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Vibrotactile Guidance for Wayfinding of Blind Walkers

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Abstract— We propose a vibrotactile interface in the form of a belt for guiding blind walkers. This interface enables blind walkers to receive haptic directional instructions along complex paths without negatively impacting users' ability to listen and/or perceive the environment the way some auditory directional instructions do. The belt interface was evaluated in a controlled study with 10 blind individuals and compared to the audio guidance. The experiments were videotaped and the participants' behaviors and comments were content analyzed. Completion times and deviations from ideal paths were also collected and statistically analyzed. By triangulating the quantitative and qualitative data, we found that the belt resulted in closer path following to the expense of speed. In general, the participants were positive about the use of vibrotactile belt to provide directional guidance.

Index Terms— Assistive technology, haptic belt, wayfinding.

1 INTRODUCTION

Navigation through unknown environments remains a significant challenge for the visually impaired. Despite technological advances that have enabled increased mobility, the problem is far from solved given the existing sensing, localization, and interface technologies. Improved sensing enables rapid re-planning in a dynamic environment, both by a computer and the individual. Improved localization allows for more effective guidance from point to point, bypassing the errors common to GPS-based navigation (a technology that has received good acceptance by the blind community). And an improved interface lets the visually impaired user make the most effective decisions, reducing time, distance, and/or confusion when using the technology. In this work, we focus primarily on improved interface, proposing a vibrotactile system for guiding blind walkers. We evaluate the system in a controlled study with 10 blind individuals, comparing our proposed vibrotactile guidance with an auditory one.

The interface developed is a belt to be worn about the user's waist. Instead of communicating directions via an auditory interaction, the belt contains a number of vibration motors, which can be turned on to indicate a direction of travel. The advantage of vibration is that it is an otherwise unused communication channel; it does not interfere with users' ability to perceive other environmental events, as does auditory feedback, but is still easily recognizable with a limited added cognitive load. This is important because as localization technologies improve, reaching 10 cm accuracy or better, the complexity of the path a visually impaired person can be guided along will also increase – keeping people outside dangerous areas near construction sites, within crosswalks, and in line with elevators, doors, and other narrow openings. Using an acoustic interface to help a blind person follow these trajectories may require too many verbal instructions, occluding otherwise important auditory events. Vibration, by contrast, can be used continuously to describe complex paths, without masking important clues from the environment.

In the remainder of this work, we will first summarize the state-of-the-art in nonvisual interfaces for navigation systems. Then we will present two interfaces for guiding people along complex paths: our proposed belt interface, and an auditory spoken dialogue system. In Section 4, the user testing scenarios are described, including the environment, the testing objectives, and supporting hardware. Sections 5 and 6 then discuss the quantitative and qualitative results of the study. Finally, in Section 7 we compare and contrast the benefits of either interface.

2 RELATED WORK

Technology that can support safe and efficient wayfinding may have tremendous potential for improving the quality of life of people with visual impairments. Non-visual navigation systems may also find application in other domains, such as search and rescue (e.g. in a burning building with thick smoke) or combat zones. Two types of non-visual interface are available: acoustic and tactile. We review the related literature for these two interface types in the following.

2.1 Acoustic Interface for Wayfinding

Audio signals for directional guidance can be in the form of synthetic speech (or "spatial language", e.g.: "turn left", "go straight") or non-verbal acoustic sound. Non-verbal sound is often "spatialized", that is, generated in a binaural form to create the impression of sound generating from a certain point in space. For example, the NavBelt

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system (Shoval et al., 1998) created binaural sound representing the distance of objects in an azimuthal sweep. This "soundscape" allows one to create a mental picture of the obstacles' location and size with respect to oneself. To compute distance to objects, the NavBelt system used a set of sonars placed on the user's belt. In a study with 15 visually impaired participants, Loomis et al. (2005) tested different acoustic modalities to guide the participants through 50 meters long paths, each with 6 turns. Location information was obtained via GPS. Subjective evaluations indicated that participants preferred spatialized speech with respect to other forms of display – even though most participants complained that the use of headphones (which was necessary to create the spatialized sound) resulted in background sound being blocked. Bonephones (which have been proven to permit correct localization with spatialized audio; McDonald et al., 2006) may be used to avoid environmental sound masking. In a different experiment with 17 blindfolded sighted participants, Klatzky et al. (2006) showed that the cognitive load associated with a spatialized tone (measured via an N-back vibrational task) is lower than with spatial language. Assessing the cognitive load associated with a spatial interface is important to model the user's performance while multitasking, e.g. when using this system in a crowded environment while trying to avoid obstacles. A system using spatialized sound, with additional distance information (represented by varying the rate of a pulsating sound) was used in the AudioGPS system (Holland et al., 2002).

2.2 Vibrotactile Interface

A wearable tactile navigation interface was designed and tested by researchers from MIT's Media Lab in the late 90s (Ertan et al., 1998). This system had a matrix of 4x4 vibrators, placed on the user's back (embedded in a vest), which could generate five possible instructions: four cardinal directions and stop. The cardinal directions were indicated by successively turning on rows or columns of motors in the direction that the user should move. A similar system (haptic back display) used a 3x3 matrix of vibrators placed on the user's back for attentional and directional cueing (Tan et al., 2003).

The first vibrotactile belt system ever reported in the literature was the ActiveBelt (Tsukada and Yasumura, 2004). This belt had eight vibrators (FM23A by TPC) with LEDs attached to check the status of the vibrators. The vibrators were activated via a pulsating signal, with 50% duty cycle, and repetition period selected among the following values: 0.4 s, 0.5 s, 1 s, 1.68 s. Experiments were conducted with 6 sighted participants, with orientation data computed by a digital compass. In a first set of experiments, participants were asked to recognize the direction represented by an active vibrator. All repetition periods gave similar results in this experiment, and all participants were able to determine the correct orientation. In the second set of experiments, participants were asked to walk following directions from the system. All participants were able to perceive vibrations with period of 1 s and 1.68 s, but at least some participants were not able to perceive vibrations with a lower period.

