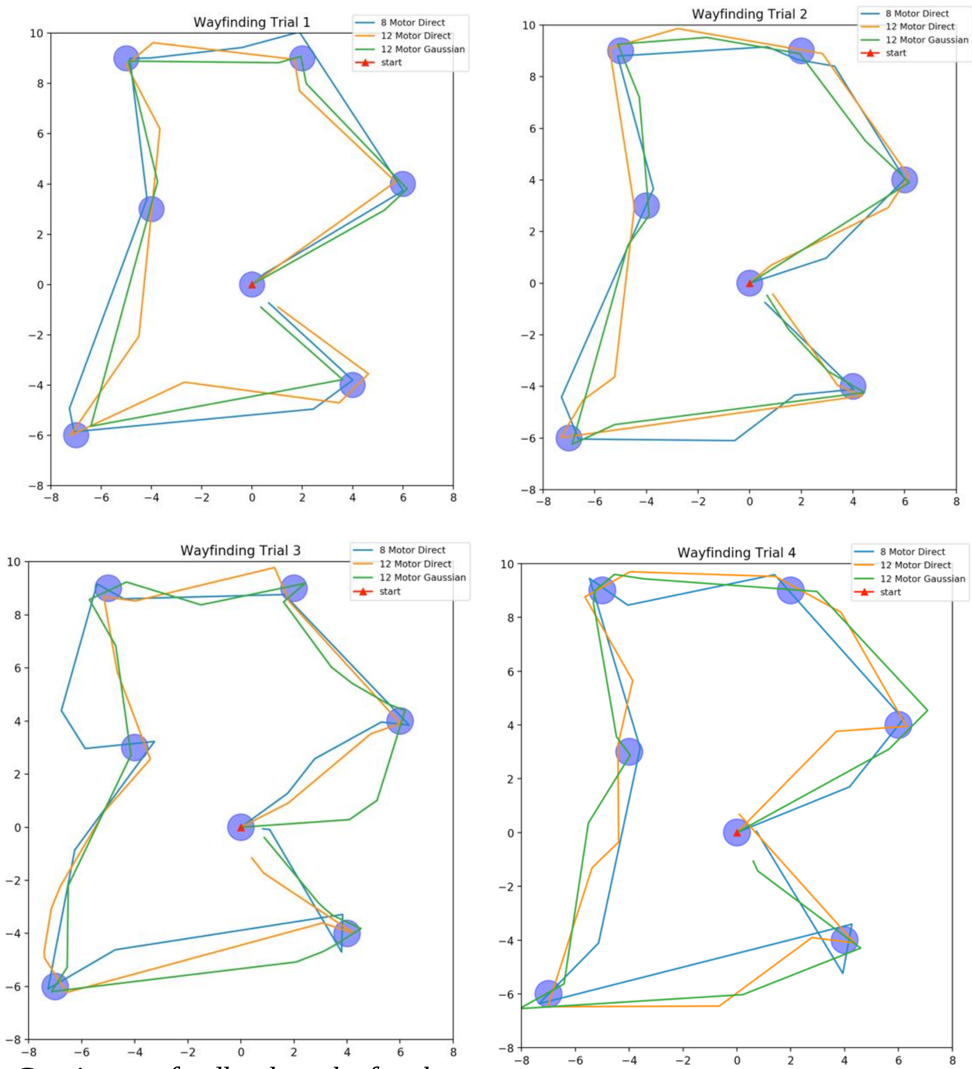


Figure 21: Continuous feedback paths for the wayfinding task. Blue circles represent a 0.5-meter threshold at which the participant is considered to have 'arrived' at the point.

