Tactile Compass: Enabling Visually Impaired People to Follow a Path with Continuous Directional Feedback

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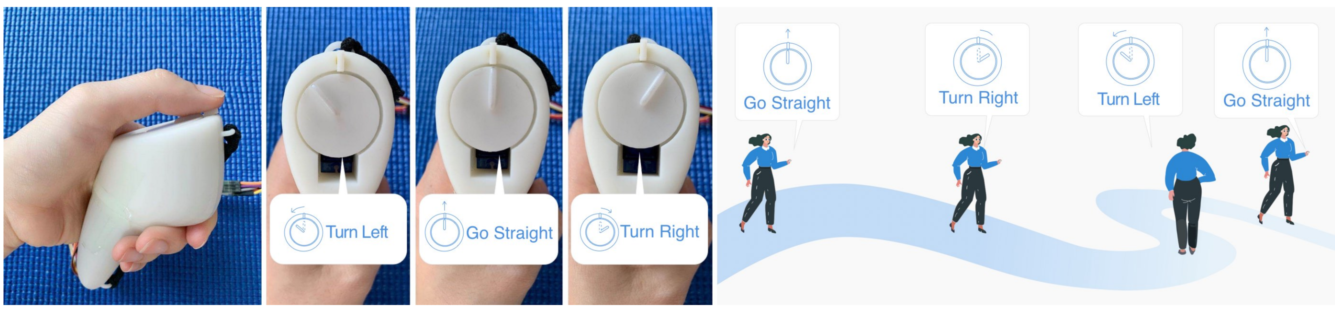

Figure 1: Under the guidance of Tactile Compass, users can follow a path smoothly and accurately by always maintaining the correct directions while walking.

ABSTRACT

Accurate and effective directional feedback is crucial for an electronic traveling aid device that guides visually impaired people in walking through paths. This paper presents Tactile Compass, a hand-held device that provides continuous directional feedback with a rotatable needle pointing toward the planned direction. We conducted two lab studies to evaluate the effectiveness of the feedback solution. Results showed that, using Tactile Compass, participants could reach the target direction in place with a mean deviation of 3.03° and could smoothly navigate along paths of 60cm width, with a mean deviation from the centerline of 12.1cm. Subjective feedback showed that Tactile Compass was easy to learn and use.

CCS CONCEPTS

• **Human-centered computing** → Accessibility technologies; *Accessibility*;

KEYWORDS

accessibility, tactile directional feedback, path-following tasks

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1 INTRODUCTION

Accurate and effective directional feedback is crucial for an electronic traveling aid device that guides visually impaired people walking along paths [41, 44]. Prior works provided many forms of directional feedback, including audio feedback [1, 13, 15, 31], vibrotactile feedback [27, 28], shape-changing feedback [30, 33, 42], and kinesthetic feedback [2–4]. In terms of direction perception in place, the most accurate feedback is Tactile Wayfinder [17], which is a belt-based vibrotactile feedback method. Users could perceive directions with a mean deviation of 15°. Regarding path-following performance, Virtual Paving [41] enabled visually impaired users to walk along a 2.1m-width path smoothly through on-shoulder vibrotactile feedback and a strategy of directional cues generation.

To explore a more accurate directional feedback method, we present Tactile Compass, a continuous directional feedback solution that includes a handle-shaped tactile device and a guidance strategy to control the device. For the tactile device, we used a tactile needle with the affordance of direction indication in shape to provide real-time directional cues for the first time. For the guidance strategy, we

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calculated the target direction according to the relative position of the user's current position and the path centerline, then generated the needle's directional cues according to the difference between the target direction and the user's current direction. As shown in Figure 1, when the needle is aligned with the home marker, it indicates that the user can go straight in the current direction. When the needle deviates from the marker, it means that the user need to adjust orientations to face the target until the needle is aligned with the home marker, then go forward.

We conducted experiments with eighteen visually impaired participants and evaluated participants' direction perception accuracy in place while using Tactile Compass. We then designed two feedback types (*Tactus-Only* vs.*Tactus+Audio*) and evaluated their path-following performance on five kinds of path types. Results showed that participants could perceive directions with a mean deviation of 3.03°, which is more accurate than all other related feedback methods. Participants successfully completed all tasks and were able to walk along a 60cm-width path smoothly and accurately. *Tactus+Audio* feedback can help participants follow a path more accurately. However, as participants suffered from confusion caused by the tactile needle and audio's inconsistent cues, they were more willing to use *Tactus-Only* feedback. Based on the results, we discussed how audio and tactile feedback could be combined to avoid confusion and how to improve path-following performance by optimizing the guidance strategy.

In summary, we contribute a new continuous directional feedback solution for accurate and smooth path-following. It includes a tactile device and a guidance strategy that allows users to maintain the correct directions while walking. Our work demonstrated the effectiveness of Tactile Compass in wayfinding tasks for visually impaired people.

2 RELATED WORK

In this section, we briefly review prior research, including path-following guidance systems for visually impaired people and non-visual feedback for navigational purposes.

2.1 Guidance Systems for Visually Impaired People to Follow a Path

When visually impaired people travel, they need to avoid obstacles and follow a given path in order to reach their destinations [45]. To support path-following tasks, a guidance system should provide path planning and navigational feedback.

The goal of path planning is to develop a safe and efficient path from place to place. Turn-by-turn guidance is a typical path planning method that plans the path as a series of turns, and, through this, users receive feedback such as audio descriptions or haptic feedback when they approach a decision point [1, 31]. Turn-by-turn guidance does not avoid local obstacles. Some studies combine path planning with obstacle avoidance to provide a collision-free path; i.e., a path is suggested by continually indicating a local safe direction [14, 25, 40]. For example, researchers examining Virtual Paving studied the design guidelines to render a walkable, safe, and smooth path for visually impaired people [41].

Navigational feedback is a bridge between path planning techniques and users. Appropriate feedback can help visually impaired users walk along a given path accurately with a positive user experience. Common non-visual feedback includes audio and haptic feedback, which will be reviewed in detail below. This paper solely focuses on feedback, presenting a continuous directional feedback solution for visually impaired people to follow a path accurately and smoothly. Tactile Compass is not restricted by path planning methods and is suitable for any given path.

2.2 Non-Visual Feedback for Path-following Tasks

2.2.1 Audio Feedback. Audio feedback includes audio descriptions and spatial audio. Audio descriptions can provide path shape descriptions and turn-by-turn action instructions [1, 13, 15, 31]. Audio descriptions has been widely used in commercial navigation applications such as Google Maps. However, audio descriptions can only provide general descriptions of path shapes and turns. Therefore, users cannot follow a path accurately and smoothly because they cannot always maintain the correct directions under these types of general descriptions. Spatial audio can map the sound source position to the target directions in order to provide non-verbal information [7, 20, 21], and it is more intuitive when indicating directions [12]. However, spatial audio is not suitable for high-frequency and continuous instructions when traveling because audio output might interfere with users' perceptions of acoustic cues from the environment [41].

Below, we review three types of haptic feedback: vibrotactile, shape-changing, and kinesthetic feedback.

