LightGuide: Directing Visually Impaired People along a Path Using Light Cues

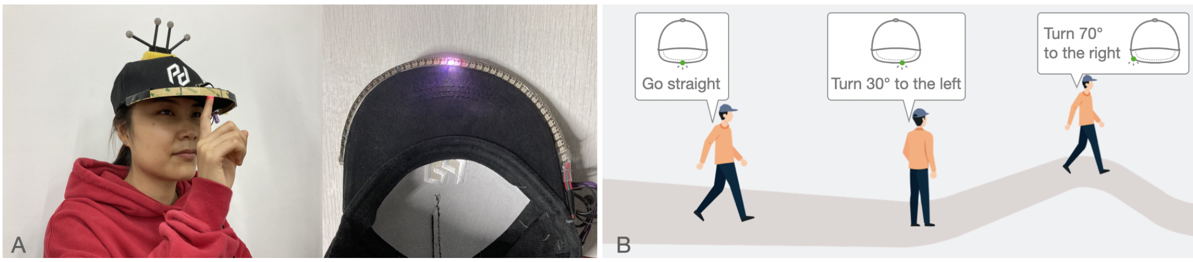

Fig. 1. (A) Most visually impaired users in our study could determine the direction of an LED light using their light perception. (B) LightGuide utilizes light direction to indicate a safe direction of travel, which can help users follow paths smoothly and accurately.

Precise and reliable directional feedback is crucial for electronic traveling aids that guide visually impaired people along safe paths. Despite suffering from vision loss, a large proportion of visually impaired people can still determine light direction using their light perception. This work presents LightGuide, a directional feedback solution that indicates a safe direction of travel via the direction of a light within the user's visual field. We prototyped LightGuide using an LED strip attached to the brim of a cap, and conducted three user studies to explore the effectiveness of LightGuide compared to HapticBag, a state-of-the-art baseline solution that indicates directions through on-shoulder vibrations. Results showed that, with LightGuide, participants turned to target directions in place more quickly and smoothly, and navigated along basic and complex paths more efficiently, smoothly, and accurately than HapticBag. Users' subjective feedback implied that LightGuide was easy to learn and intuitive to use. The potential limitations of using LightGuide in real environments are subsequently discussed.

CCS Concepts: • **Human-centered computing** → Accessibility technologies; *Accessibility*;

Additional Key Words and Phrases: visual impairment, light perception, visual feedback, path-following tasks

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1 INTRODUCTION

According to the World Health Organization, approximately 285 million people worldwide are visually impaired, including 39 million people who are blind and 246 million people with moderate to severe visual impairment (referred to as "low vision") [59]. Compared to people with low vision, people who are blind do not have functional vision to support their daily activities [1, 11, 50, 59, 63]. However, many people who are diagnosed with legal blindness still have some usable vision, such as light perception [48]. In fact, in America, 90% of people who are

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blind have the ability to perceive light [9, 48]. This light perception, while too weak to perform sight-based tasks, is often sufficient to detect the location, motion, and brightness of a light [22]. Light perception is also helpful in facilitating both mobility and orientation for visually impaired people [48]. For example, a light source at the end of a hallway could help them to maintain a straight line of travel and to look for a walkable direction [48].

People with visual impairment have difficulty in finding a path to a destination [20, 33, 35, 51]. As a result, it is reported that at least 30% of people who are blind do not travel outdoors independently [10]. To guide visually impaired people along a safe path, precise and reliable directional feedback is crucial [61, 62]. Prior works have adopted audio feedback [20, 37, 49] and haptic feedback [34, 42, 45, 61] to help visually impaired people follow a path. Moreover, visual enhancement techniques have been employed to facilitate path-finding for people with low vision through their functional vision [65]. However, to our knowledge, no prior work has leveraged on the rudimentary light perception possessed by many of the visually impaired to support their mobility.

In this paper, we present LightGuide, a directional feedback solution that indicates a safe direction of travel via the direction of a light within the user's visual field. LightGuide essentially relies on hardware that can emit light from different directions. To prototype LightGuide, we attached a flexible LED strip to the brim of a wearable cap. The strip comprises 45 individually-controllable LED pixels. For LightGuide to indicate a safe direction, the basic idea is simple: to turn on the LED pixel in the corresponding direction. However, the visual conditions of visually impaired people vary from person to person. We therefore proposed a set of methods to customize the direction indication strategy of LightGuide to suit different visual conditions.

To evaluate the effectiveness of LightGuide, we conducted three consecutive user studies with twelve visually impaired participants with light perception, and each study aimed to explore users' reactions to light cues when turning to a target direction in place, when following a path, and when navigating in real world environments, respectively. In all studies, HapticBag, an on-shoulder haptic feedback solution proposed in a latest related work [61] was adopted as the comparison baseline. Results showed that, compared to HapticBag, LightGuide enabled participants to turn to target directions in place more quickly and smoothly with a mean steady-state deviation of 3.96°. Regarding path-following tasks, participants navigated along basic paths (including straight paths and different turns) and complex paths more efficiently, smoothly, and accurately with LightGuide. LightGuide also helped users to navigate in a real-world indoor environment more safely and efficiently. Users' subjective feedback implied that LightGuide was easy to learn and intuitive to use. Based on the findings of user studies, we further discuss the strengths and limitations of using LightGuide in real environments.

In summary, we contribute a novel feedback technique that utilizes the direction of a light to indicate a safe direction for visually impaired people with light perception. We developed a set of methods employing this technique to cater to different visual conditions, and validated the effectiveness of the feedback solution in way-finding tasks for visually impaired people with light perception.

2 RELATED WORK

In this section we briefly review prior research, including non-visual feedback and visual feedback for navigational purposes. We also review existing visual enhancement techniques that exploit users' residual vision.

2.1 Non-Visual Feedback to Support Mobility for Visually Impaired People

Haptic and auditory feedback are the most common modalities through which visually impaired people interact with electronic traveling aids [17]. This section reviews their performance respectively.

The main forms of auditory feedback include spatial audio [2, 5, 30, 32, 38, 41, 43, 47] and audio descriptions [3, 18–20, 24, 37, 49]. Spatial audio utilizes the location of the audio source to indicate a safe direction of travel, which is intuitive to perceive [17]. However, prior work reported that the recognition accuracy of the four directional cues (left, right, front, back) indicated through spatial audio was 89% [61]. Besides, it is difficult to convey descriptive information through spatial audio. In contrast, audio descriptions can deliver complex verbal information and have been adopted by prior works to provide turn-by-turn instructions [3, 18–20, 24] or to describe the surrounding environment [3, 37, 49]. However, it is hard for verbal audio to indicate specific directions. Under verbal audio instructions, users had difficulty maintaining a straight line of travel or following a path accurately [17]. Moreover, visually impaired users were found to turn at the wrong locations or in wrong directions under audio instructions [46].

Regarding haptic feedback, the common forms in prior guidance systems include on-body vibrations [8, 12–14, 21, 27, 31, 34, 42, 45, 53, 58, 61] and vibrations from handheld devices [6, 26, 40, 54, 57]. On-body vibrations have gained wider adoption among the two forms, possibly due to its feedback being easily perceivable without occupying users' hands and its easy integration into wearables. Prior works have explored the effectiveness of using on-body vibrations to help users perceive directions or follow paths. As for direction perception, users recognized the directional cues presented by five motors on a belt with a mean accuracy rate of 83.4% [45]. Regarding path-following performance, Virtual Paving [61] helped visually impaired users to follow paths within 2.1m-wide area by indicating a turn to the left or right through vibrations on the left or right shoulders.

2.2 Visual Feedback to Support Mobility for Visually Impaired People

Among the research that utilizes visual feedback to support mobility for visually impaired people, most works focus on people with low vision by exploiting their functional vision. Similar to other feedback techniques, visual feedback was mainly used to assist in two mobility tasks: obstacle avoidance [15, 22, 28, 33, 55] and way-finding [65]. Some works also adopted visual feedback to help sign-reading [23] or staircase navigation [64].

Most prior studies focus on facilitating obstacle recognition for people with low vision. For example, several systems [15, 28, 33] increased the visibility of obstacles by mapping different types of obstacles with various colors and presenting the enhanced image to people with low vision through head mounted displays. Other works enhanced depth perception by mapping depth with high-contrast colors [4] or different levels of brightness [22, 55]. Besides obstacle avoidance, other works aimed to improve the visibility of signs or staircases. Huang *et al.* [23] developed a sign-reading system that assisted visually impaired users in recognizing indoor text such as room numbers. Assessments indicated that the system was effective in helping participants understand their surroundings, but the participants also walked more slowly when using the device. Another study [64] facilitated stair navigation by projecting visual highlights directly onto the stairs for people with low vision, which increased participants' self-reported psychological security.