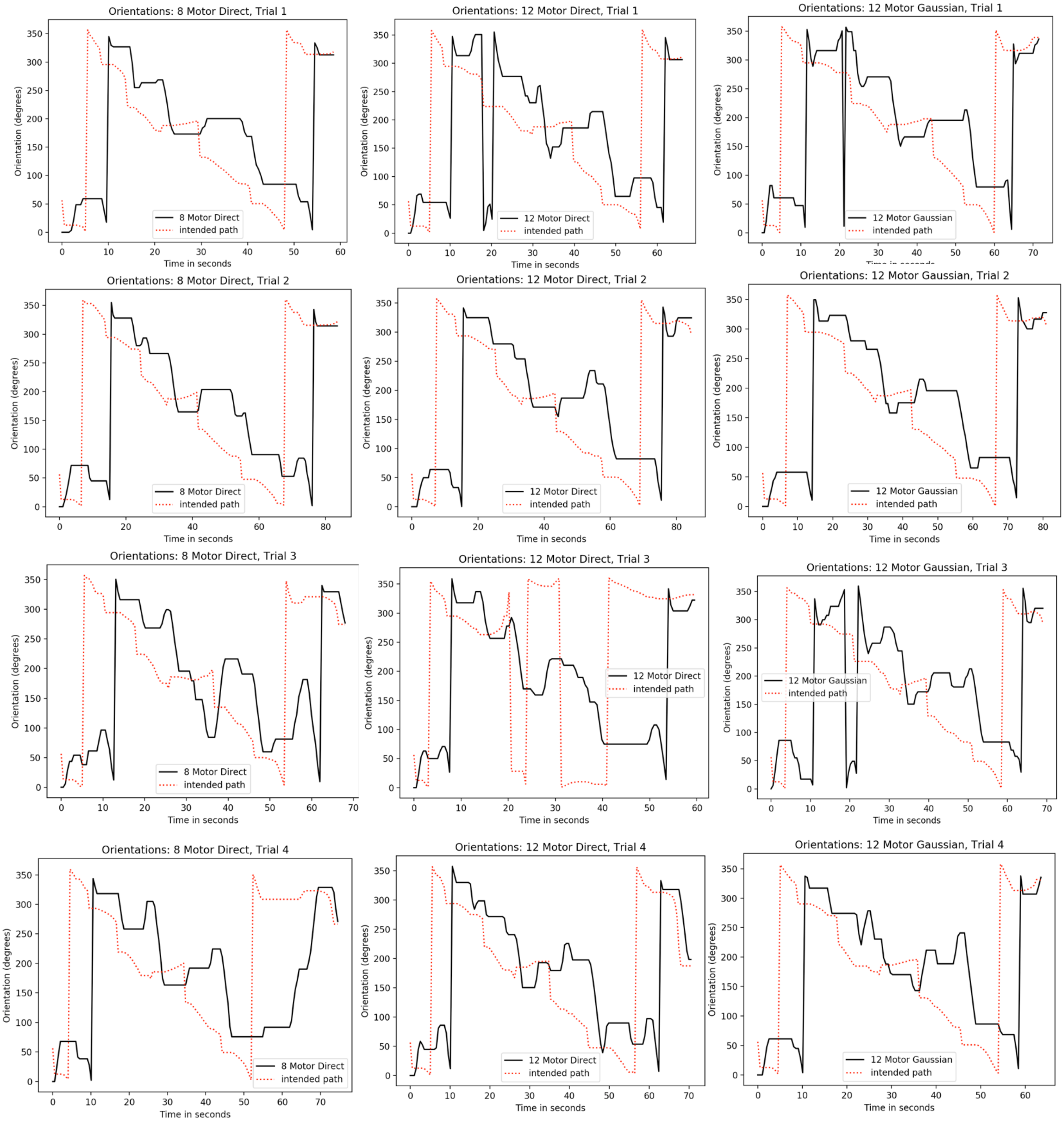


Figure 22: Plots of participant orientation (black) versus intended orientation (red) for the duration of the continuous feedback wayfinding task