2.2.2 Vibrotactile Feedback. Vibrotactile feedback, which can be used on many parts of the body such as heads [10], shoulders [41], waists [17, 19, 39], wrists [11, 26], feet [18], hands [30, 33, 37, 42] etc., is the most common form of haptic feedback. In the relationship between vibration and direction, there are indirect mappings and direct mappings. For indirect mappings, researchers used vibration patterns to indicate directions [6, 24]. For example, PocketNavigator used two short pulses to indicate moving ahead [27, 28]. Direct mappings indicate that there is a direct spatial mapping relationship between vibration locations and target directions [43]. For example, there are eight vibration motors evenly distributed on ActiveBelt, which can indicate directions in units of 45° [39]. In direct mappings, the resolution will affect the expression of direction information. Some researchers associated the approximate orientation with the body part to provide low-resolution direct vibrotactile feedback. For example, VirtualPaving [41] provides on-shoulder vibration feedback. Vibration on the left shoulder means adjusting orientation to the left, and vibration on the right shoulder means adjusting orientation to the right.

High-resolution vibration feedback will provide richer and more direct directional information. For example, Tactile Wayfinder [17] is a belt evenly equipped with six vibration motors. It could present directions between two adjacent motors by interpolating the intensities of the two adjacent motors. Thus, Tactile Wayfinder allows a smooth, continuous direction presentation with a high-resolution. Using Tactile Wayfinder, participants' mean deviation of direction perception was 15°. NaviRadar [29] is an interaction technique for mobile phones that uses a radar metaphor to communicate the user’s correct direction in a full range of 360°. A radar sweep rotates clockwise, and tactile feedback is provided where each sweep conveys the user’s current direction and the target direction. Participants’ mean deviation of direction perception was 36.7°.

2.2.3 Shape-Changing Feedback. Researchers developed shape-changing feedback to indicate directions. For example, the Tactile Handle is a barbell-shaped device consisting of vibrotactile actuators, proximity sensors, and an embedded micro-controller to match the finger phalanxes. The device indirectly indicates the directions to the user through vibration and torsion [8]. Animotus is a cube-shaped device containing an upper segment that can be rotated or extended relative to the lower part [32–37]. The device rotates and extends in the users’ hands, stimulating the inner side of multiple fingers to provide directional cues. However, researchers did not study users’ abilities of direction perception and did not provide guidance strategy for path-following.

2.2.4 Kinesthetic Feedback. Some devices use kinesthetic traction to provide directional cues. For example, Amemiya et al. presented a new haptic direction indicator. The haptic direction indicator used a kinesthetic perception method referred to as the "pseudo-attraction force" technique, which exploits the nonlinear relationship between perceived and physical acceleration to generate a force sensation [2, 3]. Antolini et al. presented a haptic device that provided kinesthetic stimuli in order to navigate the user to a target location. The haptic sensation was created by tilting one or more rotating flywheels along an axis, controlling the direction and amount of tilt, the velocity of the tilt, and the frequency of pulses [5]. However, this kinesthetic feedback method could only provide low-resolution and non-continuous direction information.

In addition, some researchers studied navigational robots [22]. For example, CaBot [16] is a suitcase-shaped autonomous navigation robot. It can avoid obstacles in its path and provides vibrotactile directional feedback through its handle. Tobita et al. [38] developed a robot to guide visually impaired people in large hospitals. The robot navigates to the destination through steering, based on the force with which the user pushes on the robot.

3 DESIGN AND IMPLEMENTATION

Tactile Compass consists of two parts, which will be described in detail below, including 1) a handle-shaped tactile device with a rotatable needle pointing toward the target direction , and 2) a guidance strategy to control the device.

3.1 Tactile Device

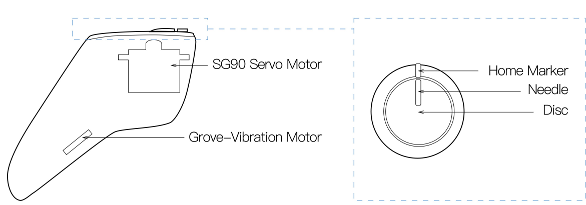

Figure 2: Design and implementation of the Tactile Device

As shown in Figure 2, the tactile device includes the following three parts: 1) a rotatable disc with a tactile needle to indicate the target direction, 2) a home marker to indicate a user’s current direction, and 3) a handle with a similar shape of Virtual Reality handles. To prevent the handle from falling due to grip fatigue, we also provided rubber band straps. We 3D printed the disc and the handle, used SG90 Servo Motor to drive the rotation of the disc, and used a Grove-Vibration Motor to support vibration feedback.

3.2 Guidance Strategy

The guidance strategy includes direction indicating strategy and path-following strategy, which will be introduced below.

3.2.1 Direction Indicating Strategy. We designed direction indicating strategy to control the disc’s rotation, aiming to indicate the target directions for the users. We defined *target direction* θ_t as the guiding direction towards a navigation target, *current direction* θ_c as the user’s current orientation which is also presented by the home marker, and *guide angle* θ_g as the rotation angle of the disc. As shown in Equation 1, θ_g is the difference between θ_t and θ_c. When $\theta_g = 0$, the tactile needle on the disc is aligned with the home marker. When $\theta_g > 0$, the needle rotates clockwise. When $\theta_g < 0$, the needle rotates counterclockwise.

$$\theta_g = \theta_t - \theta_c \quad (1)$$

Under the aforementioned direction indicating strategy, as shown in Figure 1, by feeling *guide angle* θ_g between the home marker and the tactile needle with their fingers, users could intuitively adjust their orientations to align the marker and the needle in order to face the target direction.

Due to the mechanical bounds of SG90 Servo Motor, the disc can only rotate inside the range of ±90°. If the *guide angle* θ_g is outside of ±90° (e.g., the user needs to turn ±120° to face the target), then the needle will remain at either +90° or −90°, and the handle will provide vibration feedback with a pattern of double vibrations. Users need to continuously turn clockwise or counterclockwise until they are in the range of ±90°. Then, the vibration stops, and users must continue turning until the needle is aligned with the marker.

3.2.2 Path-following Strategy. We designed path-following strategy to determine the *target direction* in real-time, aiming to guide the user to follow a path smoothly and accurately with a non-intrusive and intuitive experience. At an arbitrary moment, the *target direction* is determined as follows:

As shown in Figure 3a, point C is the user’s current position, and point N is the nearest point on the centerline to the user. Point M locates ahead of point N along the centerline by a constant *guide length* l_{guide}, which is 40cm. Then, *target direction* θ_t is determined as the direction of the plane vector $\overrightarrow{CM}$. By moving towards θ_t, users could gather towards the centerline.