In comparison, few prior work explored visual feedback to help visually impaired people find or follow a walkable path. Zhao *et al.* [65] designed a visual way-finding guidance system on HoloLens to support turn-by-turn navigation by indicating the turning instructions through high-contrast visual signs. By comparing the visual guidance with audio guidance in way-finding tasks, this work found that participants made fewer mistakes and experienced lower cognitive load with visual feedback.

However, all of the above systems relied on users' functional vision, and thus are likely unsuitable for people who are legally blind with light perception. To our knowledge, no prior work has exploited the primitive but widely possessed light perception of visually impaired people for perceiving directional cues. Moreover, no work has compared light feedback and haptic feedback to support mobility for visually impaired users.

2.3 Visual Enhancement Techniques that Help Visually Impaired People to Access Information

A variety of visual enhancement techniques were developed to help visually impaired people access information through their residual vision. Zhao *et al.* [66] summarized several common visual enhancement methods, including: magnification, contrast enhancement, edge enhancement, color reversal, and text extraction. These methods have been widely adopted in assistive devices designed for visually impaired people. For example, several devices

[55, 64, 65] adopted brightness and contrast enhancement, some studies [4, 15, 23, 28, 33, 52, 64] used high-contrast color to improve visibility, and other works [25, 66] relied on edge enhancement method. Besides the above methods, some researchers used an augmented-vision device that overlays contour images over natural vision to expand the visual field of people with tunnel vision [39, 56].

Unfortunately, most of the above visual enhancement techniques require users to have functional vision, and therefore do not work for people who are legally blind. In fact, approximately 90% of people who are blind were reported to have light perception [9, 48]. Moreover, the study by Ross [48] revealed that the ability to see light is helpful in both mobility and orientation for visually impaired people. For example, visually impaired interviewees stated that a light source at the end of a hallway could help them to maintain a straight line of travel and to look for a walkable direction [48]. However, to our knowledge, no prior work has thoroughly explored the effectiveness of indicating information through light in navigational tasks.

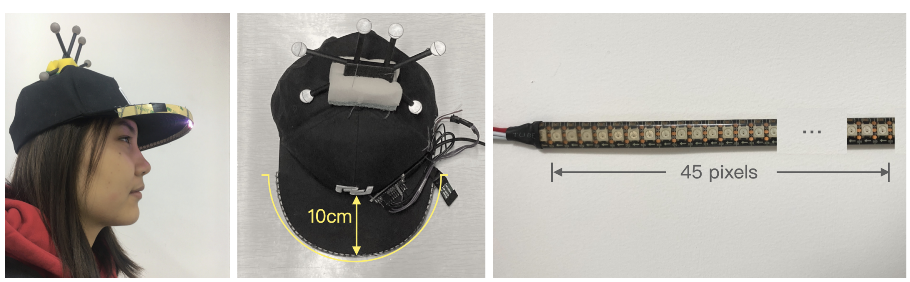
3 DESIGN AND IMPLEMENTATION

LightGuide utilizes light direction to indicate a safe direction of travel. This section describes (1) a wearable cap that can emit light from different directions, and (2) the strategy to indicate directions using light.

3.1 Hardware Specification

To emit light from different directions within the user's visual field, we designed a wearable cap with a flexible LED strip attached to the brim of the cap (see Figure 2(a)). The strip consists of 45 LED pixels on a 30cm-long printed circuit board, and each pixel can be individually controlled by Arduino. The density of the LED pixels was confirmed to be high enough for all visually impaired participants in our user studies. Each LED pixel comprises one red, green, and blue component, and the brightness of each component can be set with 8-bit precision, resulting in 24-bit color per pixel. The electric power of each pixel at its maximum brightness is 0.3W.

We determined the placement of the LED strip through pilot user tests, aiming to make the light easy to perceive. As a result, the LED strip was placed at nearly the same height as the user's eyes, and the central LED pixel was placed 10cm in front of the user's forehead. The LED strip was placed beneath the brim of the cap, which could help users to distinguish the light of LightGuide from other lights in the environment. Compared to common head mounted displays (such as HoloLens), the wearable cap is enough to provide high-resolution directional feedback to visually impaired users with lighter weight (<140g) and lower cost (<$70).



(a) The wearable cap (b) Placement of the LED strip (c) The LED strip comprises 45 pixels

Fig. 2. Hardware Specification of LightGuide.

3.2 Direction Indication through Lights

The key function of LightGuide is to indicate a safe direction of travel, which is defined as the *target direction* θ_t. As shown in Figure 3(a), to indicate the *target direction* θ_t, LightGuide determines the *directional cue* θ_g (also called the *turning angle*, unit: degree) based on the the user's current orientation θ_c as follows:

$$\theta_g = \theta_t - \theta_c \tag{1}$$

When $\theta_g < 0$, users need to turn left. Contrarily, when $\theta_g > 0$, users need to turn right. If $\theta_g = 0$, users have exactly aligned their body with the target direction, and therefore can walk forward safely.

For LightGuide to indicate the directional cue θ_g, the basic idea is intuitive: to turn on the LED pixel in the direction of θ_g (see Figure 3(b)). However, humans cannot directly see the light behind them. Moreover, many visually impaired users have constricted visual field. We therefore customized the direction indication strategy for users with different visual conditions, and describe our design in the following sections.

3.2.1 Direction Indication for Users with Full Visual Field. Users with full visual field can perceive lights emitted from all 45 LED pixels in LightGuide. Each pixel has a unique ID, which ranges from -22 (the leftmost pixel) to 22 (the rightmost pixel). ID for the central pixel is 0.

As shown in Figure 3(b), the 45 pixels are mapped with the 180° semicircle in front of the user, resulting in 4° for each pixel. Therefore, to indicate an acute turning angle (i.e., $|\theta_g| < 90°$), a single LED pixel in the corresponding direction will be turned on. The ID of the turned-on pixel is determined as follows:

$$ID = f_{id}(\theta_g) = \left\lfloor \frac{\theta_g + 2°}{4°} \right\rfloor, \text{ if } |\theta_g| < 90° \quad (\lfloor x \rfloor \text{ denotes the floor function of } x) \tag{2}$$

If the turning angle is greater than or equal to 90° (i.e., $|\theta_g| \geq 90°$), the principle is (1) to turn on more than one LED pixel starting from the leftmost/rightmost pixel, and (2) to turn on more pixels in order to indicate a larger turning angle. The determination of the turned-on pixels is illustrated in Figure 3(c). Precisely, if $|\theta_g| \geq 90°$, we turn on a series of adjacent LED pixels with the following ID:

$$\begin{aligned} -22 \leq ID \leq f_{id}(-180° - \theta_g), &\quad \text{if } -180° < \theta_g \leq -90° \\ 22 \geq ID \geq f_{id}(180° - \theta_g), &\quad \text{if } 90° \leq \theta_g \leq 180° \end{aligned} \tag{3}$$

Figure 3(d) exemplifies how the light changes as users turn. In this example, at first, five pixels starting from the leftmost boundary are turned on to indicate $\theta_t = -110°$. As users turn left, the number of turned-on pixels will

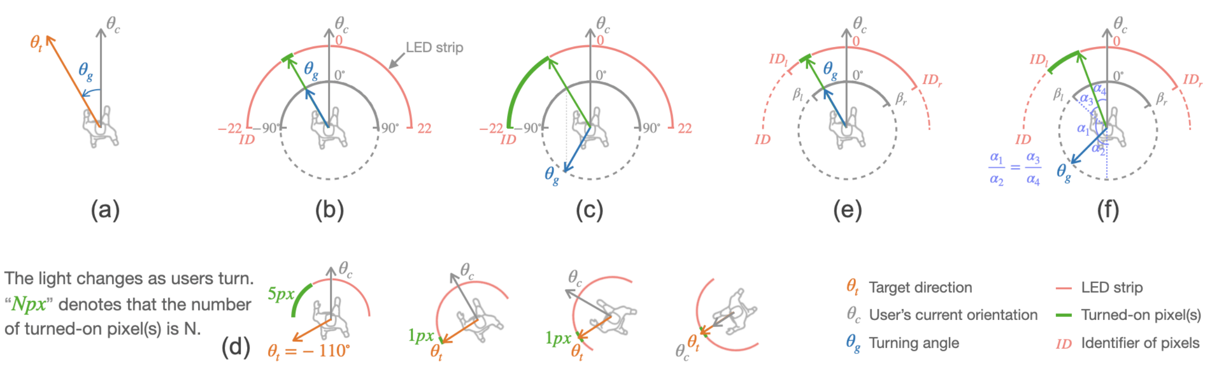


Fig. 3. Direction Indication through Lights.

gradually decrease from five to one. When there is only one turned-on pixel, the light will move from the leftmost boundary to the center of the user's visual field, indicating that the user has oriented to the target direction.