There was no significant difference in the completion time of the wayfinding task across different vibration schemes. The mean distance from the intended path was calculated at each timestep as the distance between the current position and the line connecting the two waypoints the participant was currently moving between; this is calculated from Equation 5 below. Where (x_0,y_0) represents the current position and (x_1,y_1) and (x_2,y_2) are waypoints:

$$d = \frac{|(y_2-y_1)x_0-(x_2-x_1)y_0+x_2y_1-y_2x_1|}{\sqrt{(y_2-y_1)^2+(x_2-x_1)^2}} \qquad \text{(Eqn. 5)}$$

The 12-motor Gaussian scheme had slightly lower distance error than the 8-motor and 12-motor single vibration scheme (Table 9). This might be due to the frequent sharp angular turns in the path. Since these turns are in non-cardinal directions, the Gaussian distribution of vibrations was hypothesized to yield more accurate turns than single-motor vibrations. All three motor vibration schemes had a mean error distance of less than 0.5 meters from the intended path.

Table 9: Summarized statistics from the wayfinding task under continuous feedback.

Vibration Pattern	Mean Completion Time (sec)	Mean Distance from Path (m)
8-Motor Direct	142.25 (18.27)	0.379 (0.121)
12-Motor Direct	142.25 (18.35)	0.371 (0.071)
12-Motor Gaussian	142.5 (12.66)	0.319 (0.143)

A second continuous feedback trial was run on a different navigational map. This new map guides participants from a starting point to an intermediate waypoint, before finally taking the participant to a final point. The purpose of this map was to mimic a real-world task, where an individual may have to go pick up an object from on location, and deliver it to a second; another goal of this map was to assess belt performance in a task where all directions could be specified using the four cardinal directions (North, South, East, West). However, since this task was performed using W-A-S-D computer controls in a virtual reality environment, a direct translational effect in the findings cannot be inferred. Shown below in Figure 23 is a schematic of the map and a sample path from the starting point to the intermediate waypoint and the destination. Participants navigate from the red dot to pick up an object at the blue dot, and then navigate to the black dot to drop off the object.

Results summarized in Table 10 indicate that the 12-motor single-vibration belt and 12-motor Gaussian belt had slightly faster completion times than the 8-motor belt. However, due to the high variance in times and the small sample size, these results are inconclusive. Furthermore, the 12-motor Gaussian belt had slightly lower mean distance error than the single-motor vibration scheme on the 8-motor belt. The single-motor vibration scheme on the 12-motor belt had the highest mean distance error on the maze task, though insignificantly different from the 8-motor direct vibration scheme. Across all tasks, the mean distance error was equal to or less than 0.4 meters from the ideal path outlined in Figure 23.

Based on the paths taken by participants across different trials in Figure 24, all participants successfully navigated from the start to the goal. The rectangular obstacles represent regions of the map that a participant should attempt to avoid; however, since the task was performed virtually with a keyboard, there was no tactile stimulus activated when participants collided with the obstacles. In future studies, if this task were replicated, a vibratory cue should be activated when a participant collides with a wall.

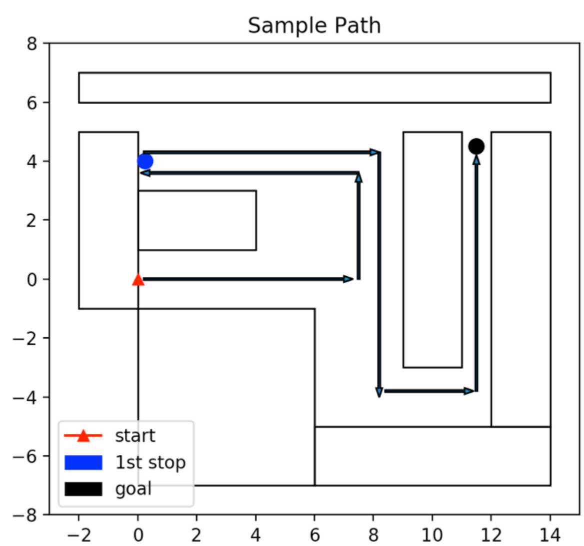


Figure 23: Sample path to complete the maze task. Black-outlined rectangles represent obstacles along the path, while the dots represent waypoints.