The above strategy can guide users to follow a path centerline successfully. However, to accurately walk along the centerline, users have to receive high-intensity direction indication, which is an intrusive experience. As people typically walk along a path with a certain width in daily life, rather than following a centerline, we optimize the strategy by weakening the direction indication when

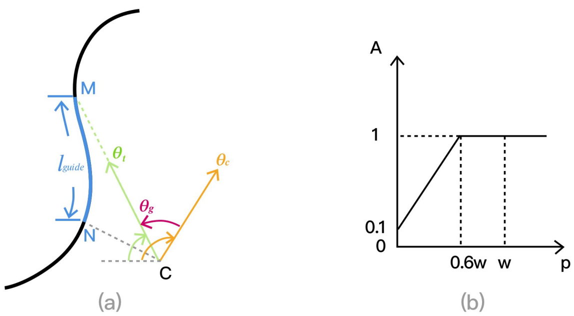

Figure 3: (a)Visualization of the Path-Following Strategy. (b)The relation of gain A and *proximity* p.

the user is close to the centerline, considering that this situation is relatively safe. The optimizing method is introduced as follows:

We set a road width w for the path according to the local construction specifications of tactile paving, which is 60cm. We defined *proximity* p as the distance between the user's position and the path centerline ($|CN|$ in Figure 3a). We then set a gain A for the *guide angle* θ_g of the disc according to the proportion of p to w. In general, the gain turned lower when the users were close to the centerline, thus making θ_g smaller than the actual guide angle. The relation of the A and p was shown in Figure 3b. The final θ_g could be expressed as Equation 2.

$$\theta_g = A\left(p\right)\left(\theta_t - \theta_c\right) \tag{2}$$

4 DIRECTION PERCEPTION STUDY

The goal of the study was to evaluate participants' direction perception in place while using Tactile Compass.

4.1 Participants and Apparatus

We conducted the study with eighteen participants (12 males, 6 females), with their ages ranging from 23 to 31. Regarding mobility aids, nine participants used canes daily, eight seldom used canes, and one used guide dogs on a daily basis. Concerning visual conditions, seven participants were blind, ten could only sense light, and the remaining participant had low vision. Only one participant had previous experience using electronic canes. Table 1 shows the details of participants' demographic information. We recruited the participants from a local supporting community for visually impaired people based on two criteria: being visually impaired and having independent travel experience.

As shown in Figure 4 We conducted our study in a 7 × 13m indoor environment. Our experiment system included an OptiTrack localization system, a guidance strategy server running on PC, a remote control application on an Android smartphone, and the tactile device. The experiment system's update frequency was 50Hz.

The OptiTrack localization system in our study consisted of 10 cameras and a marker. OptiTrack calculated the marker's 2D position and orientation according to the marker's images captured by the cameras in real-time. The measurement error of 2D position is less than 1mm, and the measurement error of orientation is less then 1° (https://www.optitrack.com/cameras/primex-41/). To prevent the body from blocking the marker, we fixed the marker to a cap worn on users' heads during the experiment. OptiTrack reported the marker's 2D position and orientation to the PC server via a network cable.

We used the PC server to implement the guidance strategy. The server worked on python programs. After receiving the data from OptiTrack, the server then determined the guidance information according to the guidance strategy in the task, including the rotation angle of the disc, the vibration signal, and the verbal audio. The server played the verbal audio via a speaker and transmitted the rotation angle of the disc and the vibration signal to the application on the Android smartphone via Transmission Control Protocol (TCP).

We used an application on the Android smartphone as a transfer station between the PC server and the tactile device. The experimenter could use the application to set an offset to the rotation angle in order to zero the disc. The smartphone communicated with the tactile device via Bluetooth.

The tactile device used Arduino to receive data from the smartphone and to control the servo motor and the vibration. The tactile device was powered by a portable battery. In the experiment, users carried the Arduino and the battery in a small bag.

4.2 Procedure

First, we spent ten minutes to explain the experiment procedure and the approach to using Tactile Compass. We guided participants to hold the tactile device in a comfortable posture, touching the needle and the home marker with the thumb. We also taught participants to align their head and body orientations to mitigate the effect of different head and body orientations. We then explained how to recognize directions through the deviation between the needle and the marker. Next, we asked participants to turn their bodies in place and feel the process of adjusting orientations in order to make the needle align with the marker. After that, we took participants to the center of the experiment site, asked them to put on the hat with a location marker of the OptiTrack, and taught them how to use the experimental system.

Prior to the study, participants were required to stand still and wait for the calibration from OptiTrack for five seconds. In each task of the study, the needle first rotated to a target direction to provide a direction cue, then participants needed to turn their bodies in place according to the cues provided by the needle. When they aligned the needle with the home marker, they would report to the experimenter that the task was completed. The needle automatically returned to the home position after each task. The next task began after three seconds.

In the learning phase, participants completed six tasks with random directions to adapt to the experimental system. In the test phase, participants needed to distinguish 23 directions with randomized presentation order, including the following angles: 180°, ±165°, ±150°, ±135°, ±120°, ±105°, ±90°, ±75°, ±60°, ±45°, ±30°, and ±15°. Negative angles denoted turning left, and positive angles

Table 1: Demographic information of 18 participants. All information was self-reported, exp with ETA = experience of electronic travelling aids

No.	Age	Gender	Visual Condition	Canes or Dogs	exp with ETA
1	25	F	blind	daily cane user	no
2	24	F	blind with light perception	daily cane user	no
3	29	M	blind	guide dog	only tested a electronic cane
4	31	M	blind with light perception	daily cane user	no
5	29	M	blind	seldom cane user	no
6	28	F	blind with light perception	seldom cane user	no
7	26	F	blind	daily cane user	no
8	23	M	blind	daily cane user	no
9	25	M	blind with light perception	seldom cane user	no
10	25	M	blind	seldom cane user	no
11	28	M	blind with light perception	seldom cane user	no
12	27	F	blind	daily cane user	no
13	26	M	blind with light perception	daily cane user	no
14	24	F	blind with light perception	seldom cane user	no
15	23	M	blind with light perception	daily cane user	no
16	25	M	low vision	seldom cane user	no
17	27	M	blind with light perception	daily cane user	no
18	25	F	blind with light perception	seldom cane user	no

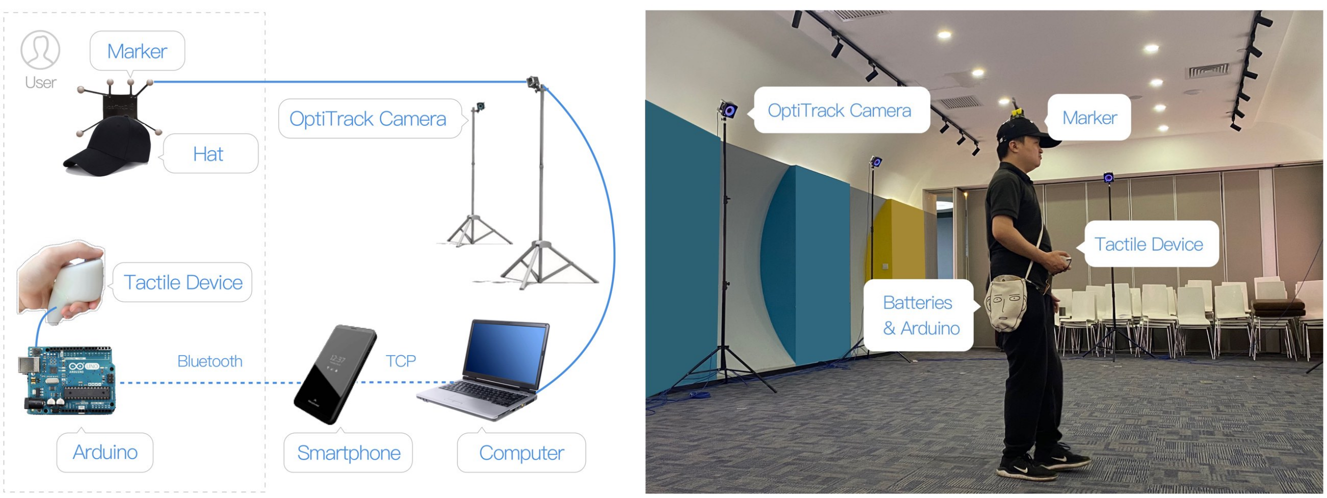

Figure 4: Apparatus and experimental setup

denoted turning right. The system recorded each task completion time and the the reported angles.