3.2.2 Direction Indication for Users with Constricted Visual Field. For users with constricted visual field, we describe their visual field using the ID of the leftmost and rightmost LED pixel they could see, and define these two parameters as the *leftmost limit* (ID_l) and *rightmost limit* (ID_r). Their visual field could also be expressed by two angle limits: $\beta_l = (ID_l * 4 - 2)^\circ$ and $\beta_r = (ID_r * 4 + 2)^\circ$.

To indicate a direction within users' visual field (i.e., $\beta_l < \theta_g < \beta_r$), we directly turn on a single LED pixel in the corresponding direction (see Figure 3(e)). The ID of the turned-on pixel is determined as follows:

$$ID = f_{id}(\theta_g), \quad \text{if} \;\; \beta_l < \theta_g < \beta_r \tag{4}$$

To indicate a direction out of users' visual field, we adopt the same principle as section 3.2.1: (1) to turn on more than one LED pixel starting from the leftmost/rightmost pixel, and (2) to turn on more pixels in order to indicate a larger turning angle. The range of turned-on pixels is determined such that $\alpha_1/\alpha_2 = \alpha_3/\alpha_4$ in Figure 3(f). Precisely, if $\theta_g \geq \beta_r$ or $\theta_g \leq \beta_l$, we turn on a series of adjacent LED pixels with the following ID:

$$\begin{aligned} ID_l \leq ID \leq f_{id}[K_l(-180^\circ - \theta_g)], \quad K_l = \beta_l/(-180^\circ - \beta_l), \quad \text{if} \;\; \text{-}180^\circ < \theta_g \leq \beta_l \\ ID_r \geq ID \geq f_{id}[K_r(180^\circ - \theta_g)], \quad K_r = \beta_r/(180^\circ - \beta_r), \quad \text{if} \;\; \beta_r \leq \theta_g \leq 180^\circ \end{aligned} \tag{5}$$

Overall, to indicate directions through lights for users with constricted visual field, the principle is to exploit their functional visual field, and to convert the direction out of their visual field into a direction within the field.

3.3 Customizing LightGuide to Suit Users' Visual Conditions

This section describes the customization of LightGuide to suit users' different visual conditions.

3.3.1 Brightness and Color Adjustment. We customized the brightness and color of the LED pixels, such that the user could easily and comfortably perceive the light. As mentioned in section 3.1, each pixel could emit 24-bit color. Therefore, the color of each pixel could be expressed by (R, G, B), where $0 \leq R, G, B \leq 255$.

For each user, the brightest color $(R, G, B)_{max}$ of a single LED pixel was determined such that the user could easily and comfortably perceive the light emitted from each pixel, and distinguish it from other lights in the environment (e.g., ceiling light and sunlight).

Furthermore, to avoid dazzling the user when more than one LED pixel was turned on, the brightness of all pixels was decreased based on N_{px}, the number of turned-on pixels, according to the following rule:

$$(R, G, B) = \lfloor (R, G, B)_{max} \times 3/(2 + N_{px}) \rfloor \tag{6}$$

3.3.2 Colored Home Indicator. When using LightGuide, users need to orient their body such that the directional cue θ_g is close to zero. In other words, users need to find the *home direction*. However, some visually impaired users have *depressed central vision*, and have difficulty in identifying the *home direction* accurately (i.e., $|\theta_g| < 10^\circ$). For these users, we tried to exploit their color vision to explicitly indicate the home direction.

If a user with depressed central vision could distinguish the hue of the light, we would change the color of the central five LED pixels (i.e., $ID = 0, \pm 1, \pm 2$; corresponding to $|\theta_g| < 10^\circ$) to be different from the other pixels. We name such a design as *colored home indicator*. This design was used for three participants in this work.

3.3.3 Home Direction Calibration. Some visually impaired users do not perceive the central LED pixel to be in the center of their visual field. For these users, we updated the ID of each LED pixel by adding an offset ΔID to the original ID (i.e., $ID := ID + \Delta ID$), so that the pixel with $ID = 0$ (updated value) was exactly in the center of users' visual field. The direction indication strategy would then be the same as mentioned above.

4 EXPERIMENTAL SETUP

4.1 Participants

We conducted all user studies with the same twelve participants (7 males, 5 females), whose ages ranged from 23 to 64 (mean = 30.33) . All participants were legally blind, meaning that either (1) their best-corrected visual acuity in their better eye was 20/200 or worse, or (2) their visual field was 20 degrees or narrower [65]. Each participant had at least one eye with light perception while their visual field was quite different. Half of the participants had color vision. Regarding mobility aids, three participants used canes daily, four used canes in special situations such as unfamiliar places, and three seldom used canes. Table 1 shows their detailed information.

The participants were recruited from a local support community for visually impaired people based on two criteria: being visually impaired and being able to distinguish the direction of a light. Each participant's eligibility was ensured by a two-stage screening. First, the participant self-reported to be visually impaired with light perception on the phone. Second, we conducted a brief on-site screening to confirm the participant's ability to distinguish the direction of a light. The screening lasted three minutes with ten trials. During each trial, we turned on a random LED pixel within the participant's visual field, and recorded whether he/she pointed a finger to the turned-on pixel with a deviation no more than three LED pixels (i.e., $\leq \pm 12°$). A participant would be ineligible only if less than six out of the ten trials were successfully completed.

Overall, among the seventeen visually impaired people with light perception, twelve passed the on-site screening. As for the five people who were ineligible, three were unable to identify the light in the home direction due to depressed central vision, and the other two had difficulty in distinguishing the light from any directions.

4.2 Procedure

Prior to the experiment, we customized LightGuide for each participant to suit their visual condition.

First, we tested the leftmost and rightmost LED pixel within users' visual field, and recorded their ID as ID_l (for the leftmost pixel) and ID_r (for the rightmost pixel). For participants who did not perceive the central LED pixel to be in the center of their visual field, we also performed the home direction calibration in section 3.3.3.

Second, we adjusted the brightness and color of the LED pixel as stated in section 3.3.1, such that the participants could perceive the light easily and comfortably. If a participant with color vision had difficulty identifying the home direction $|\theta_g| < 10°$, we would adopt the colored home indicator in section 3.3.2.

The customized parameters for each participant were shown in Table 1. After customization, each participant joined in three user studies. The first two studies were conducted in a controlled environment, aiming to evaluate users' direction perception (in Study 1) and path-following performance (in Study 2) when using LightGuide. The

Table 1. Demographic information of the twelve participants. All participants were **legally blind with light perception.** In "**Others**", $(R, G, B)^c$ denotes the color of the *color home indicator*. ΔID denotes the *home direction calibration*.

No.	Sex/Age	Diagnosis	Visual Field	Color Vision	Cane Use	ID_l / ID_r	$(R, G, B)_{max}$	Others
P1	F/25	Retinitis pigmentosa	Full (both eyes)		1-2 times a week	-22 / 22	100,100,100	
P2	F/23	Cataract, Retinal detachment	Peripheral vision loss (both eyes)		seldom	-16 / 16	70,50,0	
P3	M/28	Retinitis pigmentosa	Narrow (left), Tunnel vision (right)		daily	-22 / 22	100,80,80	
P4	M/32	Cataract	Full (both eyes)		1-2 times a week	-22 / 22	100,80,80	
P5	M/26	Retinitis pigmentosa	Full (left), Tunnel vision (right)	T	daily	-22 / 22	100,80,80	$(100,10,10)^c$
P6	M/23	Unknown	Full (left), None (right)		daily	-22 / 10	100,80,80	
P7	F/64	Cataract, Glaucoma	Tunnel vision (left), None (right)	T	seldom	-16 / 5	20,20,20	
P8	M/27	Cone dystrophy	Full (both eyes)		in unfamiliar places	-22 / 22	20,20,0	
P9	M/25	Cataract	None (left), Tunnel vision (right)	T	in unfamiliar places	-10 / 13	50,50,50	ΔID = -3
P10	F/26	Cataract	Peripheral vision loss (left), None (right)	T	at night	-16 / 16	50,50,50	$(50,0,0)^c$
P11	F/40	Cataract, Retinal detachment	Peripheral vision loss (both eyes)	T	in unfamiliar places	-16 / 16	50,50,50	
P12	M/25	Glaucoma	None (left), Full (right)	T	seldom	-3 / 13	50,0,0	$(50,50,50)^c$

third user study (Study 3) was conducted in real world environments to evaluate the feasibility to use LightGuide in real life. After all studies, an interview was conducted to collect participants' subjective feedback.