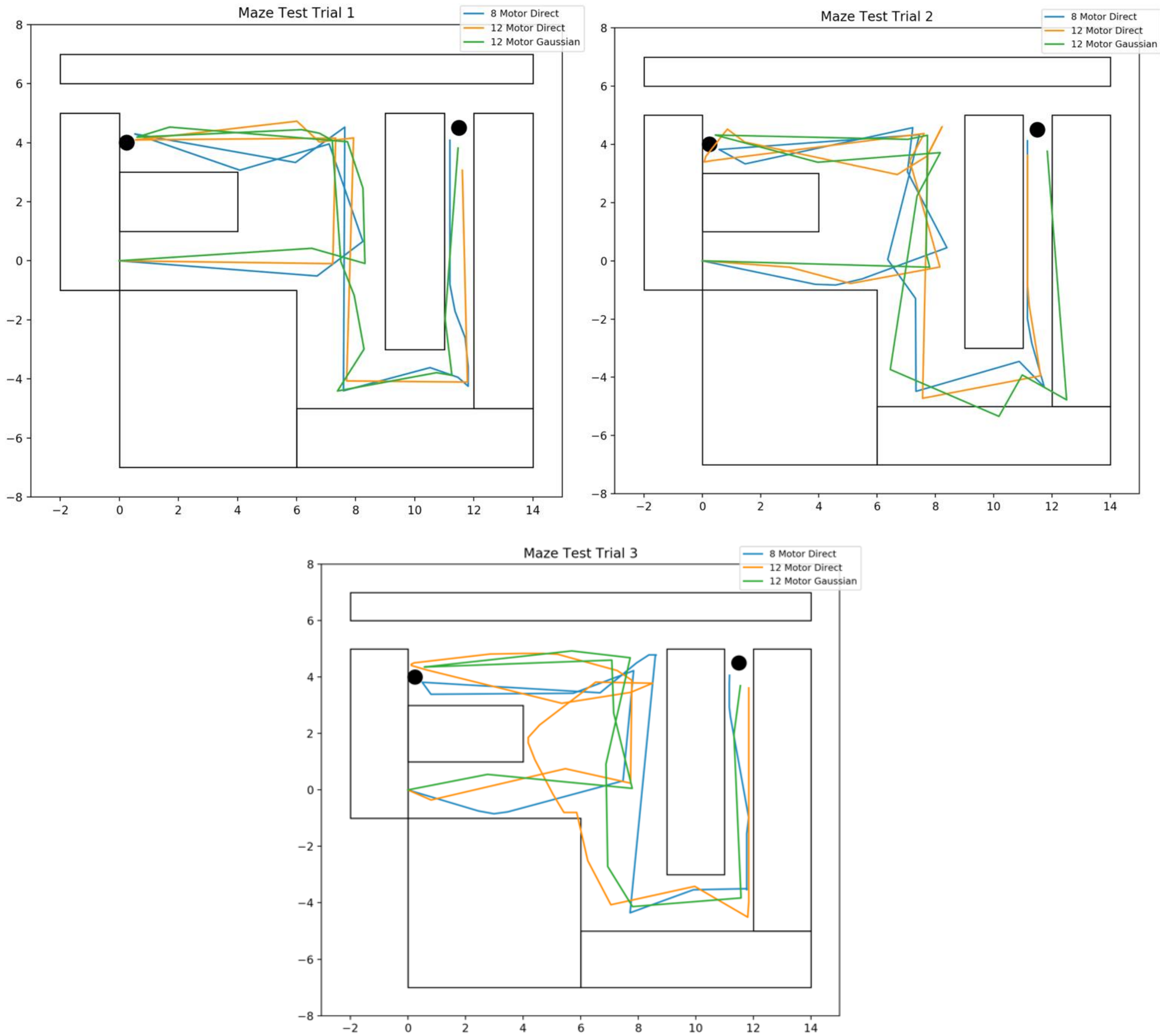


Fig. 24: Continuous feedback paths for the maze task.