Van Erp et al. (2005) tested a belt with eight actuators ("tactors") based on pager motors, spaced uniformly to represent cardinal directions. The tactors had a contact area of 1.5 by 2 cm and vibrated at 160 Hz. Tactors were activated with pulses with period of 1 second. Location and orientation information was produced by GPS and digital compass. Experiments were conducted with 12 sighted participants, as well as with a helicopter pilot and a fast boat pilot (later experiments considered more challenging military operational conditions; Elliott et al., 2010). Participants walked on routes between 360 and 380 meters in length, each with 6 waypoints. These experiments considered different versions of the vibrotactile interface. In the first (control) version, only directional information was given, by activating the proper tactor. The other versions considered different vibrotactile modalities to represent the distance to the next waypoint. The results showed no statistically significant difference between the control and the other modalities in terms of effective walking speed. This may indicate that knowledge of the distance to the next waypoint may not be important for efficient guidance, although it was argued that this result might also be due to the participants not being able to correctly interpret the distance information, or to the particular method chosen to encode the distance information, which affected the rate at which orientation information was given.

The Tactile Wayfinder (Heuten et al., 2008) employed a belt with 6 vibration motors. Two adjacent motors could be activated at the same time to produce the sensation of an in-between direction. In experiments with 13 sighted participants, the direction indicated by the signal produced by the belt was perceived with a median deviation of 15 degrees. Seven participants undertook navigational experiments by walking along two routes, one 375 m long and with 6 waypoints, and one 430 m long and with 5 waypoints. The users' position was measured and recorded by GPS. In 99% of the recorded positions, the deviation from the desired path was of 15 meters or less; in 78% of the cases, the deviation was of less than 10 meters. The Tactile Wayfinder was later modified (Pielot and Boll, 2010) to include 12 vibrational motors, and a control system that informed the user not only about the direction to the next waypoint, but also about the direction to the waypoint after next ("look-ahead waypoint"). A sequence of two outputs was produced every 4 seconds. The first output (representing the next waypoint) was encoded by a heartbeat-like pulse, which was repeated five times by the appropriate tactor. The second output represented the look-ahead waypoint by way of a single pulse. Distance information was not produced. Fourteen sighed participants tested the system against a more traditional GPS device (TomTom) that produced visual output, walking on routes 800 m long with 6 waypoints in a crowded urban environment. Results showed that participants made significantly more navigation errors using the Tactile Wayfinder. However, use of the Tactile Wayfinder allowed users to pay more attention to the environment, as measured by a "photo recall" test. Subjective workload reporting showed no significant difference between the two methods.

Lee et al. (2008) built a wayfinding system with 8 sonars and a camera that can recognize specific markers placed on the ceiling. Directions are given to the user via a "vibration jacket" with 8 vibrators placed at chest height. No information was provided about the specific control of the vibrators (except that the two front vibrators were activated at the same time to indicate a "forward" direction, and that the two back vibrator were activated at the same time to indicate a "stop"). The NAVI system (Zöllner et al., 2011) uses a Kinect range camera to detect obstacles. The presence and location of an obstacle is communicated to the user by activating one of three vibrators, placed at the left, center, or right of the user's chest. No user studies with these last two systems have been reported.

A "minimalistic" wayfinding system with a single wrist-worn vibrator was tested by Marston et al. (2007) with eight legally blind participants on 80 meters long outdoor paths that contained both 90-degree and 45-degree turns. Two activation modes were considered. In the *on-course* mode, the vibrator was activated when the user was oriented towards the next waypoint; in the *off-course* mode, activation occurred when the user was oriented away from the next waypoint. The user's position and orientation were measured by GPS and digital compass. The experiments compared this system with a similar device based on acoustic interface (a chime sound delivered through an earbud). The results showed that this simple binary output was sufficient for route following, that vibrational and acoustic outputs were equally useful, and that the *off-course* mode was preferred. The authors also pointed out that a disadvantage of a single-vibrator system is that, once at a waypoint, the user needs to actively rotate his or her body to detect the direction towards the next waypoint; this information could be conveyed immediately (without the need for search) using a multi-vibrator interface or through spatialized sound.

We should note that the use of vibrotactile actuators has been proposed also in contexts different from wayfinding, which is the application considered in this article. For example, Palmer et al. (2012) designed a system with vibrators placed in different parts of the body so that users can "feel with their skin the spatial environment around them", while Giudice et al. (2012) used the vibrator in a mainstream tablet to enable tactile access to lines and shapes.

2.3 Motivation and Contributions of Our Work

As this brief review has shown, while substantial prior work exists concerning vibrotactile displays embedded in a belt, there are no experiments reported in the literature involving blind walkers using this type of devices (except for the paper of Marston et al, 2012, which however only considered a single vibrator.) This is a critical knowledge gap, considering that visually impaired users are potentially prime beneficiaries of this this technology. The main contribution of this paper is a within-subject experimental study with blind participants comparing two different types of non-visual interface: a vibrotactile belt with 8

Figure 1. Vibrotactile belt prototype

vibrators and an acoustic system producing short synthetic speech sentences. We used a custom-designed tracking system that can accurately localize the walker and compute his or her orientation at each time. This allowed us to produce walking traces with a spatial resolution that is much higher than in previously reported work, and to extract multiple metrics for evaluating the effectiveness of these interface mechanisms. In addition, we present a thorough qualitative analysis (from videos taken of the experiments) of the users behavior. This analysis brings to light important characteristics that could not be measured directly from quantitative measurements.

3 Interface Overview

Since blind individuals rely heavily on their sense of hearing for environmental awareness, we decided to convey navigation information through haptic means. Our main goal for the interface was to obtain a design that would be natural, discreet, easy to equip, and would have sufficient resolution for our purpose. To this end we developed a vibrotactile belt to be used as a wayfinding tool for people who are visually impaired.

The vibrotactile belt is an interface that depends on an external localization system to measure the position and orientation of the blind person wearing the belt with respect to a desired path. As the users' orientation relative to the path changes, vibrators on the belt in the direction of the path are activated to indicate the correct orientation for forward motion.