4.3 Comparison Baseline: HapticBag that Indicates Directions through On-body Haptic Feedback

LightGuide aims to enable people with visual impairment to follow a path through directional feedback. Regarding this topic, the most recent work is Virtual Paving [61], which enabled visually impaired users to walk along 2.1m-wide basic paths through haptic cues provided by a backpack. We therefore reproduced the design in [61] as our comparison baseline, and name it as HapticBag.

HapticBag comprised three vibration motors. Two motors were placed on users' left and right shoulder to indicate that users needed to turn left or right, respectively. The third motor was placed in front of users' chest to indicate walking straight. The vibration pattern of all motors was the same as [61], where each motor was periodically turned on for 500ms and then turned off for 500ms. All motors were controlled by Arduino. In our work, if the directional cue $|\theta_g| < 10°$, the front motor would vibrate. Otherwise, the left motor would vibrate if $\theta_g < -10°$, and the right motor would vibrate if $\theta_g > 10°$. In [61], a fourth motor was placed close to users' back to indicate an emergency stop. However, we removed this motor because we hope to explore how much users could deviate without additional emergency alarm.

4.4 High-Accuracy Localization System Used for Study 1 and Study 2

To evaluate the feedback technique while avoiding errors related to positioning and path planning (e.g., wrong directional feedback caused by an unstable positioning system) and to collect accurate quantitative data, we developed a localization system with Optitrack in an indoor space, which was used in Study 1 and Study 2.

As shown in Figure 4, the size of the indoor space was 8×5m. The OptiTrack localization system consisted of 10 cameras and a marker. OptiTrack calculated the marker's position and orientation according to the marker's images captured by the cameras in real-time. The measurement error of position is less than 1mm, and the measurement error of orientation is less than 1° [44]. To prevent the body from blocking the marker, we fixed the marker to a cap worn on participants' heads during the experiment. All participants were trained to align their head and body orientation to mitigate the effect of different head and body orientations. During the experiment, we did not find significant difference between participants' head and body orientations.

OptiTrack reported the marker's position and orientation to a PC server via a network cable, with python programs running on the PC server. After receiving the data from OptiTrack, the server determined the directional cue according to the guidance strategy in each task, and then transferred the cue to the feedback device (LightGuide or HapticBag) via Bluetooth. Both feedback devices used Arduino to receive data from the PC server and to control the LED strip or the vibration motors. The update frequency of the whole system was 50Hz.

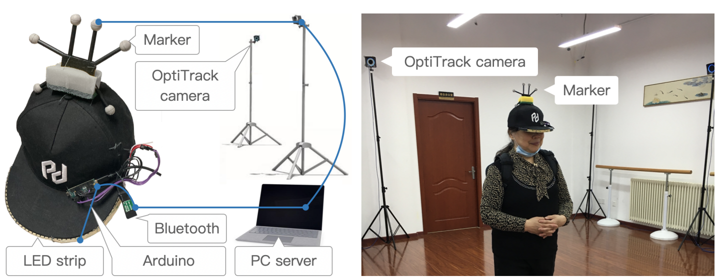


Fig. 4. High-accuracy localization system used for Study 1 and Study 2.

5 STUDY 1: UNDERSTANDING USERS' REACTION TO LIGHT FEEDBACK

Study 1 aimed to understand how users react to directional cues indicated by lights. In doing this, we evaluated users' performance when orienting to different directions in place using LightGuide, and compared it to HapticBag.

5.1 Task and Performance Metrics

In each task of Study 1, participants needed to turn their bodies to a target direction in place as quickly as possible. Figure 5 (a) illustrates how users' orientation $\theta_p(t)$ would change after being instructed to orient to the target direction θ_t at time $t = 0$. To characterize such a dynamic response, we defined four metrics:

(1) reaction time (t_r): the time delay before users' orientation actually started to change.
(2) settling time (t_s): the time it took for users' orientation to settle. t_s also suggests the task completion time.
(3) steady-state deviation (D_{ss}): the deviation of users' steady-state orientation θ_{ss} from the target direction θ_t. D_{ss} quantifies user's direction perception accuracy. Precisely, $D_{ss} = |\theta_t - \theta_{ss}|$, where $\theta_{ss} = \theta_p(t_s)$.
(4) maximum overshoot (OS): the amount of angle that users over-adjusted before settling. OS indicates whether users turned to the target direction smoothly. Precisely, $OS = |\theta_{peak} - \theta_{ss}|$.

5.2 Design and Procedure

The independent variable is Technique (LightGuide vs. HapticBag), which was counterbalanced among participants. A training phase was conducted prior to the experiment, during which participants were introduced to both techniques, and then practiced each technique by finishing six tasks with the turning angles of ±45°, ±90°, and ±135° (negative angles denoted turning left, and positive angles denoted turning right).

The experiment lasted around half an hour, during which the participant completed two trials for each technique, and each trial consisted of 23 tasks in randomized presentation order. The turning angles of the 23 tasks were $k \times 15°(k = \pm1, \pm2, \pm3, \ldots \pm 11, +12)$. Each task was as follows: First, the participant would stand still with the feedback device indicating the zero direction. Next, when the device started to indicate a non-zero direction θ_t, the participant needed to align his/her body with that direction in place. Finally, when the system determined that the participant's orientation stopped changing (using the settling criterion in section A), a beep sound would be played to inform the participant that the task was finished. The device was automatically set to indicate the zero direction after each task. The next task began after two seconds. During each task, participants' orientation $\theta_p(t)$ with respect to the time t was recorded for data analysis. Users' verbal comments were also audio-recorded throughout the experiment.

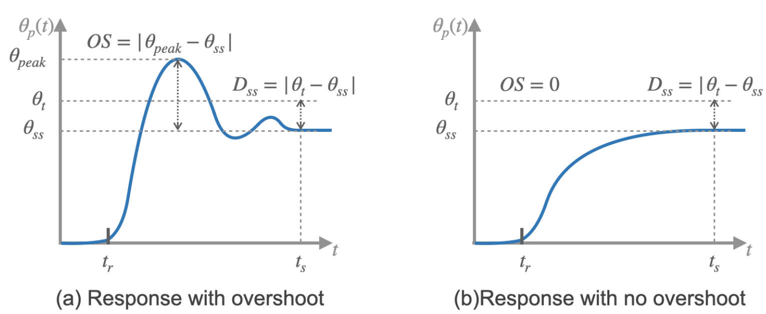


Fig. 5. Transient Response Metrics in Study 1.

5.3 Results and Findings

All participants learnt both techniques by finishing the 6 training tasks. A total of 1104 samples (2 techniques × 23 tasks × 2 trials × 12 participants) were collected. Figure 7 shows the waveforms of participants' orientation $\theta_p(t)$ for all samples. For each sample, we computed the performance metrics automatically using the method in section A, and then manually checked the correctness. Among the 1104 samples, the reaction time of 91 samples and the settle time of 5 samples were manually corrected.

We have two within-subject factors, Technique (LightGuide vs. HapticBag) and Direction (23 directions). For normally distributed metrics, we used 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. For non-normally distributed metrics, we used the Aligned Rank Transform for nonparametric factorial ANOVAs (ART) [60] to check for significant effects.

5.3.1 Reaction Time and the Effect of Individual Difference. The mean reaction time (t_r) was 0.574s (SD=0.026) for LightGuide and 0.487s (SD=0.015) for HapticBag. RM-ANOVA showed a significant effect of Technique on t_r ($F_{1,23} = 10.730, p = .003$). We did not find a significant effect of the Direction ($F_{8.799,202.388} = 1.312, p = .234$) or the interaction between Technique and Direction ($F_{8.652,199.001} = 1.759, p = .081$). The above results indicated that most participants were more sensitive to the haptic cues on shoulders than the visual cues from LightGuide.