4.3 Results

We used deviation and task completion time to evaluate direction recognition performance. Deviation denotes the absolute value of the difference between the reported angle and the target angle.

We used non-parametric tests to analyze non-normally distributed measures. We used the Wilcoxon signed-rank test to analyze two paired samples, using the Friedman test to analyze three or more paired samples. For normally distributed measures, we used RM-ANOVA for significance analysis. We used Mauchly's test to assess sphericity. If Mauchly's Test of Sphericity was violated, Greenhouse-Geisser was employed to correct the degrees of freedom. The mean deviation was 3.03°(SD=1.02), and the median of deviation was 2°. A Friedman test showed that there was no significant effect of directions on deviation. When the target angle was in the range of ±90°, the deviation was significantly smaller than when the target angle was outside the range of ±90°, with $z = -2.199, p = 0.028$, at 2.78° and 3.30°, respectively. To the best of our knowledge, 3.03° is the lowest deviation of direction recognition in related researches.

Figure 5 showed the location of reported angles under different directions. The mean task completion time was 6.71s(SD=2.56).

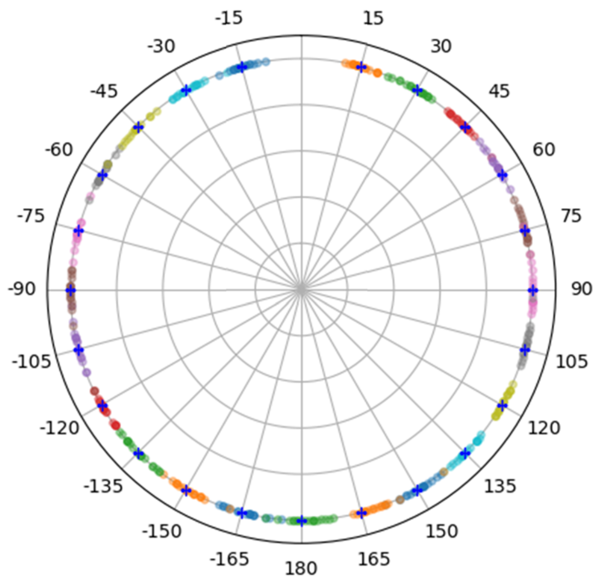

Figure 5: Results of direction perception study. The scatters in different colors denote participants' reported angles under different directions.

5 EVALUATION OF PATH-FOLLOWING PERFORMANCE

The goal of this study is to evaluate path-following performance under the guidance of Tactile Compass. As shown in prior studies, verbal audio feedback can be additionally employed to describe the road conditions ahead of the users to better prepare them for upcoming situations [41]. Therefore, in addition to *Tactus-Only* feedback, we also designed *Tactus+Audio* feedback and compared the performance of these two types of feedback designs.

5.1 Participants and Apparatus

We used the same apparatus as direction perception study and conducted the experiment with eighteen participants. For *Tactus+Audio* feedback, we used a Bluetooth earphone to play pre-recorded audio cues. In order to reduce the negative influence of a user's body shaking on spatial localization, the user's 2D position data was filtered by a first order low-pass filter (f_c=0.2Hz) on the PC server in real-time.

5.2 Experimental Paths

Based on daily navigational scenarios and prior studies [41], we adopted the following five types of basic paths shown in Figure 6: straight path (SP), winding path (WP), right-angle turn (RT), acute-angle turn (AT), and obtuse-angle turn (OT). These five types of paths may not cover all scenarios, but they are mostly representative of the daily paths.

Each turning path included a left turn or a right turn (e.g., acute-angle turn included an acute left turn or an acute right turn). Therefore, there were eight experimental paths: SP, WP, RT-left, RT-right, AT-left, AT-right, OT-left, and OT-right.

The specifications of the paths were as follows: The length of the straight path was 9m. The degree of RT was 90°; the degree of AT was 45°, and the degree of OT was 135°. The centerline's radius for three turn paths were all 1m. The winding path was an S-shaped path consisting of two turns with a radius of 3.2m. According to the path-following strategy in 3.2.2, the width of each path was 60cm.

5.3 Feedback Specifications

The specification of *Tactus-Only* feedback was described in 3. For *Tactus+Audio* feedback, we designed the verbal audio based on the industry standards of navigational applications, including the following types of information: distance to turn, turn action, and destination descriptions [44]. We also added descriptions of the path shape.

- Straight path: "Go straight ahead 9 meters."
- Turning path (RT, AT, and OT): Before arriving at the decision point, the system verbally announced the direction and approximate angle of the turn, e.g., "Turn left forward after 5 meters." When users arrived at a decision point, the system verbally announced the turning instruction, e.g., "Start turning, please pay attention to the handle instructions." After finishing a turn, the system reminded users by announcing, "Turn completed. Please go straight ahead."
- Winding path: Winding path consists of two winding paths with alternative directions. When arriving at the starting point of each path, the system indicated the directions by announcing, "Left/right winding path ahead."
- When users reached the destination, the system notified them by announcing, "Arrived at the destination."

Table 2 shows the correspondence between the paths and verbal audio in detail.

5.4 Procedure

A learning session was conducted prior to the test phase. We asked participants to walk along the learning path shown in Figure 7 under the *Tactus+Audio* and *Tactus-Only* guidance, respectively. After that, participants decided whether or not to continue learning. If they chose to continue, they could decide under which type of feedback to learn. We emphasized the directional cues provided by the needle. When the needle deviated from the home marker, participants could either adjust orientations while walking or stop to adjust orientations and then move forward. The handle vibrated when participants walked out of the 60cm path area. At this time, participants followed the directions indicated by the needle and returned to the path area. The experimenter also corrected participants' incorrect behavior while walking, if any.