Table 10: Summarized statistics from the maze task under continuous feedback.

Vibration Pattern	Mean Completion Time (sec)	Mean Distance from Path (m)
8-Motor Direct	153.93 (37.12)	0.381 (0.08)
12-Motor Direct	120.33 (9.39)	0.400 (0.17)
12-Motor Gaussian	125.67 (14.82)	0.356 (0.132)

5. Discussion

The purpose of the first set of experiments (4.1) was to understand how people interpret belt vibrations. This informs predictions on how belts might perform in a physical navigational task. Vibrotactile perception was assessed in the eight-motor and twelve-motor belts using vibrational cues from cardinal and inter-cardinal directions (Set I: 0, 45, 90, 135, 180, 225, 270, 315). The results of the vibrotactile perception trials (4.1) suggest that increasing the number of motors on a haptic belt does not necessarily increase the spatial acuity of individuals in the directions outlined in Set I. However, with more motors, a greater range of directions can be specified, allowing for directional cues with a high degree of specificity. Thus, there may be a benefit to increasing the motor density for tasks with a low tolerance for error in orientation and position.

These results should be confirmed in future experiments by rotating the belt to different configurations and running the same test to ensure that results are not mischaracterized by differences between motors, motor spacing along the belt, or unevenness in the weight distribution around the belt. It is possible that the added weight due to the Arduino and battery case at the back and sides of the belt may skew vibrotactile perception. Higher errors were observed in the directions associated with a participant's back, which may suggest that incremental navigation schemes may be more effective.

Section (4.1) also studied the Gaussian vibration scheme across all possible spatial directions around the waist (Set II: [0 - 360]). This assessment yielded a mean error of 13.77^{o}. This is slightly higher than the mean error of the eight and twelve-motor belts in Set I. No single direction or region of directions had persistently higher or lower errors on average, suggesting that spatial perception accuracy was invariant in position for the Gaussian scheme. These findings suggest the 12-motor Gaussian vibration scheme can expand the range and specificity of directions covered, without significantly reducing perception accuracy. The Gaussian vibration scheme thus demonstrates potential as a comprehensive navigation system that allows for a high degree of specificity in spatial perception.

These findings expand upon the findings of Pielot *et al.*, where it was discovered that individuals have the capacity to accurately interpolate vibrations of different intensities on a tactile belt [20]. The Gaussian vibration scheme builds upon the idea of interpolation by vibrating motors at different intensities along an arc in the localized region of a goal. Across five different levels of vibration intensities, individuals were able to accurately discern which motors vibrated at a higher intensity in most trials, lending further support to the hypothesis that individuals are capable of interpolating motor intensities. This was seen across all levels except at the two highest levels of vibration intensity. As demonstrated by the spatial errors observed in the Gaussian scheme, it is likely that individuals also possess the capacity to interpolate differential vibration intensities at different locations to pinpoint a specific direction.

Section (4.2) extended the perception findings in (4.1) to a navigational task. The navigational task used in discrete control consisted of navigating between six waypoints before returning to the origin. Each waypoint was located at an angle from the second such that it could not be directly traversed directly using cardinal directions. The purpose of this task was to examine how well participants could assess and move in a direction given a three-second vibrational cue. The mean angle deviation and mean accuracy fraction (Table 8) represent the angle difference between the subject's navigated path and the intended path communicated through the belt while the subject was in motion, and the percent of time that the subject's path was within 15 degrees of the intended path respectively. Although the eight-motor belt led to significantly faster completion times than the twelve-motor belts, it also led to the highest mean angle error and the lowest percent accuracy. The twelve-motor belt with single-motor vibrations had the lowest mean angle error (26^{o}) and the highest percent accuracy. These findings suggest that having additional motors in the belt provides higher spatial acuity that translates to better interpretation of vibrational cues. The Gaussian scheme performed in-between the single-motor schemes for the eight and twelve-motor belts, which indicates that without consistent feedback, Gaussian cues may not be particularly effective.