To explore whether the effect of Technique on t_r differed individually, we conducted paired t-tests for each participant. As shown in Figure 6 (a), t_r for LightGuide was significantly lower than HapticBag for two participants (P4 and P11). Contrarily, for other six participants, t_r for LightGuide was significantly higher. No significant difference of t_r between two techniques was found for the other four participants (P2, P6, P9, P12). However, based on our samples, we did not find the above individual difference to be related to participants' visual conditions.

5.3.2 Settling Time and Steady-state Deviation. The settling time (t_s) for LightGuide (M=3.18s, SD=0.99) was significantly lower than HapticBag (M=3.70s, SD=1.03) ($F_{1,23} = 32.718, p = .000$). There was no significant interaction between Technique and Direction on t_s ($F_{8.179,188.121} = 1.801, p = .078$). These results suggested that LightGuide enabled the participants to reach the target direction faster than HapticBag for the 23 target directions.

Moreover, RM-ANOVA also showed a significant effect of Direction on settling time ($F_{6.077,139.781} = 50.217, p = .000$). We further tested the correlation between settling time (t_s) and the absolute value of Direction ($|\theta_t|$) for each technique. A positive linear correlation was found between t_s and $|\theta_t|$ for LightGuide ($F = 313.665, p = .000$, adjusted $R^2 = 0.362$) and HapticBag ($F = 384.327, p = .000$, adjusted $R^2 = 0.410$). The results are shown in Figure 6 (b), indicating that a larger turning angle would likely result in a longer settling time.

The mean steady-state deviation D_{ss} was 3.96° (SD=3.03) for LightGuide and 3.65° (SD=2.56) for HapticBag. Since D_{ss} was not normally distributed, we used ART analysis to model the impact of Technique and Direction on D_{ss}. Results showed no significant effect of Technique ($F_{1,23} = .424, p = .521$), Direction ($F_{22,506} = .387, p = .995$), or the interaction between Technique and Direction ($F_{22,506} = 1.061, p = .387$) on D_{ss}, suggesting that there was no significant difference in participants' direction perception accuracy between the two techniques for all 23 directions. Moreover, to the best of our knowledge, both LightGuide and HapticBag outperformed prior works in direction perception accuracy. In prior work, the smallest mean steady-state deviation was 15° achieved by Tactile Wayfinder [21], which indicated directions through six vibration motors placed on a belt.

5.3.3 Maximum Overshoot and Turning Smoothness. The maximum overshoot (OS) was 5.12° (SD=6.35) for LightGuide and 20.69° (SD=13.71) for HapticBag. ART analysis showed a significant interaction between the effects of Technique and Direction on OS ($F_{22,506} = 5.825, p = .000$). Wilcoxon signed-rank tests for each direction showed that OS of LightGuide was significantly lower than HapticBag for all 23 directions (see Fig 6 (d)), implying that LightGuide helped participants to turn to target directions more smoothly with less over-adjustment. Moreover, as shown in Figure 7, users tended to adjust their orientations repeatedly around the target direction

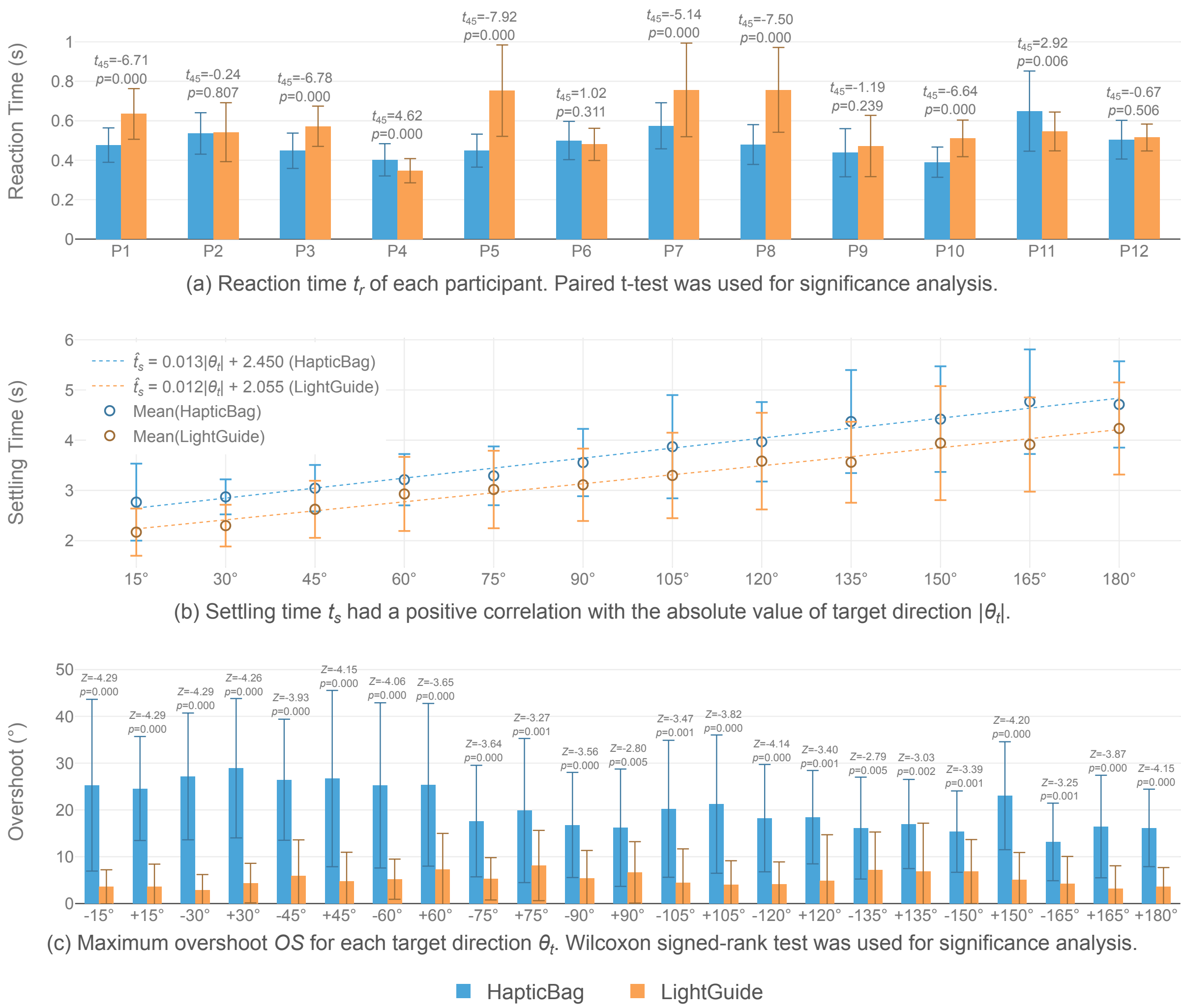


Fig. 6. Results of the four metrics in Study 1. Error Bars Indicate Standard Deviation.

with HapticBag, resulting in zigzag waveforms. In contrast, users' orientation for LightGuide changed more smoothly with fewer zigzags, indicating that LightGuide enabled users to fine-tune their orientations more easily.

Overall, compared to HapticBag that only indicated whether to turn left or right, LightGuide informed users of the specific turning angle, which effectively helped users to turn more smoothly, and also reduced the zig-zag pattern when fine-tuning around the target direction.

5.3.4 Reasons for Wrong Turns. Although all tasks were completed with small steady-state deivations, users might turn to the opposite direction at the beginning of the task (see Figure 7). Among all samples, participants turned wrongly at beginning (with the turning angle > 10°) 6 times with LightGuide, and 14 times with HapticBag.