In the test phase, participants were instructed to walk along the eight experimental paths under the guidance of *Tactus-Only* feedback and *Tactus+Audio* feedback, respectively (8 paths × 2 feedback types = 16 tasks). The feedback order was counterbalanced among eighteen participants in the following manner: Half of the participants finished tasks with the *Tactus+Audio* feedback first,

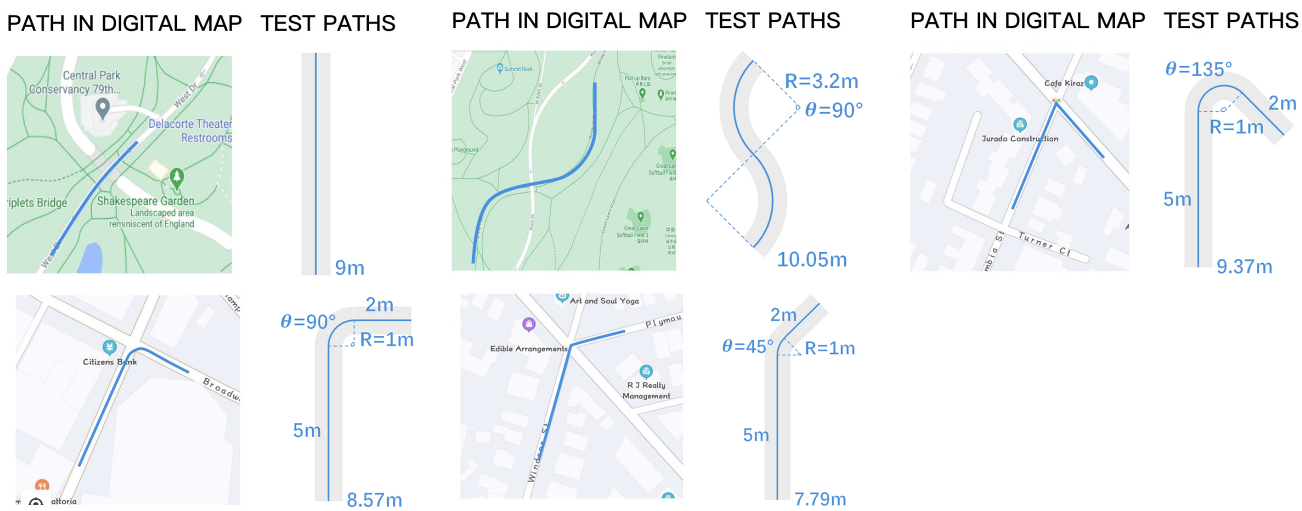

Figure 6: Five types of paths used for experimental tasks. These paths are extracted from daily navigational scenarios.

Table 2: Mappings between paths and verbal audio. RT, AT, and OT denote right-angle turn, acute-angle turn, and obtuse-angle turn, respectively. L denotes left, and R denotes right.

<table>
<tr><th colspan="5">Verbal audio for straight path</th></tr>
<tr><td>SP</td><td colspan="4">Go straight ahead 9 meters.</td></tr>
<tr><th colspan="5">Verbal audio for winding path</th></tr>
<tr><td></td><td colspan="2">Before the first winding path</td><td colspan="2">Before the second winding path</td></tr>
<tr><td>WP</td><td colspan="2">Right winding path ahead</td><td colspan="2">Left winding path ahead</td></tr>
<tr><th colspan="5">Verbal audio for turning path</th></tr>
<tr><td colspan="2"></td><td>Before a decision point</td><td>arrive at a decision point</td><td>Finish a turn</td></tr>
<tr><td rowspan="2">RT</td><td>L</td><td>Go ahead and turn left after 5 meters.</td><td rowspan="6">Start turning. Please pay attention to the handle instructions.</td><td rowspan="6">Turn completed. Please go ahead</td></tr>
<tr><td>R</td><td>Go ahead and turn right after 5 meters.</td></tr>
<tr><td rowspan="2">AT</td><td>L</td><td>Go ahead and turn left backward after 5 meters.</td></tr>
<tr><td>R</td><td>Go ahead and turn right backward after 5 meters.</td></tr>
<tr><td rowspan="2">OT</td><td>L</td><td>Go ahead and turn left forward after 5 meters.</td></tr>
<tr><td>R</td><td>Go ahead and turn right forward after 5 meters.</td></tr>
</table>

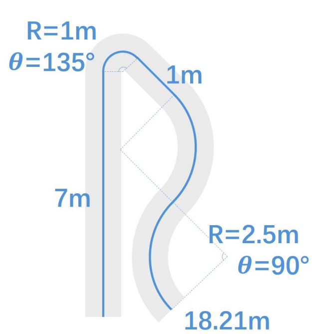

Figure 7: Specification of the learning path

while the other half finished tasks with the *Tactus-Only* feedback first. The path order for each feedback type was randomized.

After completing the tasks of each feedback type, we conducted semi-structured interviews with the participants. First, we asked about the walking experience of the tasks they previously completed. When interesting points emerged, we followed up with questions to obtain more details and concrete examples. When participants finished all of the tasks with two feedback types, we asked them which feedback type they preferred and the reason behind it. The interviews were audio-recorded and transcribed into text. After the interview, we asked participants to give their ratings on the six statements in Table 3.

5.5 Performance Metrics

We used the following metrics to evaluate the path-following performance: *deviation*, *out-of-area proportion* (OAP), *velocity*, and *user's trajectory*. The *deviation* was defined as the mean of *proximity* over time in one task (*proximity* is the instantaneous distance between a user's position and path centerline, shown as |CN| in Figure 3). The *out-of-area proportion* was defined as $OAP = \frac{T_{out}}{T_{total}}$, where T_{out} is the time when the users walked out of the path area of one task, and T_{total} is the task completion time of that task. As the length of each path is different, we used *velocity* instead of task completion time to measure efficiency. We defined *velocity* as $velocity = \frac{L_{Trajectory}}{T_{total}}$, where $L_{Trajectory}$ is the length of a user's trajectory of one task, and T_{total} is the task completion time of that task.

5.6 Results

5.6.1 Task Performance. Participants learned our prototype in less than 7 minutes (M=239.37s, SD=55.48), ranging from the shortest 140.72s to the longest 369.26s. All the participants completed all tasks.

Figure 8 showed the *proximity* distribution of all tasks completed by all participants under two feedback types.

For *Tactus-Only* feedback, the mean of *proximity* was 12.2cm (SD=10.5). Participants' *proximity* was less than 45.5cm within 99.0% of the time, less than 30.0cm (the halfway width of paths) within 92.6% of the time, and less than 27.0cm within 90.0% of the time.

For *Tactus-Audio* feedback, the mean of *proximity* was 10.7cm (SD=10.1). Participants' *proximity* was less than 47.5cm within 99.0% of the time, less than 30.0cm (the halfway width of paths) within 94.8% of the time, and less than 23.5cm within 90.0% of the time.

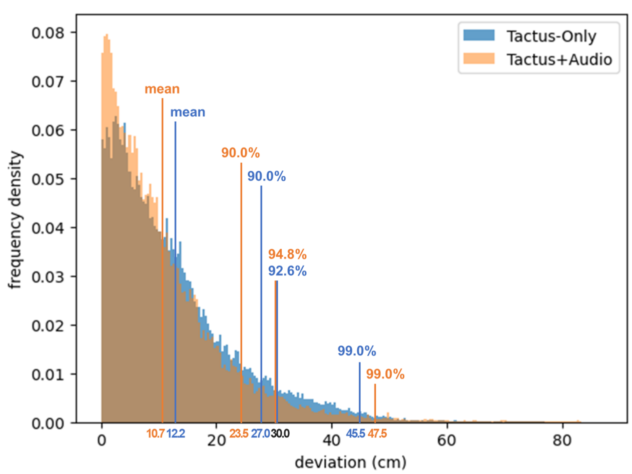

Figure 8: *Proximity* distribution of all tasks under two feedback types

To explore the effect of feedback type on user's path-following performance, we evaluated *deviation*, *velocity*, and *out-of-area proportion* under *Tactus-Only* and *Tactus+Audio* feedback, respectively. Figure 9 shows the results; the metrics for two feedback types were also calculated for each path type.