Since discrete control trials were performed with subjects using navigational keys on a computer, it is not possible to conclusively generalize the findings to the way in which people navigate in the real world. However, the results do shed light on the effect that the vibration scheme and the number of motors have on perception. In general, discrete control results had very high levels of error across all belts, regardless of whether direct or Gaussian vibrations are used. Without the ability to receive corrective feedback, across all trials, navigational errors compounded to give a high total integrated error. This is the primary reason behind the high level of deviation and low accuracy fraction observed.

Overall, these findings indicate that discrete control does not provide a suitable level of navigation feedback to be applied in any practical sense. However, it does shed light on how people interpret directions from vibrational cues, and how positional error can accumulate significantly without any corrective feedback intervention. Since all participants were still able to successfully navigate across all waypoints, discrete control does appear to provide navigational information to a limited extent.

Continuous feedback trials in (4.3) were also performed entirely using a computer and with keyboard navigation. The first continuous feedback task was the same map as the discrete control task. Here, with consistent feedback, the three completion times of the three schemes tested were not significantly different from one another. However, both schemes with the twelve-motor belt yielded a slightly lower mean distance error than the eight-motor belt. The mean distance error was calculated as the mean distance between each point on the ideal path and the observed path taken. Since this task consisted of navigating between waypoints located at sharp angles from one another, this demonstrates that having a higher motor density on the belt appears to improve task performance in tasks where a high degree of angular specificity is required. Thus, with consistent feedback, the Gaussian belt appears to significantly improve navigational performance due to participants' ability to interpret specific angles better through a Gaussian scheme than a single-motor vibration scheme.

To check whether the Gaussian scheme yielded better results due to improved spatial acuity, a second task map was built and assessed through continuous feedback. The intended path for this new map solely consisted of travel in the cardinal directions. In this task, the mean distance from the path between all three testing groups did not significantly differ from one another. This lends further credibility that the improved performance of the Gaussian scheme in the previous trial was caused by higher levels of spatial acuity provided by the vibrational cues.

The significantly improved performance of the eight-motor belt under continuous feedback can be attributed to the corrective signals that are continuously sent to participants as they navigate the map. Indeed, this is seen in Tables 9 and 10, where the mean distance from the path varied between 0.3 and 0.4 meters across all testing schemes. For wayfinding tasks with distances between 50 – 200 meters, a navigational aid that provides a 0.3-0.4-meter deviation from the desired path is likely an acceptable outcome. However, there is a significant practical challenge in implementing a continuous feedback system to navigate indoor tasks; any such system would need a means to continuously update the position of the user and respond to changing environments. In the virtual reality environments tested, this was a simple feat. However, in practice, it is likely that users would also need a wearable computer vision rig to interpret their local environment [22].

A persistent error remains in the continuous feedback task for all belts and schemes tested. Often, when a participant is off-course by a small amount ($< 10^o$), they cannot distinguish between their current path and the desired path. By qualitatively analyzing Figures 21 and 24, participants only correct their course when the magnitude of their error is large enough to be discernible under the given vibration scheme. This often happens as the target approaches the waypoint, and the magnitude of the angular error significantly increases. Two possible solutions to this have been postulated and should be examined closely in future experiments.

First, adding more waypoints to a path might lead to a higher degree of course correction, leading to smaller persistent errors. Future experiments should look into the effect of waypoint density along a path, and whether it significantly improves navigational ability.

A second possible solution is to magnify the error magnitude to ensure that small errors in orientation and position are noticeable. In this scheme, orientation errors under a certain threshold could be multiplied by a factor of 3 in order to induce a positional change; this might lead small errors to be quickly corrected before they compound. Two distinct modes of navigation, incremental turning control and unguided turning control, would allow people to maintain strict adherence to a prescribed path. It is hypothesized that this might be an effective alternative vibrotactile encoding scheme to communicate directions.