3.1 Vibrotactile Belt

The vibrotactile belt contains 8 small vibrators, placed in different locations in the belt. These vibrators are akin to the vibrators used in regular cell phones. We considered the following factors in designing the belt:

- *Ergonomics*: The belt needs to be comfortable, easy to put on, and easy to remove.
- *Self-sufficiency*: The belt needs to include power, communication, and control units for wireless operation.
- *Resolution*: The belt needs to incorporate a sufficient number of actuators to provide a good direction resolution.

- *Aesthetics*: The belt should be visually appealing with hidden electrical and mechanical components.

3.1.1 Hardware

A common way to produce vibrations is to use a vibration motor. These motors consist of a standard DC motor with an uneven weight, which causes the motor to generate vibrations whose strength depends on the rotation speed of the shaft.

We selected flat coin motors over cylindrical motors. Although these motors provide less strength, their size and shape make them an ideal choice for the belt application. For the vibrotactile belt we used 8 KOTL C1026B002F Flat coin vibration motor operating in 3V up to 9000rpm. We also attached an LED to each motor where we set the brightness proportional to the rotation speed of the motor. This helps the observer to verify the status of the motors.

We used an OSEPP™ Bluetooth board to control the motors and LEDs. Motors are driven with Pulse Width Modulation with a 20 kHz square signal. The Bluetooth 2.1 protocol is used to communicate with the controller.

All of the components above were placed in an elastic belt. The motors were placed at 8 cardinal directions with 45 degrees between each adjacent pairs. The board was inserted in a casing at the back of the belt, which also contains a 9V battery to power the overall system. Figure 1 shows the final vibrotactile belt prototype.

3.1.2 Software Architecture

The goal of the belt software was to guide the user by activating the vibrator in the belt aligned with the goal position in space. The system assumed that the guidance path (in the form of a set of intermediate waypoints) was already provided. At the beginning of the trial, the system selected the first waypoint as the intermediate target, and activated the motor aligned with this target. Once the user was close enough to the intermediate target, the target was moved to the next waypoint. Users reached all waypoints one by one and finally reached the ultimate destination.

The system's overall architecture is illustrated in Figure 2. As seen in this figure, the software components (modules) were distributed between the station and the belt (on the user). There were two main modules controlling the belt: the Belt Signal Controller and the Belt Controller.

3.1.2.1 Belt Signal Controller

The goal of this module was to calculate which vibrators needed to be activated given the current waypoint and user location and orientation. This module generated a list of 8 integer numbers, representing the vibration strength for the motors in the belt.

There were two inputs to the Belt Signal Controller:

- A waypoint W (a position in space defined by (x,y) coordinates).
- The current pose of the user in form of (x_H, y_H, θ_H) representing the user's 2D position and the orientation.

At each time, the controller evaluated the distance and bearing angle of the next waypoint to the user. Given the user's current pose (x_H, y_H, θ_H), and the next waypoint $W_i = (x_i, y_i)$, the controller computed the bearing angle θ_{W_i} representing how much the user should turn to face to the waypoint:

$$\theta_{W_i} = \text{atan}\left(\frac{y_i - y_H}{x_i - x_H}\right) - \theta_H$$

Next, it computed the distance between the user and the waypoint:

$$D_{W_i} = \sqrt{{(y_i - y_H)}^2 + {(x_i - x_H)}^2}$$

D_{W_i} was continuously evaluated to decide whether the user was close enough to the current waypoint. Once the user was at a distance of less than 0.75 m to the waypoint, the controller was allowed to skip to the next waypoint.

Based on the values taken by θ_{W_i} and D_{W_i} a specific type of control was chosen. We defined 3 types of control:

- *Directional*, indicating that the user should move toward a particular direction.
- *Rotational*, indicating that the user should rotate in place.
- *Stop*, indicating that the user should stop moving.

Directional Control:
The directional control was activated when the user was at a distance D_{W_i} larger than 0.75 m to the next waypoint, and the bearing angle to the waypoint θ_{W_i} was less than 67.5° in magnitude. In this type of control, the bearing angle θ_{W_i} was directly mapped to the choice of motor to be activated (Figure 3). Only one motor was activated at a time, and specifically the motor i whose location in the belt was best aligned to the waypoint:

$$i = round\left(\theta_{W_i} \frac{8}{2\pi}\right)$$

Note that, as the belt contains 8 equally spaced motors, this modality could provide an angular resolution of 45°. In fact, due to the restriction in the maximum bearing angle, only one of the three frontal vibrators could be activated with this type of control. The strength of the vi-