In terms of *deviation*, RM-ANOVA showed the *deviation* of *Tactus+Audio* (M=10.9cm, SD=3.3) was significantly less than that of *Tactus-Only* (M=12.1cm, SD=2.5) with $F_{1,17} = 7.48, p = 0.014$. This indicated that the *Tactus+Audio* feedback could help users follow a path more accurately. With a Wilcoxon signed-rank test, we also found a trend towards significance for the effect of feedback type on *out-of-area proportion* (z=-1.917 , p=0.055).

Tactus+Audio significantly outperformed *Tactus-Only* in *velocity* for straight path with $F_{1,17} = 6.62, p = 0.020$. These results could be explained by the following rationale: The audio description, "Go straight ahead 9 meters," could cause users to think that the road conditions ahead are straightforward, prompting them to become less cautious and walk fast.

Besides, We also tested the correlation between *velocity* and *deviation* in order to explore the effect of walking speed on path-following accuracy. There was a positive linear correlation between *velocity* and *deviation* with $F = 9.41, p = 0.007$, adjust $R^2 = 0.331$. The results are shown in Figure 10, indicating that a faster walking pace would likely result in a greater deviation.

5.6.2 Trajectory Observation. Figure 11 shows the trajectory of all participants on all paths. We found that the trajectory at a turn tended to deviate from the centerline, which could easily cause a user to walk out of the path area. This indicates that users often turned later than the decision point.

Besides, we found that both the winding path and the straight path after a turn tended to contain zigzag patterns. Compared to the trajectories of P5, who completed all tasks with the smallest deviation of 6.8cm, some participants (e.g., P7, P14, P16) tended to adjust orientations with a large turning angle and a fast pace. When these participants walked out of the 60cm-width path area, they slowed down or stopped to adjust orientations and, as a result, moved forward in a stop-and-go manner. Such deviation and zigzag still has room to optimize, which will be addressed in the discussion section.

5.6.3 Subjective Feedback. Table 3 shows the subjective score of the experience of the two feedback types. For *Tactus-Only*, subjective ratings of smoothness, learnability, ease-of-use, willingness, and convenience were all high (≥ 6). Learnability was the highest score (M=6.67, SD=0.58). A Wilcoxon signed-rank test showed that *Tactus-Only* significantly outperforms *Tactus+Audio* on willingness ($z = -2.401, p = .016$) and convenience ($z = -2.401, p = .041$).

The overall qualitative feedback regarding the use of the Tactile Compass was very positive. All participants agreed that the needle could indicate directions accurately and intuitively. While walking, the needle could correct users' directions in real-time according to the deviation of users' positions and paths' centerlines, making users feel that the feedback is timely and sensitive with a non-intrusive experience. This kind of real-time direction correction provides participants with a sense of security and trust, giving them the confidence that they can arrive at the destination by following the needle's guidance.

Five participants participated in other studies about vibrotactile feedback on shoulders for path-following [41]. Compared with vibrotactile feedback–which vibrates when users deviate from the target direction and stops vibrating when users face the right direction—Tactile Compass is always tactile, which provides users a

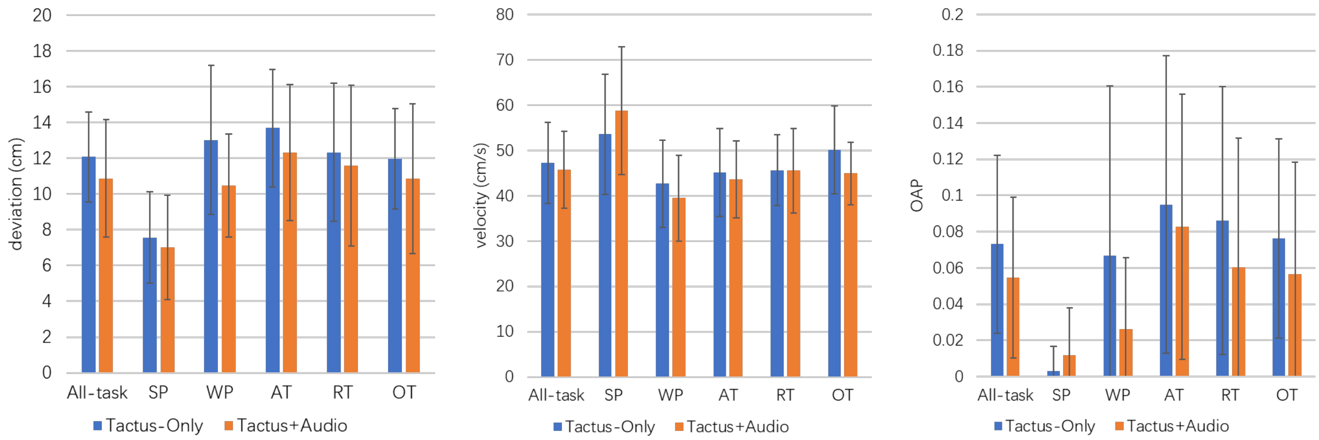

Figure 9: Path-following performance. "All-task" denotes the task-averaged performance under a certain feedback type. SP denotes Straight Path, WP denotes Winding Path, RT denotes Right-angle Turn, AT denotes Acute-angle Turn, OT denotes Obtuse-angle Turn. Error bars indicate standard deviation.

Table 3: Subjective ratings. 1=strongly disagree, 7=strongly agree. * denotes significant effect

Metrics	Statements	Tactus+Audio	Tactus Only
Smoothness	Technique helped me walk smoothly.	5.94 (SD=1.22)	6.06 (SD=0.78)
Learnability	Technique was easy to learn.	6.50 (SD=0.83)	6.67 (SD=0.58)
Ease-of-use	Technique was easy to use.	5.94 (SD=0.97)	6.17 (SD=0.76)
Low Cognitive Load	Technique required low concentration.	5.06 (SD=1.08)	5.22 (SD=1.47)
Convenience in daily use*	Technique would be convenient for daily life.	5.67 (SD=1.15)	6.00 (SD=0.88)
Willingness to use*	I am willing to use this technique.	5.89 (SD=1.29)	6.39 (SD=0.89)