All three experiments have results that support the viability of a Gaussian encoding scheme as a means of vibrotactile navigation for the visually impaired. Participants who used the belt could accurately discern between differences in vibrational intensity, as well as differences in vibrational location. A recent study by van Erp *et al.* found that encoding distance into vibratory patterns did not significantly improve navigational performance [23]. However, the study did suggest that vibratory patterns could encode different variables that might help the visually impaired to navigate certain situations. A Gaussian scheme on a vibrotactile belt opens the opportunity to encode more than just directional information;

obstacles, people, and environmental cues can also potentially be encoded through different intensities and patterns of Gaussian vibrations without negatively affecting a subject's navigational ability.

Future studies should also expand upon the belt configurations used in these experiments and examine the efficacy of a sixteen-motor belt with a Gaussian encoding scheme. The virtual reality environment provides an easy-to-use mechanism to test the performance of these haptic belts under different scenarios without physically constructing different maps. This allows for rapid testing of different belts and vibration patterns in varying scenarios, which can quickly lead to an optimal configuration. Given a belt configuration and vibration scheme that minimizes path error, further tools can be integrated with the belt to provide real-time feedback and guidance outside of a pre-configured virtual reality environment.

6. Conclusion

This thesis examined three studies that add to the growing literature on vibratory perceptions and hyperacuity. The first study provided evidence that vibrational cues from a Gaussian vibration scheme on a 12-motor belt can be perceived within 13 degrees of the intended direction. This provides a high level of specificity and supports the use of a Gaussian vibrational scheme as a basis of communicating directional information. The second and third study examined individual performance using a keyboard, as they navigated virtual environments with vibrational cues under discrete control and continuous feedback. Here, the Gaussian scheme led participants to have the least path error, while navigating the tasks in the same amount of time as the single-motor vibration scheme. This lends evidence supporting the use of haptic belts as a means of navigation for the visually impaired. Future work should look to better understand individual perceptions of different vibration levels, and study the performance of these belts in real-life scenarios.

7. References

[1] Real, Santiago, and Alvaro Araujo. “Navigation Systems for the Blind and Visually Impaired: Past Work, Challenges, and Open Problems.” *Sensors (Basel, Switzerland)* vol. 19,15 3404. 2 Aug. 2019, doi:10.3390/s19153404

[2] Iyengar, N., Vembar, D., Pauls, K., Hewitt, J., Clark, K. (2004). “Effect of Visual Cues on Human Performance in Navigating through a Virtual Maze.” Eurographics Workshop on Virtual Environments. doi: 10.2312/EGVE/EGVE04/053-060

[3] Giudice, N. A., & Legge, G. E. (2008). Blind navigation and the role of technology. In A. Helal, M. Mokhtari & B. Abdulrazak (Eds.), Engineering handbook of smart technology for aging, disability, and independence (pp. 479- 500): John Wiley & Sons.

[4] Maidenbaum, S., Hanassy, S., Abboud, S., Buchs, G., Chebat, D.R., Tzedek, S., Amedi, A. (2014). The EyeCane, a new Electronic Travel Aid for the Blind: Technology, Behavior & Swift Learning, Restorative Neurology and Neuroscience 32, pp. 813-824. doi: 10.3233/RNN-130351

[5] Wachaja, A., Agarwal., P., Zink, M., Adame, M.R., “Navigating Blind People with a Smart Walker,” 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg, German, 2015. doi: 10.1109/IROS.2015.7354233

[6] Katzschmann, R. K., Araki, B., & Rus, D. (2018). Safe Local Navigation for Visually Impaired Users with a Time-of-Flight and Haptic Feedback Device. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 26 (3), 583–593. doi: 10.1109/tnsre.2018.2800665

[7] Tsukada K., Yasumura M. (2004) ActiveBelt: Belt-Type Wearable Tactile Display for Directional Navigation. In: Davies N., Mynatt E.D., Siio I. (eds) UbiComp 2004: Ubiquitous Computing. UbiComp 2004. Lecture Notes in Computer Science, vol 3205. Springer, Berlin, Heidelberg

[8] A. Cosgun, E. A. Sisbot and H. I. Christensen, "Guidance for human navigation using a vibro-tactile belt interface and robot-like motion planning," 2014 IEEE International Conference on Robotics and Automation (ICRA), Hong Kong, 2014, pp. 6350-6355.