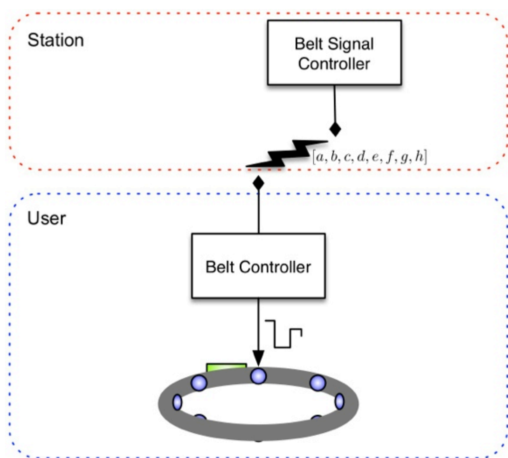

Figure 2. Guidance system architecture

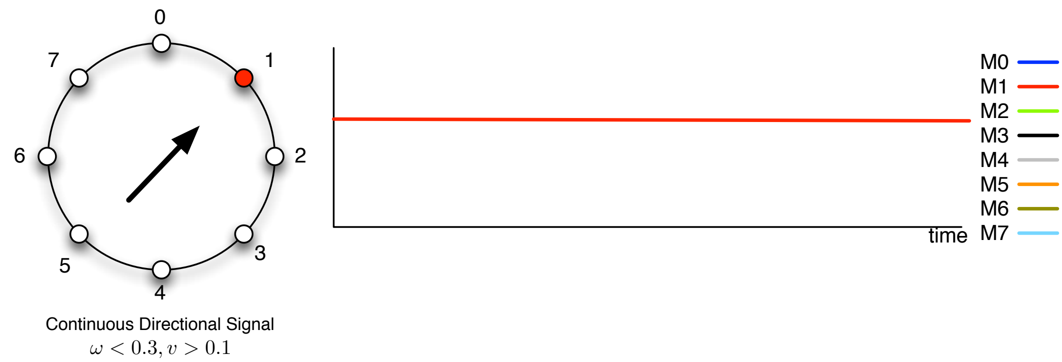

Figure 4. Continuous direction signal

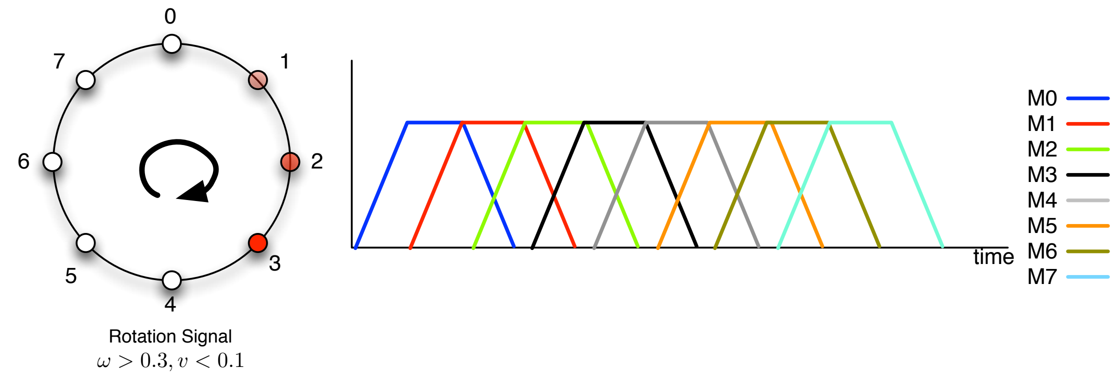

Figure 5. Rotation signal

bration was also selectable (for example, it could be tuned according to the user's preference). However, in our experiment we always activated all motors with the same strength.

Rotational Control:
This control modality was activated when the user was at a distance larger than 0.75 m to the next waypoint, and the bearing angle to the waypoint is larger than 67.5° in magnitude. In this case, rather than directing the user to the waypoint by activating a single motor, the system directed the user to rotate in place, with the goal of aligning him or her with the waypoint before starting walking again.

Stop Control:
If the user reached the final destination (more precisely, when he or she was within 1 meter from the final waypoint), a special stop message was created.

3.1.2.2 Belt Controller

The Belt Controller was in charge of translating motor commands coming from the Belt Signal controller to electrical signals, and sending them through the correct cables. This was the only component that ran on the belt in the OSSEPP micro controller. The three different types of control mentioned above (directional, rotational, and stop) were translated into specific vibrational patterns.

Directional Control: Under this type of control, the system continuously vibrated one motor at a time, signaling the user to move in the direction of the vibration. Figure 4 illustrates this modality with the activated motor on the belt, along with the time-activation graph of the vibration signal. As seen in the left figure, the system activates motor number 1 (M1) to represent the motion (Black arrow). The right plot shows the vibration signal applied to the belt. In this example a constant signal is applied to motor 1.

Rotational Control: The rotational control was designed so as to indicate a direction of rotation in place by activating and deactivating motors to give the feeling of rotation. Figure 5 illustrates a clockwise rotation. As seen in this figure, the motors were enabled sequentially from 0 to 7.

Stop Control: This signal signaled the user to stop moving through a distinctive vibration pattern. Specifically, all 8 motors in the belt vibrated at the same time twice for the duration of 0.5 seconds.

3.2 Audio Guide

An alternative interface technique for wayfinding is audio guidance through spoken directions. To enable comparative assessment of our vibrotactile interface, we created an auditory guidance system that responds to the Belt Signal Controller, generating audio output instead of vibration signals.

The audio interface used five utterances to guide the user along the desired path. These utterances were: *for-*

ward, *left*, *right*, *turn around*, and *you have reached your destination*.

- *Forward*: This command was issued only once the user was facing an intermediate waypoint along the path with ±15° margin. The command was not repeated so long as the user was moving along the correct direction.
- *Left, Right*: Left and right commands were issued when the user was facing more than 15° away from the intermediate waypoint, but less than 135°.
- *Turn around*: This command was issued when the users was facing more than 135° away from the target waypoint.
- *You have reached your destination*: The audio guide issued this utterance once the user arrived to within 1 m of the final destination. This was not uttered for intermediate waypoints along the path.

It should be noted that there was a difference between the number of "commands" that the belt can issue compared to that of the audio guide, and that the angular span represented by acoustic directions was larger than for directions given by the belt. Specifically, the belt had two signals for both right and left turns (45° turn and 90° turn), while the audio guide had one signal each for left and right turns. We chose this audio command setup to avoid overloading the participants with longer commands. In a pilot experiment that preceded the study, we observed that even one-word audio commands were processed more slowly by the participants compared to the equivalent haptic command.

4 User Testing Setup

All of the authors (one of whom is legally blind) tested the experimental setup prior to the actual user testing.

10 blind persons participated in this user study. The participants were recruited by advertisement through mailing lists posted at various organizations for people who are blind as well as personal contacts. To be included in the study, participants needed to be 18 years of age or older, be not pregnant, have at most some residual light perception, be able to walk safely and independently (using a long cane or a dog guide), and be able to understand and follow directions and explanations in English.

The study was conducted in a large (30' by 30') indoor space in the Toyota ITC facility in Mountain View, CA. After arriving at the location, participants were greeted by the experimenters in charge of the test on that day, and taken to the experimental space. The participants were read and asked to sign the IRB-approved consent form. Users' demographics and walking habit were then acquired through a questionnaire that was read to the participants.