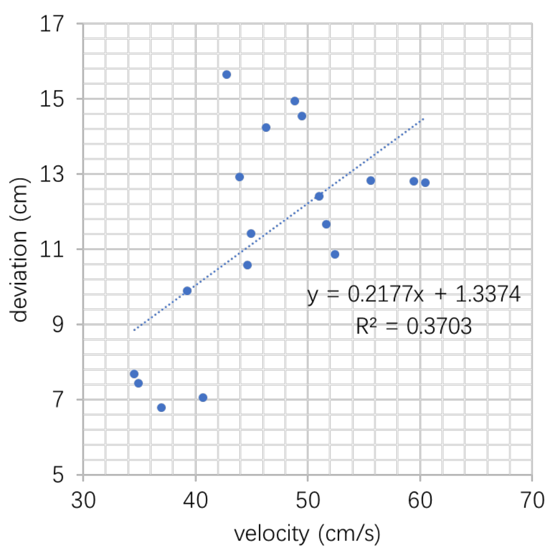

Figure 10: Linear regression result of *deviation* and *velocity*. Each scatter denotes the mean *deviation* and mean *velocity* of each participant under all tasks.

sense of control. As stated by P18, *"For Tactile Compass, the degree of the orientation adjustment can be always touched. I feel everything is in my control. Our sense of touch is equivalent to your vision. However, for the vibrotactile feedback, I have to adjust orientations repeatedly until the vibration stops, which is a passive process."*

Regarding the two feedback types' user experience, participants agreed that the audio descriptions were useful to some extent. Audio descriptions can help users build mental maps of the path and prepare for upcoming situations, which is useful in the real environment. However, in this study, participants suffered from confusion, mainly because the directional cues provided by audio and needle were not consistent. For example, after completing a turn, a user heard "Go straight ahead," while the needle's cues at that moment indicated that the direction needed to be adjusted to the right. At this time, the user became confused. When similar situations occurred, participants' response strategies were to ignore the audio description and follow the needle's guidance.

Participants also developed coping strategies to improve comfortability. Although we recommended participants use the thumb to touch the needle, three participants insisted on using the index finger because they felt that the finger pulp of the index finger was more sensitive to the thumb. While walking, all participants ignored the needles' slight rotation. Instead, they focused on the large rotation for the following reason: The slight rotation indicated that they were not far away from the centerline of the path,

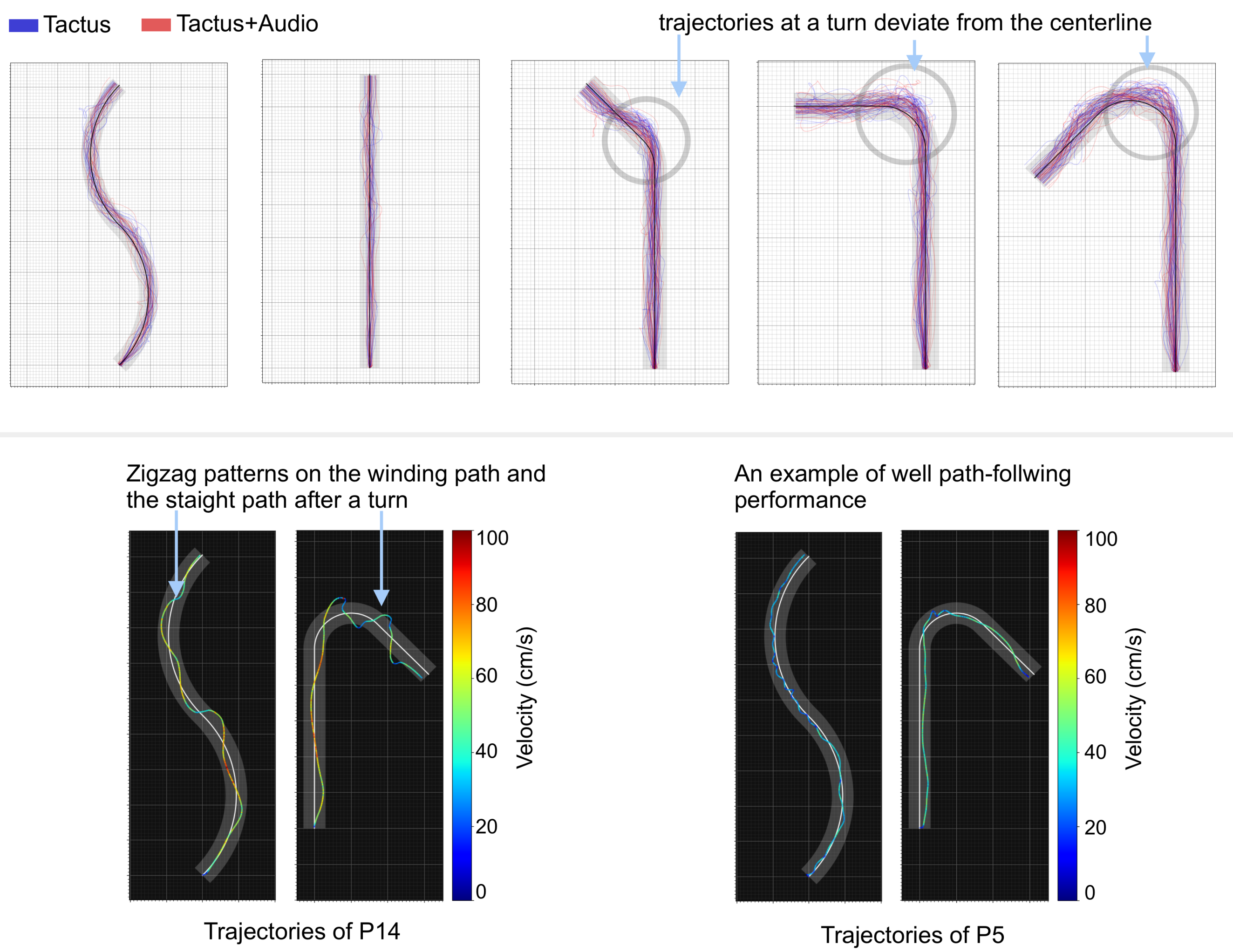

Figure 11: Trajectories in the path-following performance evaluation study. Upper part: the trajectories of all participants under two feedback types. The trajectory at a turn tended to deviate from the centerline. Lower part: the zigzag patterns after a turn and on the winding path.

while the large rotation indicated a turn ahead or deviation too far from the path. These results suggest that the design of gain in our path-following strategy corresponded with the user's natural habit. When participants were not familiar with Tactile Compass, they tended to hold the handle in front of the body to form a direct mapping relationship between the needle and spatial directions. However, as they familiarized themselves with the device, they held it with the hand drooping naturally, causing them to feel relaxed, which showed the flexibility of a user's posture in using Tactile Compass.

6 DISCUSSION

Our work provided a basic feedback design and demonstrated the effectiveness of Tactile Compass in path-following tasks for visually impaired people. In this section, we will primarily discuss ways to further optimize the path-following performance, based on our results, which is a direction for future work.

6.1 Integrate into Navigational System for Practical Use

We chose Optitrack (at millimeter level) as our positioning module in the lab to explore feedback performance while avoiding errors related to positioning and path planning, such as wrong directional feedback caused by an unstable positioning system. Currently, the accuracy of positioning tools used in prior work focusing on feedback is varied. We hope to inspire researchers to unify the accuracy of positioning tools when studying feedback itself for better comparisons across feedback results.