[9] Vinther, A., Vinter, M. (2015). Pathfinding in Two-Dimensional Worlds. Master's Thesis, Aarhus University, Computer Science.

[10] Daniel Harabor and Alban Grastien. 2011. Online graph pruning for pathfinding on grid maps. In Proceedings of the Twenty-Fifth AAAI Conference on Artificial Intelligence (AAAI'11). AAAI Press, 1114–1119.

[11] Wang, H.-C., Katzschmann, R. K., Teng, S., Araki, B., Giarre, L., & Rus, D. (2017). Enabling independent navigation for visually impaired people through a wearable vision-based feedback system. 2017 IEEE International Conference on Robotics and Automation (ICRA). doi: 10.1109/icra.2017.7989772

[12] Lam, A. (2006). Vibrotactile Pattern Recognition on the Torso with One- and Two-Dimensional Displays. Massachusetts Institute of Technology Undergraduate Thesis Archive.

[13] Durá-Gil, J. V., Bazuelo-Ruiz, B., Moro-Pérez, D., & Mollà-Domenech, F. (2017). Analysis of different vibration patterns to guide blind people. PeerJ, 5, e3082. doi: 10.7717/peerj.3082

[14] Jóhannesson, Ó. I., Hoffmann, R., Valgeirsdóttir, V. V., Unnþórsson, R., Moldoveanu, A., & Kristjánsson, Á. (2017). Relative vibrotactile spatial acuity of the torso. Experimental brain research, 235(11), 3505–3515. https://doi.org/10.1007/s00221-017-5073-6

[15] Heuten, W., Henze, N., Boll, S., Pielot, M. (2008). Tactile Wayfinder: A Non-Visual Support System for Wayfinding. Proceedings of the 5th Nordic Conference on Human-Computer Interaction: Building Bridges, pp. 172-181. doi: 10.1145/1463160.1463179

[16] Marston, J., Loomis, J., Klatzky, R., Golledge, R. (2007). Nonvisual Route Following with Guidance from a Simple Haptic or Auditory Display. Journal of Visual Impairment and Blindness, 101 (4), 203-211. doi: 10.1177/0145482X0710100403

[17] “Bluno_Nano_SKU_DFR0296.” *DF Robot*, https://wiki.dfrobot.com/Bluno_Nano_SKU_DFR0296.

[18] Craig, James C. “Difference Threshold for Intensity of Tactile Stimuli.” Perception & Psychophysics, vol. 11, no. 2, 1972, pp. 150–152., doi:10.3758/bf03210362.

[19] Erp, Van. (2002). Guidelines for the use of vibro-tactile displays in human computer interaction. Proceedings of Eurohaptics. 2002.

[20] Pielot, Martin, et al. “Evaluation of Continuous Direction Encoding with Tactile Belts.” Haptic and Audio Interaction Design Lecture Notes in Computer Science, 2008, pp. 1–10., doi:10.1007/978-3-540-87883-4_1.

[21] Cholewiak, Roger W., et al. “Vibrotactile Localization on the Abdomen: Effects of Place and Space.” *Perception & Psychophysics*, vol. 66, no. 6, 2004, pp. 970–987., doi:10.3758/bf03194989.

[22] “Wearable Computer-Vision Rig for the Visually Impaired (Case 2241).” *Commercial Opportunity -Wearable Computer-Vision Rig for the Visually Impaired (Case 2241)*, brown.technologypublisher.com/technology/18485.

[23] Erp, Van B. F. Van, et al. “Waypoint Navigation with a Vibrotactile Waist Belt.” *ACM Transactions on Applied Perception*, vol. 2, no. 2, Jan. 2005, pp. 106–117., doi:10.1145/1060581.1060585.