Before the beginning of the tests, participants attended a short training phase, during which they were shown the correct use of the belt (how to wear it properly, how to react to a vibration), and underwent two rehearsal trials. The participants were allowed to request a break at any time. A chair was made available for rest, and drinking

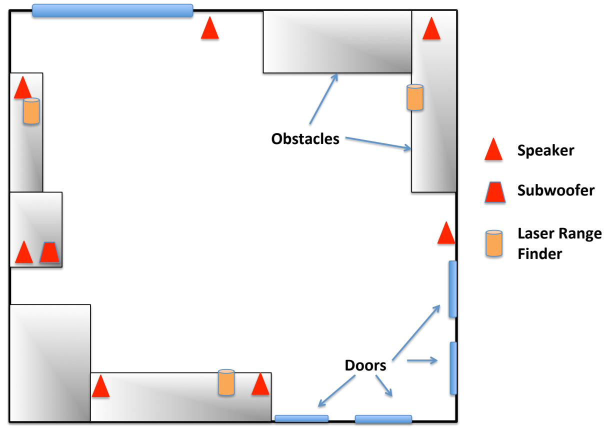

Figure 6. Layout of the testing environment

water was provided. The overall study lasted two hours or less per participant. After the study, each participant was asked to respond to a short questionnaire and to give their feedback about the system.

The space in which the participants walked (see Figure 6) was obstacle-free; protruding furniture at the periphery of the space was covered with soft material to minimize the risk of injury in case of collision. There were no steps, curbs, or staircase in the designated trial space. Speakers from a 7.1 channel system were distributed on the walls to reproduce background traffic noise at low volume; this helped mask other environment noise (e.g. rattle from the garage door) that could otherwise be used as directional references. Likewise, the use of a distributed sound system minimized the risk that participant could use sound direction for orientation.

One or more experimenters were present at each trial and carefully monitored the blind participants at all times to make sure that they would not mistakenly hit a wall or a piece of furniture. If a blind participant moved too close to an obstacle, the experimenter asked the participant to stop. The whole session was video recorded, and the answers to the final questionnaire were audio recorded.

Each participant underwent a number of short trials; in each trial, the participant was asked to walk along a path as guided by the belt or by a speech signal. We adopted a counterbalanced experimental design: five participants underwent the trials with the vibrotactile belt first, followed by the trials with the acoustic interface; the order was reversed for the remaining five participants. During the tests, the participants were allowed to use any mobility tool they normally use (long cane or dog guide). Only two participants were regular dog guide users, but they decided to not use their dog guide in the test.

4.1 Localization System

The purpose of the localization system was to compute the position (within 10 cm accuracy) and orientation of each participant at all times during the trials. Although such localization systems are not generally available as yet, vision-based odometry solutions have been demonstrated in real-time on embedded hardware for multicopter localization (Forster et al., 2012). This type of sys-

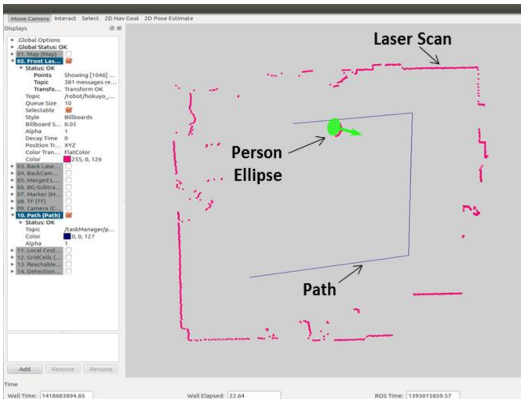

Figure 7. Experimenter interface showing a single laser scan, detected person ellipse, and the path to follow.

tem could also be deployed to a smartphone or wearable solution for ground-based navigation. The pose determined by this localization system can then be sent to the vibrotactile belt controller or audio guide to produce guidance commands.

Our localization solution was composed of three Hokuyo laser rangefinders, placed in fixed locations in the environment (see Figure 6) and manually adjusted to the height of the participant's shoulders. We chose to measure range at shoulder height to reduce the risk of obstruction from the user's hands or long cane. Note that one's shoulders (unlike one's head) are normally oriented in the direction of travel.

Once the lasers were adjusted to the correct height, an Iterative Closest Point algorithm (pointclouds.org, 2014) was used to align all 3 laser scans into a single combined laser scan. A further optimization step subtracted the walls from the final scan by removing points within 5 cm of an initial background scan without the participant present. The remaining point clusters measured by the system indicated people in the room, including the participant and experimenters. Before each trial, the experimenter manually selected (through an appropriate user interface) the cluster corresponding to the participant and an initial orientation. The location of the participant was tracked by fitting an ellipse to the cluster of points (Fitzgibbon et al., 1999) closest to the last known position. The center of the ellipse defined the participant's current location, while the direction of motion was estimated from the minor axis orientation, using the last detected direction to identify the correct flip about the major axis. With full coverage of the room and lasers sampled at 50 Hz, tracking handoff was reliable for all paths. Figure 7 shows the graphical interface used by the experimenter to view a single laser scan, with the detected ellipse fitting the point cloud around a participant, and showing the path defined for that particular trial.

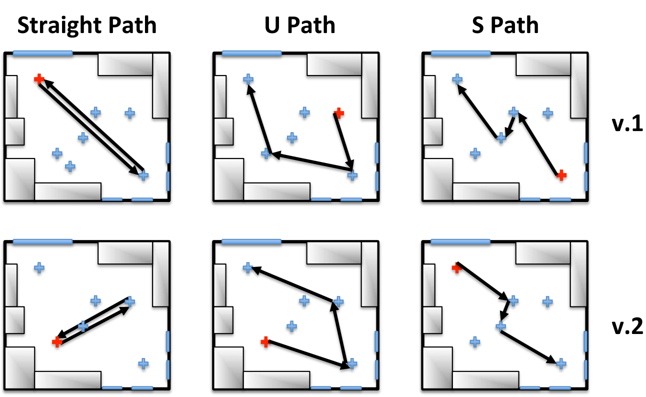

Figure 8. Paths evaluated during testing. The blue crosses represent waypoints. Each path is defined by an ordered sequence of waypoints

4.2 Paths

A total of six different paths were evaluated, with two paths for each one of three different types: straight-line, U-shaped, and S-shaped (Figure 8). These paths were chosen so as to provide a variety of complexities, including turns at angles different than 90° that were assumed to be more challenging for the guidance system to communicate than right-angle turns. Paths to be followed were defined by the segments joining subsequent waypoint pairs in an ordered list.