A navigation system for the visually impaired includes positioning, path planning, and a feedback module. This paper focused on the feedback module, which is most closely connected with users. For practical use, given current technology conditions, SLAM is considered to be the most feasible positioning and path planning solution to integrate with our feedback. SLAM can plan a local, walkable path dynamically and also obtain a user's high-precision position and orientation relative to the local path (at centimeter-level) [9, 23]. This information will map to the tactile needle based on guidance strategy. We estimate a navigation system with such precise positioning technology and our feedback will reach a deviation at a decimeter level. We leave the test of the actual performance to future work.

6.2 Avoid Confusion Caused by the Inconsistent Cues Provided by Tactile and Audio Feedback

As shown in 5.6.1, audio descriptions can reduce the deviation while following a path. However, subjective feedback revealed that participants' willingness to use *Tactus+Audio* was significantly lower than *Tactus-Only*. Participants were also confused by the inconsistent directional cues provided by audio and the needle. This occurred because the needle provides a real-time orientation correction based on users' position relative to the path centerline, which may be inconsistent with the audio descriptions based on road conditions. For example, when users heard, "right winding path ahead," they veered to the right off of the road centerline and, thus, received the opposite directional cues from the needle.

We used a simple and fixed voice description as a probe to explore the path following performance of *Tactus+Audio* feedback. There is still much room for improvement in the coordination of audio and tactile feedback. To address the aforementioned issues, one possible solution is to develop cues provided by the needle and audio in a way that is complementary. The needle should provide accurate, real-time directional feedback. The audio description should focus on providing users with road conditions ahead of a certain distance to help them prepare for the upcoming situations (e.g., verbally announcing, "Turn left 5 meters ahead."). Designers should avoid incorporating words such as 'left' or 'right' when describing the immediate road conditions (i.e., using "start turning" instead of "start to turn left.") Without these parameters, users may suffer from confusion caused by inconsistency.

Another solution is to make the audio descriptions dynamically consistent with tactile cues so they can provide the same information. But designers should avoid raising new issues such as information redundancy and disturbance.

6.3 Reduce Deviation and Zigzag

As shown in Figure 11, through trajectory observation, we found that some of the users' trajectories at a turn deviated from the centerline, meaning that users often turned later than the decision point. There are also zigzag patterns on the winding path and the straight path after a turn. This issue can be alleviated as follows:

First, audio feedback could be used to remind users to slow down at a certain distance before a turn. The distance should be dynamically determined based on users' walking speed and response time. Second, the gain parameter (mentioned in 3.2.2) could be adjusted dynamically according to road conditions. As shown in Figure 3b, the gain turns lower and makes the needle's *guide angle* smaller than the actual guide angle when the users are close to the centerline. As users tend to ignore the needle's slight rotation, users who walk near the centerline may unconsciously miss the decision point. Therefore, in complex or dangerous road conditions, the gain should be dynamically increased to magnify the needle's *guide angle* so that users can follow the path safely and accurately.

Also, *guide length* l_{guide} is an important parameter for guidance strategy, which may affect the walking deviation and smoothness. Assuming that l_{guide} is infinite, the target direction will tend to point to the end of the path, and the user's trajectory will tend to be a straight line directly leading to the end of the path. As a result, increasing l_{guide} may improve the smoothness, but it may also increase the deviation to the centerline; therefore, the trade-off between deviation and smoothness should be considered. Future research should investigate the quantitative relationship between l_{guide} and deviation.

6.4 Determine the Optimal Path Width

In this study, we set the path width as 60cm, which is the standard width of tactile paving under local standards. In the real environment, the path width w should be determined according to actual road conditions. For example, the guidance strategy should increase the path width on a wide, obstacle-free road.

To determine a path width w that is appropriate for real-world road conditions, the following factors need to be considered: 1) Safety: The maximum walking *proximity* (which is defined in 3.2.2 as the distance between the user's position and the path centerline) needs to be within the width of road's safe walking zone. Therefore, the *deviation* d (which is defined in 5.5 as the mean of *proximity* over time in one task) should also be within an upper limit, which may have a positive correlation with the width of the road's safe walking zone; 2) User experience: Users' *velocity* v should be similar to their natural and comfortable walking speed. We regard the above considerations as two requirements for d and v when determining w. Moreover, based on the potential relationship between w, d, and v found in our study (explained later), we propose that designers in the future determine the optimal w regarding the requirements of d and v with a mathematical optimization model.

We infer the relationship of path width w, *deviation* d, and *velocity* v as follows: 1) As shown in the path-following study, at a certain w, v and d have a positive linear correlation (Figure 10). 2) At a certain v, d and w are probable to have a positive correlation. This occurs because when w increases, the path area with lower gain A will be enlarged proportionally. In that area, the needle's *guide angle* is smaller than the actual guide angle (mentioned in 3.2.2), and users tend to ignore the needle's slight rotation, thus, users are more likely to deviate further from the centerline. However, the quantitative relationship of w, d, and v has not yet been researched, so we propose it as a future research question.

7 LIMITATIONS

We now summarize the limitations of this work, which we also see as opportunities for future work.

Due to the mechanical bounds, the disc can only rotate in the range of ±90°. Although this did not negatively affect the path-following performance, we still regard it as a problem worth improving.

We conducted experiments in a quiet indoor environment. Limited by the area, the length of the experimental paths was short. In the future, feedback could be integrated into the navigational system and evaluated in real-world environments.

We didn't set a baseline for the experiments. On the one hand, there is no general standard for the feedback solution that supports path-following tasks. One the other hand, it is difficult for us to obtain the equipment of other studies. Therefore, we compared the experimental results with other related works to highlight the accuracy of Tactile Compass.

We assigned empirical values to the guidance strategy (e.g., *guide length* = 40cm, etc.) and demonstrated the effectiveness. Future research should evaluate the effect of different parameters on users' walking experience to find the optimal framework.

We used OptiTrack to localize participants' positions. As the location marker was worn on the head, we required participants to keep the head still during walking, which may have affected the naturalness of the walking behavior.

We designed the tactile needle to be flexible to integrate with other carriers. In this work, we used a handle as the carrier of the tactile needle and occupied one of the users' hand. In the future, we will explore form factors that free users' hands as an alternative to carrying the needle to facilitate daily use for people who walk with a white cane or a guide dog.

In addition to the path-following performance, other human factors under the guidance of Tactile Compass are worth studying, such as the mental map of the paths or the subjective cognitive load using the NASA-TLX scale or secondary task.

8 CONCLUSION

This paper presents Tactile Compass, a continuous and intuitive tactile feedback solution for visually impaired people to better follow paths through invariable maintenance of the correct direction. Through user studies with eighteen participants, we demonstrated that, using Tactile Compass, users could perceive directions precisely and navigate along a 60cm-width path smoothly and accurately. We also evaluated the effect of feedback type (*Tactus-Only* vs. *Tactus+Audio*) on path-following performance. Based on the results, we discussed how the audio and tactile feedback could be better combined and how to improve path-following performance by optimizing the guidance strategy. We hope this work could provide useful insights into the feedback solutions to support visually impaired people's mobility.

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