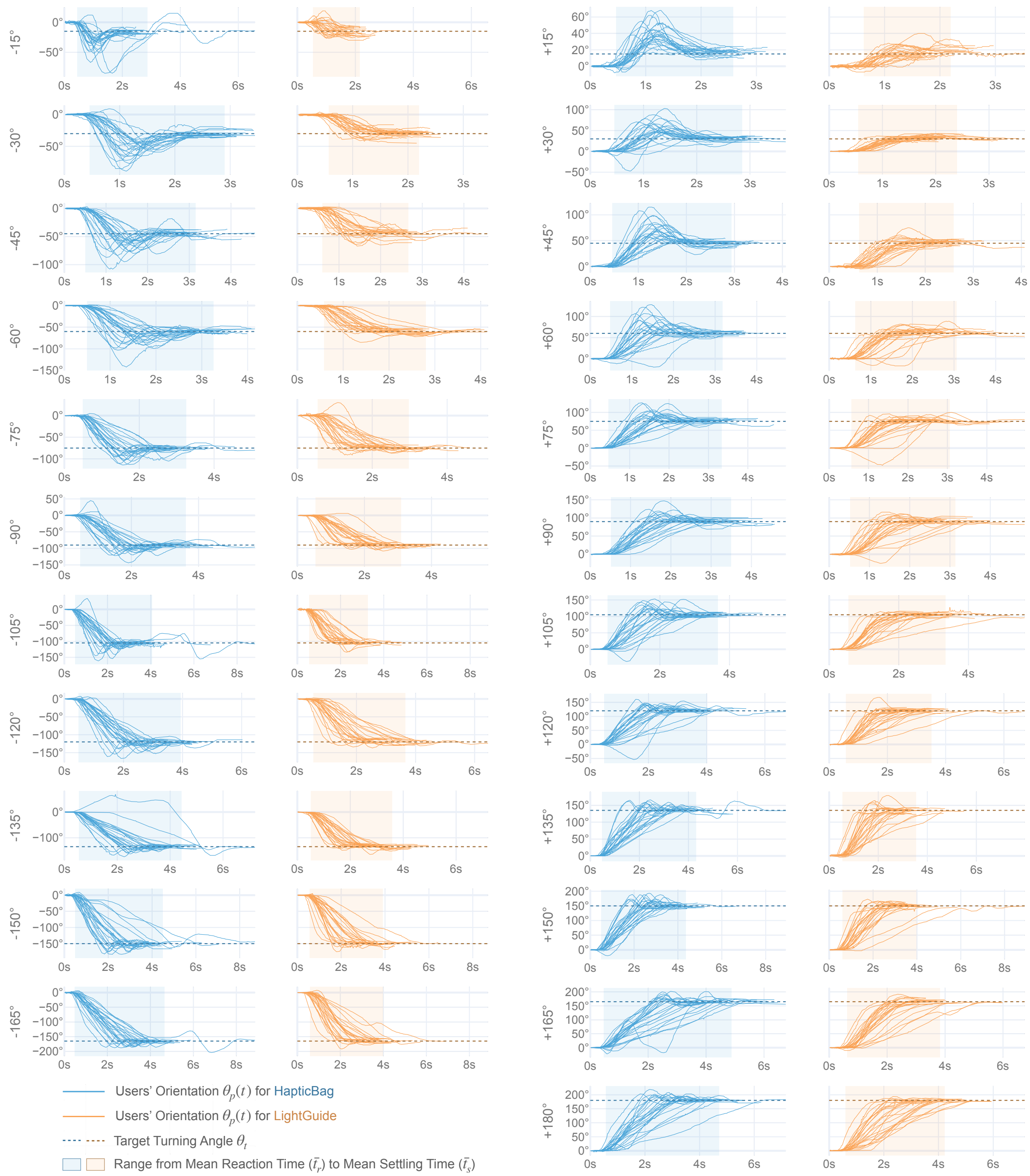


Fig. 7. Waveforms of users' orientation $\theta_p(t)$ for each turning angle θ_t. The range of axes is unified for the same θ_t.

Interestingly, the reason for wrong turns was different for the two techniques. With HapticBag, users turned to the wrong direction when the cue was misinterpreted as an alarm. As P9 indicated, “I unconsciously thought vibrations on my left shoulder as an alarm of dangers on the left”. However, none of the twelve participants reported to turn to wrong directions due to misconceiving the light as a warning. In contrast, The underlying reason was: “The light was almost outside my visual field, so I couldn’t tell in which direction to turn” (P6, P7). This finding highlighted the importance for the light to reliably stay within users’ visual field when using lights as feedback. Designers must take care when exploiting users’ peripheral visual field, because visual cues in this field might not be reliably perceived by visually impaired users.

5.4 Discussion on Users’ Reaction to Light Feedback in Place

In Study 1, participants turned to 23 different target directions in place with a mean steady-state deviation of 3.96° when using LightGuide. Compared to HapticBag, LightGuide enabled participants to complete tasks significantly more quickly (i.e., with smaller settling time) and smoothly (i.e., with less overshoot or repeated adjustment). The short settling time of LightGuide is also likely explained by the smooth turns.

Compared to light feedback, most participants were more sensitive (i.e., with smaller reaction time) to the vibration on shoulders. However, two participants still reacted faster with LightGuide than HapticBag. We did not discover the possible factors related to this individual difference, which would be an interesting direction for further study. Besides, we did not exclude the time delay caused by wireless communication when computing the reaction time. Therefore, the reaction time reported in this paper is longer than the actual reaction time.

Although participants have light perception in their peripheral visual field, we found that visual cues in this field were not always reliably perceived by users. This finding should be considered when designing systems that exploit the light perception of visually impaired users.

Study 1 evaluated users’ reaction to light feedback when turning to a fixed direction in place. However, users’ performance during walking might be different, which was further investigated in Study 2.

6 STUDY 2: EVALUATION OF PATH-FOLLOWING PERFORMANCE

Study 2 aimed to evaluate users’ path-following performance when using LightGuide (compared to HapticBag).

6.1 Experimental Paths

We adopted two categories of experimental paths: *basic paths* that represent the basic elements of daily paths, and *complex paths* to test the path-following performance in complex environments.

(a) Four types of basic paths (b) Four variations of complex paths (c) The learning path (d) Determining the directional cue

Fig. 8. Experimental paths and the determination of directional cues in Study 2.

6.1.1 Basic Paths. Based on daily navigational scenarios and prior studies [61], we distilled four types of basic paths shown in Figure 8(a): straight path (SP), right-angle turn (RT), acute-angle turn (AT), and obtuse-angle turn (OT). These four types of paths may not cover all scenarios, but they are mostly representative of the daily paths.

The specifications of the basic paths were as follows: The length of the straight path was 6m. The turning angle was 90°, 45°, and 135° for RT, AT, and OT, respectively. The centerline's radius was 1m for all three turning paths.

Each turning path came in left and right turn variations (e.g., acute-angle turn included an acute left turn or an acute right turn), resulting in seven paths in total: SP, RT-left, RT-right, AT-left, AT-right, OT-left, and OT-right.

6.1.2 Complex Paths. To assess users' path-following performance in complex environments, we designed a complex path as shown in Figure 8(b). The complex path included all the basic turns: RT-left, RT-right, AT-left, AT-right, OT-left, and OT-right, and each basic turn occurred exactly once. Besides, the complex path also comprised several straight paths (SP), among which the longest SP was 3.414m long.

Moreover, the complex path came in four variations with identical path centerline. The only difference was the starting direction (see Figure 8(b)). Each variation was presented to a user only once, so that the user could not remember the path. These four variations were treated as the same path during data analysis.

6.2 Generating Directional Cues to Guide Users along a Path

As shown in Figure 8(d), the directional cue θ_g is generated by $\theta_g = \theta_t - \theta_c$, where θ_c is the user's current orientation, and θ_t is the target direction. To guide users to follow a path, θ_t is determined in real-time as follows.

In Figure 8(d), point C is the user's current position at an arbitrary moment, and point N is the nearest point on the centerline to the user. Point M is located ahead of point N along the centerline by a constant guide length l_{guide} of 60cm. Then, the target direction θ_t is determined as the direction of the vector $\overrightarrow{CM}$. By moving towards θ_t, users can draw closer to the centerline.

6.3 Performance Metrics

We used the following metrics to evaluate the efficiency, accuracy and smoothness of each path-following task.

First, to assess the walking efficiency by time and distance, we defined *task completion time* (T) as the time for the user to walk through a path, and *trajectory length* (L) as the length of the user's trajectory in one task.

Next, to evaluate the path-following accuracy, we adopted *maximum deviation* (D_{max}) and *mean deviation* (D_{avg}, the mean of *deviation* over time) in one task, where *deviation* (D) is the instantaneous distance between the user's position and path centerline, shown as $|CN|$ in Figure 8(d).

Third, we needed to quantify the path-following smoothness. Intuitively, the walking smoothness would be low if a user was frequently instructed to turn left or right. Luckily, the angle a user was instructed to turn at a moment was exactly the absolute value of the directional cue $|\theta_g(t)|$. We thus adopted the integral of directional cues over time to quantify users' path-following smoothness, and defined it as *impulse of cues* (I_{cue}). Precisely, $I_{cue} = \int_0^T |\theta_g(t)| \mathrm{d}t$. For the same path, a larger I_{cue} means that users needed to adjust their orientation more frequently. Contrarily, if users followed the path more smoothly with fewer zigzags, I_{cue} would be smaller.