Each path was traversed twice (but not consecutively) by each participant for each interface modality (vibrotactile or acoustic). Thus, participants underwent 24 trials in total (12 trials for each interface modality).

5 Quantitative Analysis

5.1 Metrics

For each path traversed by a participant, we took multiple measurements:

- *Total distance travelled (D).* This is a direct measure of travel efficiency: shorter distances mean more efficient traversal. Note that the total distance travelled is a function of the path length.
- *Time to completion (T).* The total time taken by the participant from the "Start" direction until the system determined that he or she was arrived in the vicinity of the last waypoint. This is also a function of the path length.
- *Average absolute angle away from next target waypoint (A).* The most efficient traversal is obtained by walking straight towards the next waypoint. An indirect way to measure traversal efficiency is to compute the angle between the walker's orientation and the direction to the next waypoint: a large absolute value of this angle means that the participant is not walking along the "best" direction.
- *Average distance from segment joining two consecutive waypoints (H).* This quantity measures the distance at each time from the path taken by the participant and the "ideal" path.

Based on these measurements, we also computed a number of derived quantities:

- *Path inefficiency ((D-L)/L).* This is equal to the difference between the distance travelled and the actual path length, normalized by the path length. Large values indicate inefficient traversal.
- *Effective average speed (L/T).* The length of the path, divided by the total time to completion.
- *Actual average speed (D/T).* The total travelled distance, divided by the time to completion.

Each measurement was computed over the whole path taken by the participants. We also computed the

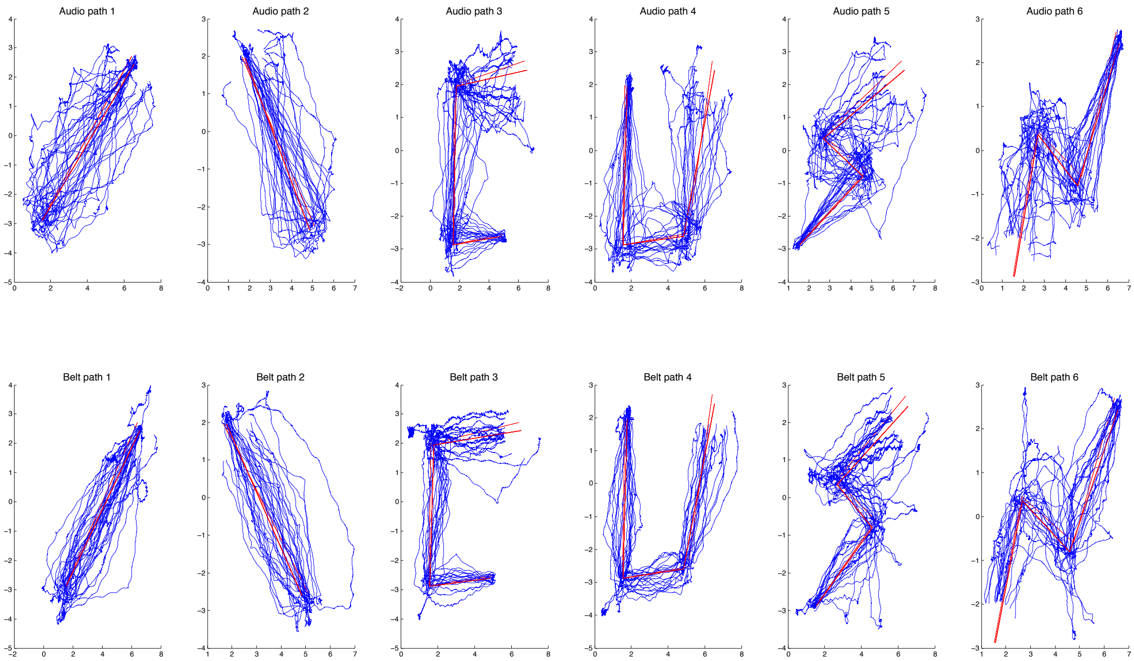

Figure 9. Participants paths (blue) overlaid on the real path (red). Units are in meters

same measurements but starting from the first waypoint, rather than from the actual beginning of the path. This is because we found that occasionally the localization system produced incorrect values at the beginning of the path, due to incorrect body alignment of the participants. Quantities measured from the first waypoint are represented by a symbol with the subscript '1' (e.g. A_1).

It should be noted again that each participant traversed the same path twice using the same modality (audio or belt). The two measurements over the same path (with the same modality) were averaged together before our analysis. Due to human errors during data collection, in four cases one of the two measurements was missing; in these cases, the only measurement collected was used in lieu of the average. For one participant, both measurements in one path using the belt were not recorded. In this case, we filled in the missing value with the average value for the same modality and the same path from all other participants.

We modeled the measurements using a 2-factor (*modality*, *path*) repeated measures model with interaction between factors. Specifically, indicating by y_{ijk} a measurement taken with the i-th modality (audio or belt) over the j-th path (where j is the path index, $1 \le j \le 6$) from the k-th participant ($1 \le k \le 10$), we model y_{ijk} as follows:

$$y_{ijk} = \mu + \tau_i + \beta_j + \gamma_k + \delta_{ij} + \varepsilon_{ijk}$$

where ε_{ijk} is independent Gaussian noise, and δ_{ij} models factor interaction. Main effects are discovered via ANOVA. Only the main effect of *modality* is considered in this analysis, as our main focus is in the comparison of the audio and the belt interface mechanisms.

5.2 Quantitative Results

Table 1 shows the average values (over paths and participants) μ_{audio} and μ_{belt} of the various measurements considered for the two interface modalities (audio and belt). When the difference in mean was found to be significant by ANOVA, the values were displayed in boldface. We also tested for interaction between interface modalities and paths; when interaction was deemed significant by ANOVA, we tested for difference in means between the two interface modalities at each individual path using a paired t-test with Bonferroni correction. The only significant interactions were found for measurement A at path 3 (p=0.06; μ_{audio}=39°,μ_{belt}=28°) and for L_1/T_1 at path 2 (p=0.06; μ_{audio}=0.44 m/s,μ_{belt}=0.29 m/s).

Several interesting observations can be drawn from these measurements. The average absolute angle away from the target waypoint A is quite large (more than 30°) for both modalities. This shows that participants did not take direct paths toward the next waypoint. This is seen clearly in the path traces shown in Figure 9 and indirectly confirmed by the inefficiency $(D\text{-}L)/L$ values, which show that the actual distance travelled was, on average, larger by 50% or more than the path length. The data also shows that, when directed by the belt, participants kept at a closer distance to the path than when listening to audio directions. Observation of the traces in Figure 9 also confirms this measurement. The audio modality enabled faster traversal, both when measured as actual speed (L/T) and as effective speed (D/T).

Table 1. Summary of quantitative results. Each row represents a specific measurement. The columns μ_{audio} and μ_{belt} contain the average measurement for the two conditions. When the difference in average is significant ($p \leq 0.05$), these quantities are typed in boldface

	$F(1,99)$	p	μ_{audio}	μ_{belt}
A	5.34	0.02	**37°**	**34°**
A_1	0.48	0.49	41°	39°
D	0.46	0.50	19.39 m	19.93 m
D_1	1.83	0.18	12.24 m	13.17 m
H	11.07	0.001	**0.55 m**	**0.46 m**
H_1	9.81	0.002	**0.61 m**	**0.49 m**
$(D - L)/L$	1.22	0.27	0.64	0.71
$(D_1 - L_1)/L_1$	2.51	0.12	0.70	0.84
T	7.11	0.009	**39.3 s**	**46.5 s**
T_1	9.00	0.003	**24.7 s**	**31.1 s**
D/T	14.72	$2.2 \cdot 10^{-4}$	**0.52 m/s**	**0.47 m/s**
D_1/T_1	18.31	$4.3 \cdot 10^{-5}$	**0.53 m/s**	**0.46 m/s**
L/T	9.76	0.002	**0.33 m/s**	**0.29 m/s**
L_1/T_1	14.45	$2.5 \cdot 10^{-4}$	**0.33 m/s**	**0.27 m/s**

6 Qualitative Analysis

After the trials with either interface modality, we asked the participants what they thought about the use of such modality to provide directional guidance. In general, the participants were positive about the belt, more so than about the auditory guidance, given the concern that an acoustic interface system would require them to wear headset that would impede their ability to hear the environment. However, as one of the purposes of this study is to objectively assess how users interact with both modalities, we observed the participants' behaviors and recorded comments in both conditions.

In this section we discuss the main themes that surfaced from content analysis of the videos for participants P1 through P10 (except for P1 who did not consent to being video recorded) along with their frequency and the difference between the guidance systems (if any). The themes were extracted from video footages and audio interview transcripts using content analysis technique by three independent coders.

6.1 Specific Annotations

Our qualitative analysis is based on the video data collected from nine participants. However, some exceptions were taken due to specific problems with individual participants:

- Participants P2 and P3: Due to incorrect camera placement, parts of the paths were outside the field of view of the camera. In this case, handwritten notes were taken from direct observation during the trials.
- Participant P5: The belt was too large for this participant's waist, so it was placed around her hips instead. The participant was still able to sense the motors' vibrations even with this placement, albeit with reduced sensitivity for the side vibrators, which hampered her ability to recognize "turn" signals (that is, directional signals from vibrators at her right or left). For this reason, we decided not to include this participant the data analysis concerning the participants' behavior under a "turn" signal.
- Participant P5 sometime neglected to wait for a "forward" signal in the audio interface mode. As a consequence, the system issued multiple correction signals, resulting in a zig-zag motion pattern.
- Participant P5 often got confused about the meaning of the control signals for both the vibrotactile and audio modality. This required frequent interaction with the experimenter.
- Participant P6 misinterpreted the signals from the side vibrators during the first trials of the session with the vibro-tactile belt. Rather than rotating in response to a signal from a side vibrator, P6 would step to the side. However, after a few trials, this participant learnt to react correctly to these signals by changing the direction of walk rather than side-stepping. Only these last trials were considered in our analysis.

6.2 Analysis

We analyzed the videos with the experimental trials to extract common "themes" of user behaviors. Note that not all themes were observed in all path traversals. After defining the themes (which are listed and described below), we counted the occurrences of each theme in the sessions with the vibrotactile belt and with the audio interface. The occurrence counts are presented in Table 2, along with the variance of occurrences across participants for each interface modality. For each theme, we ran a Mann Whitney U test to look for significant difference in mean between the theme occurrence counts in the two

Table 2. Total count of themes occurrences for the two interface systems, standard deviation of occurrences across participant, and p-values produced by the Mann Whitney U test comparing the mean of theme counts between the two interfaces.

	Theme	1	2	3	4	5	6	7	8	9	10	11	12
Belt	*Count*	12	4	**10**	3	9	9	29	**24**	9	N/A	12	8
	Std Dev	1.500	0.527	1.167	1.000	1.118	2.646	1.856	1.581	3.000	N/A	1.500	0.782
Audio	*Count*	**65**	**31**	0	**22**	15	0	30	11	N/A	2	6	**33**
	Std Dev	1.922	2.651	0.000	2.555	1.414	0.000	2.550	1.641	N/A	0.441	0.707	3.742
P-value		**0.0000**	**0.0050**	**0.0110**	**0.0210**	0.1420	0.1450	0.4590	**0.0380**	N/A	N/A	0.1260	**0.0290**

interface modalities. Situations with p-value less than 0.05 (indicating a significant difference) are marked in red in Table 2. The themes that emerged from analysis of the experimental videos are listed in the following.