6.4 Design and Procedure

The factor Technique (LightGuide or HapticBag) was counterbalanced among the twelve participants. A training phase was conducted prior to the experiment, during which participants were asked to walk along the learning path shown in Figure 8(c) using LightGuide or HapticBag, respectively.

The experiment lasted around one hour with two consecutive tests: the basic-path test and the complex-path test. First, in the basic-path test, the participant completed two trials for each technique, and each trial consisted of the seven basic paths in randomized presentation order. After that, the participant took a five minute break.

Next, in the complex-path test, each participant completed two trials for each technique, and each trial consisted of one complex-path. The four complex-path variations (Figure 8) were randomly paired with the four trials for each participant, such that the participant would not encounter the same variation in more than one trial.

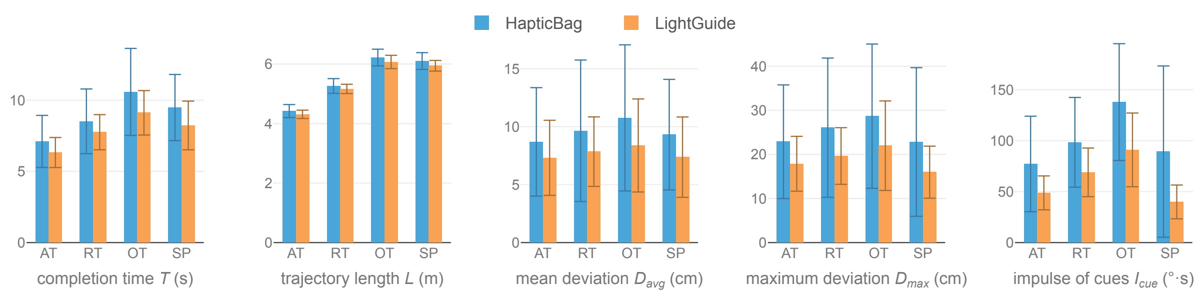
In total, each participant completed 28 basic-path tasks (2 techniques × 7 paths × 2 trials) and 4 complex-path tasks (2 techniques × 2 trials). During each task, participants' position and orientation were recorded. Users' verbal comments were also audio-recorded throughout the experiment.

6.5 Path-Following Performance for Basic Paths

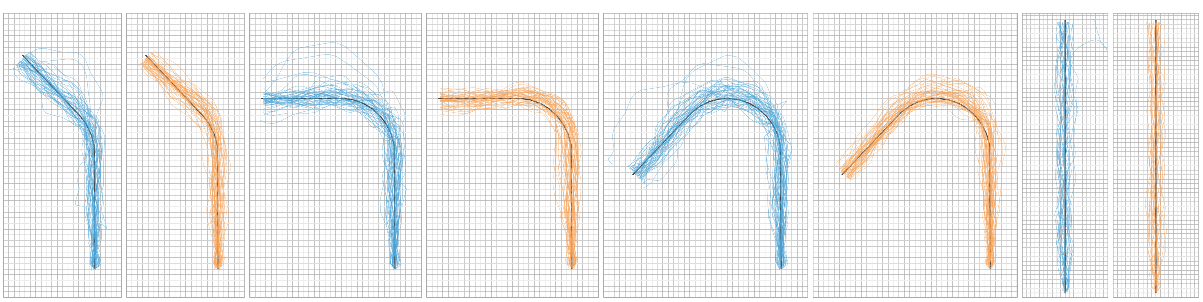
All participants learnt both techniques by walking along the learning path. The twelve participants completed all basic-path tasks, resulting in 168 samples for each technique.

We have two within-subject factors, Technique (LightGuide, HapticBag) and PathType (seven basic paths). RM-ANOVA showed no significant interaction between the effects of Technique and PathType on all metrics: task completion time ($F_{3.659,122.262} = 1.812, p = .140$), trajectory length ($F_{6,138} = 1.166, p = .331$), mean deviation ($F_{6,138} = .553, p = .767$), maximum deviation ($F_{6,138} = .469, p = .830$), and impulse of cues ($F_{4.053,93.227} = .844, p = .502$). We therefore removed PathType from our model, and used paired t-test to further analyze the effect of Technique on the path-following performance. Based on the metrics and trajectories, we have following findings:

6.5.1 Efficiency. As for walking efficiency, the task completion time T for LightGuide (M=7.80s, SD=1.73) was significantly shorter than HapticBag (M=8.84s, SD=2.75) ($t_{167} = 6.954, p = .000$). Participants also finished all



(a) Performance metrics for basic paths. Error bars indicate standard deviation.



(b) Users' trajectories for basic paths. (Trajectories of right turns are flipped to align with the left turns.)

Fig. 9. Path-following performance and trajectories for basic paths in Study 2.

tasks with significantly shorter trajectory length L when using LightGuide (M=5.29m, SD=0.74) compared to HapticBag (M=5.42m, SD=0.78) ($t_{167} = 5,830, p = .000$). For each type of basic paths, the time T and distance L for LightGuide were also shorter (see Figure 9(a)), suggesting that LightGuide helped participants to walk along basic paths more efficiently than HapticBag in both time and distance.

6.5.2 Accuracy and Trajectory Convergence. Regarding path-following accuracy, the mean deviation D_{avg} when using LightGuide (M=7.78cm, SD=3.44) was significantly smaller than HapticBag (M=9.64cm, SD=5.62) ($t_{167} = 3.745, p = .000$), indicating that LightGuide helped users to follow the path more accurately.

The max deviation D_{max} for LightGuide (M=19.28cm, SD=7.78) was also significantly smaller than HapticBag (M=25.42cm, SD=15.4) ($t_{167} = 4.783, p = .000$). Moreover, as shown in Figure 9(b), users' trajectories for LightGuide were more convergent to the path centerline than HapticBag, implying that LightGuide could help users walk through narrow environments more safely. Regarding maximum deviation, LightGuide also outperformed significantly prior work [61], which was reported to help users walk along basic paths within the 2.1m-wide area.

6.5.3 Smoothness. LightGuide enabled participants to walk more smoothly than HapticBag. The impulse of cues I_{cue} for LightGuide (M=65.33°·s, SD=31.76) was significantly lower than HapticBag (M=102.3°·s, SD=60.29) ($t_{167} = 8.248, p = .000$), indicating that users were instructed to make fewer orientation adjustments when using LightGuide. In Figure 9(b), we could also see that the trajectories of HapticBag had more zigzag patterns, while the trajectories of LightGuide were more smooth.

6.5.4 Deviation at a Turn. As shown in Figure 9(b), when walking along the three types of turning paths (OT, RT, and AT) using HapticBag, users' trajectories at a turn tended to deviate from the centerline, indicating that users often turned later than the decision point with HapticBag, possibly because HapticBag did not inform users of the exact turning angle. In contrast, the trajectories at a turn were more convergent to the path centerline when using LightGuide.