1. **Waypoint veering**: The participants walked "next" (1-4 steps to the side) to a waypoint. Frequent correction signals by the system when the participant was not correctly oriented towards the waypoint resulted in a zig-zag pattern.
2. **Waypoint turning back**: The participant walked past a waypoint but not within 0.75 m from it. Consequently, the system guided the participant to turn back towards that waypoint.
3. **Path rigidness**: The system appeared to send consecutive correction signals when the user veered off the intended path.
4. **Rapid consecutive signals**: The participant received multiple commands in rapid succession (e.g., "left – turn around – right"). This typically resulted in confusion and possibly in the participant following the previous direction of motion, rather than updating it.
5. **Zig-zag pattern**: The participant walked in a zig-zag pattern. This seemed to be a consequence of veering off-path or of delayed control signal.
6. **Swivel**: The system issued multiple contradictory commands (e.g. "turn left/right") even when the participant was not moving. This was likely due to incorrect estimation of the participant's orientation.
7. **Missing or delayed follow-up signal**: After walking past a waypoint, the participant did not receive a follow-up signal directing him or her towards the next waypoint. This typically caused the participant to either stop or keep walking forward. In other situations, the participant received a follow-up instruction but long after passing by a waypoint.
8. **Guided towards obstacle**: The system directed the participant to walk towards an obstacle at the periphery of the walking area. This often appeared to be caused by a delay in the control signal.
9. **[Belt] Dulled sensitivity of front vibrator**: The participant observed a reduced sensitivity of the front vibrator over time.
10. **[Audio] Confusing consecutive turn signals**: When a "turn around" signal was followed or preceded by a "left" or "right" signal, the participant either neglected this signal or stopped completely.
11. **Incorrect direction at beginning**: At the beginning of the trial, the participant was given a wrong direction. This was likely due to incorrect estimation of the participant's orientation.
12. **Wrong direction**: This is similar to Theme 11, except that a wrong direction was given anytime in the path, rather than at the beginning of the path

As shown in Table 2, no statistically significant difference was found between the belt guidance system and the audio guidance system for 4 out the 10 shared themes (themes 5-7 and 11). It is important to note that both guidance systems had a relatively high frequency of missed/delayed follow up signals (theme 7). Statistically significant difference was found between the belt guidance system and the audio guidance for 6 out of the 10 shared themes (themes 1-4, 8, and 12). In particular, trials using the audio interface clearly displayed a higher count of occurrences of themes 1-2, 4 and 12, whereas trials using the vibrotactile belt system displayed a higher count of occurrences of themes 3 and 8.

7 Discussion

7.1 Summary of Results (Triangulating Quantitative and Qualitative Analysis)

In this project, we developed a vibrotactile belt interface that we posit could help guide blind walkers follow a path by receiving directional information. We also posit that the vibrotactile belt can produce guidance that is easier to follow than using a speech-based audio interface. To test this informal hypothesis, we compared our vibrotactile belt with an audio guidance counterpart in a variety of path scenarios. We collected path data to enable quantifiable statistical analysis, and collected video and verbal comments for a qualitative comparative analysis of the walkers' behaviors when receiving guidance from the two interface systems.

The quantitative analysis of path described in Section 5.2 suggests that there are significant differences between the two guidance modalities on multiple metrics: *"Average distance from segment joining two consecutive waypoints"* (the average is higher for the audio interface) and *"Time to completion"* (the average is lower for the audio interface). These contribute to significant differences in two derived metrics, *"Actual average speed"* and *"Effective average speed"*. A first reading of these results is that, while the participants more closely follow the paths when they are directed by the belt, they did so at the cost of higher time to completion and consequently lower speed.

Triangulating the quantitative with the qualitative findings, we argue that the fact that the participants were able to more closely follow the paths with guidance from the vibro-tactile belt is consistent with the statistically significant differences found in the frequency of themes 1 and 2. This suggests that haptic guidance can be more immediately perceived and processed than audio guidance.

7.2 Interview results – Suggested Improvements

During the final interviews, the participants produced a number of suggestions for improvement of the interface system. One suggestion was to use the vibrator at the back of the belt to indicate a 180 degrees turn. It was also suggested to use a progressively faster vibration frequency to indicate closing in on an obstacle or a target, and producing a very distinct vibration to indicate an immediate stop (e.g., in case of a hazard). Some participants suggested using different vibration intensity for different body parts, to match the user's preferences, or to account for different clothing thickness. In addition, changing the vibration pattern through time could ensure that the user does not "get used to it." It was suggested that receiving frequent corrections may be difficult if one is using a dog guide. Some participants noted an unpleasant ghost "after-vibration" (a tingling sensation even after the vibration stops). Ergonomics is also important: some participants noted that the belt needs to be durable in case of falls, or when the user hits an object or is sprayed with water (e.g., from a sprinkler or in the case of rain). Some suggested that the system could be packaged in a regular belt that could be worn as a garment.

For what concerns the audio guidance, some participants suggested using a finer spatial resolution, and exchanging the "turn around" signal with a sequence of "left" or "right" commands. In addition, several participants noted that it may be difficult to produce audio guidance without occluding sounds from the environment.

8 Conclusion

In this paper we describe a vibrotactile interface in the form of a belt for guiding blind walkers through possibly complex paths. The belt interface was evaluated in a controlled study with 10 blind individuals and compared to a system using synthetic speech for guidance. The experiments were videotaped and a thorough analysis of the participants' behaviors was conducted. Completion times and deviations from ideal paths were also collected and analyzed. Triangulating the quantitative and qualitative data, we found that the vibrotactile belt enabled closer path following, at the cost of reduced average speed.

Several lessons can be learned from this study with blind pedestrians. First and foremost, there is merit in providing a guidance system that enables blind walkers to receive haptic directional instructions without negatively impacting their ability to listen and perceive the environment. The qualitative data shows that, in general, the participants were positive about the use of vibrotactile belt to provide directional guidance. Some exemplar comments are:

"I believe that the vibration would work better because it would eliminate having to listen…" (P7).

"You know some people prefer audio, I prefer… not to have my, my hearing interrupted." (P9).

A second lesson we learned is that it is important to combine qualitative and quantitative data from the user studies. Only by triangulating observations from video clips with quantitative results did we find the explanations for some behaviors or performance.

Thirdly, there is a need to carefully consider the directional granularity vs. cognitive processing speed tradeoffs between different modalities. In our case, we chose to use a lower angular resolution for the audio interface in order to produce short sentences that could be quickly processed by the walkers. This coarser granularity may be one reason why the belt interface resulted in closer path following.

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