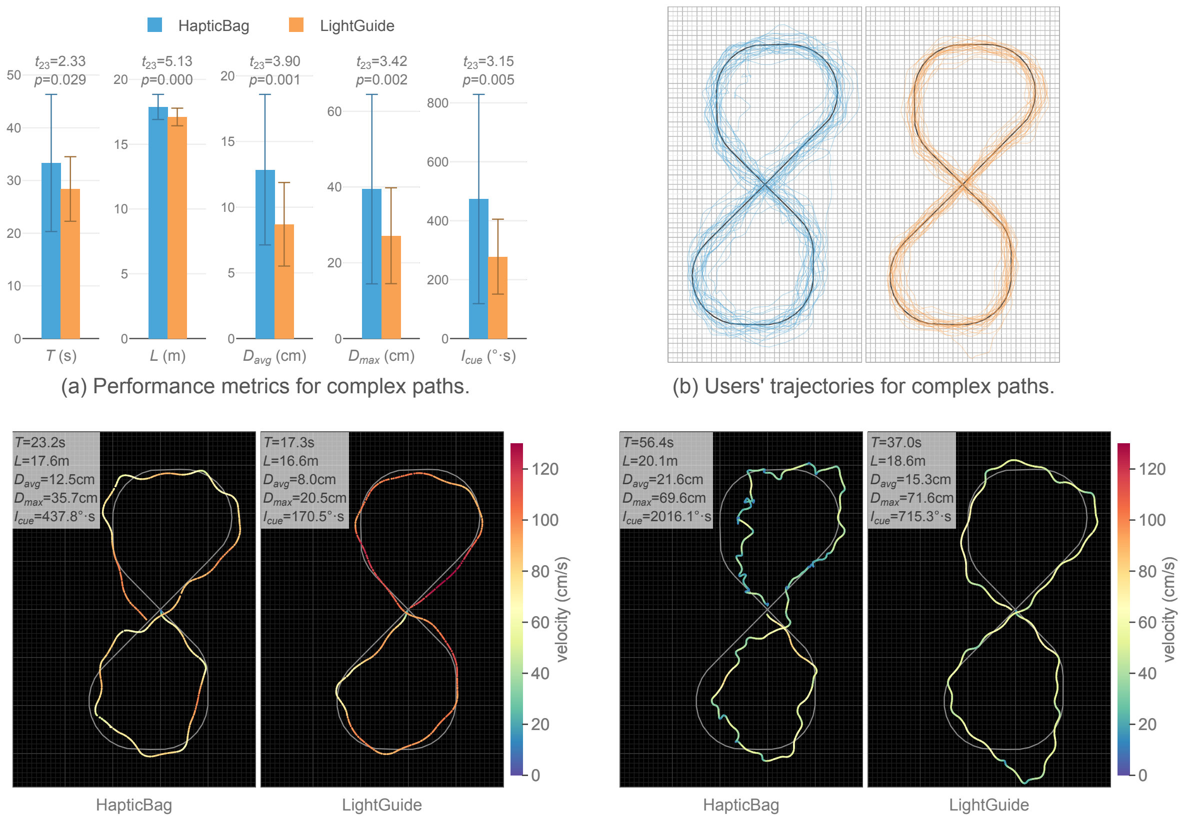
Interestingly, compared to right-angle turns and acute-angle turns, users tended to turn later when walking along obtuse-angle turns with LightGuide. This might be explained by the indication strategy of obtuse angles. For LightGuide to indicate an obtuse turning angle, several LED pixels will be turned on, so that users would know that they needed to turn more than 90°. However, the exact degree of obtuse angles was difficult to perceive at first. In contrast, users could easily identify the exact degree of acute or right angles, since these angles were indicated by a single light. Likely due to this reason, users' deviation at an obtuse-angle turn tended to be slightly larger than right-angle turns and acute-angle turns.

6.6 Path-Following Performance for Complex Paths

All complex-path tasks were completed by the twelve participants, resulting in 24 samples for each technique. Figure 10 shows the performance metrics and users' trajectories for the two techniques.

6.6.1 Efficiency, Accuracy, and Smoothness. Similar to the results for basic paths, LightGuide outperformed HapticBag with higher efficiency, accuracy, and smoothness. When using LightGuide, participants completed path-following tasks with significantly shorter completion time, shorter trajectory length, smaller mean and maximum deviation, and lower impulse of cues. The detailed statistics of significance analysis are reported in Figure 10(a). Moreover, from Figure 10(b), we can see that users' trajectories for LightGuide were more convergent to path centerline, implying that most users followed the complex path more closely with LightGuide.

6.6.2 Case Analysis for LightGuide. Among all 168 samples for LightGuide, the shortest task completion time (17.3s) was achieved by P12, while the largest deviation from path centerline (71.6cm) occurred in a sample finished by P7. Trajectories of the two corresponding samples with LightGuide are shown in Fig 10(c) and (d). Also shown on the left of each figure are the trajectories of P7 and P12 using HapticBag. From these figures, it could be



(a) Performance metrics for complex paths.

(b) Users' trajectories for complex paths.

(c) Trajectories of P12.
The shortest time for LightGuide was achieved by P12.

(d) Trajectories of P7.
The largest deviation for LightGuide was achieved by P7.

Fig. 10. Path-following performance and trajectories for complex paths in Study 2. Error bars indicate standard deviation.

seen that the trajectories for HapticBag had more zigzags, and users' walking velocity around the zigzag points significantly decreased. In contrast, the trajectories for LightGuide had a more even velocity distribution with fewer zigzags for both P7 and P12. These observations confirmed the aforementioned findings that LightGuide enabled users to walk more smoothly (with more even pace and fewer zigzags) than HapticBag.

However, when using LightGuide, users with limited visual field might lose track of the light and deviate much from the path. As shown in the right of Figure 10(d), P7 still walked forward when instructed to turn left, resulting in a maximum deviation of 71.6cm. As recalled by P7, "the light was moving from my left to right, and I tried to track the light by rolling my left eye. However, I still lost track of it (the light) when it was approximately in front of me, so I kept walking straight until I found the light again." In fact, P7 was totally blind on the right eye, and thus could only perceive lights by rolling her left eye, which had a very constricted visual field. This finding indicates that visual feedback might be not always reliable for visually impaired people, especially for people with constricted visual field. To address this problem, additional warnings from other feedback modalities might be necessary, which will be discussed in section 8.

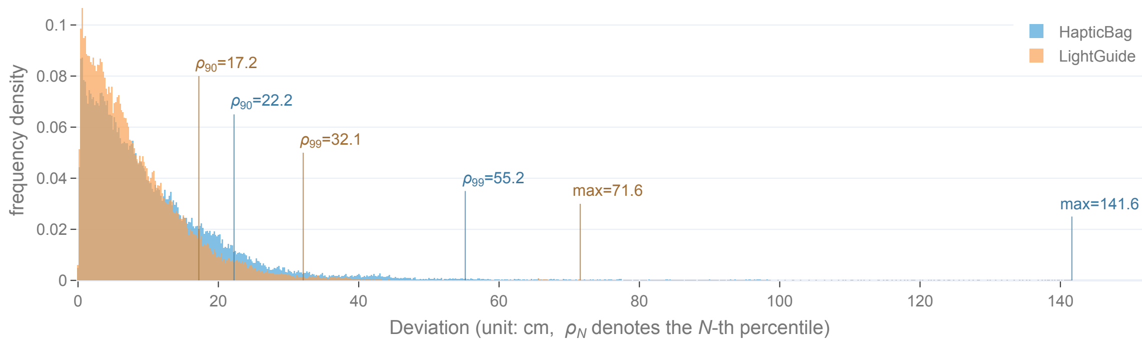


Fig. 11. Frequency distribution of *Deviation D* in all tasks (including both basic paths and complex paths).

6.6.3 Distribution of Instantaneous Deviation in all Tasks. The metric *deviation* (D) quantifies users' positional deviation from centerline when using a feedback technique, which importantly indicates the safe area within which users could walk. Figure 11 shows the distribution of the instantaneous deviation in all tasks (including 336 basic-path tasks and 48 complex-path tasks). The maximum deviation of all samples for LightGuide was 71.6cm. Moreover, with LightGuide, participants' deviation was no more than 32.1cm within 99% of the time, and no more than 17.2cm within 90.0% of the time. These metrics for LightGuide were all lower than HapticBag, indicating that users could safely walk within a narrower area with LightGuide compared to HapticBag.

6.7 Discussion on the Path-Following Performance

In study 2, LightGuide enabled all participants to walk along basic paths and complex paths with the deviation less than 72cm. LightGuide significantly outperformed HapticBag in efficiency (with shorter task completion time and trajectory length), accuracy (with smaller deviation and more convergent trajectories), and smoothness (with fewer zigzags, more even pace, and smaller impulse of cues). LightGuide also helped users to follow turning paths more closely than HapticBag.

However, we found that users with limited visual field might lose track of the light and walk in wrong directions, resulting in large deviation from path centerline. This finding highlighted the importance to provide additional alarms through other modalities when users fail to respond correctly to the visual feedback.

7 STUDY 3: EVALUATION IN REAL WORLD ENVIRONMENTS

Study 3 aimed to evaluate the feasibility of LightGuide in real world environments.

7.1 Task and Apparatus

To assess LightGuide in environments with different lights, we conducted Study 3 in an indoor space with two types of lights: (1) automatic ceiling lights that would be activated by human movement, and (2) sunlight through French windows (see Figure 12(a)). The study was conducted around 2:00 p.m. so that the sunlight was nearly the brightest in the day. During the experiment, the site was open with occasional passers-by, and the noise level was no more than 50 decibels. All participants in Table 1 had never been to the site before the experiment.

In the above indoor space, we designed two paths as the experimental tasks (see Figure 12(b)). Both paths were approximately 100 meters long with four turns (two left, two right). Most of the paths were in 2.4m-wide corridors with automatic ceiling lights placed every five meters. Each path also passed through a 0.9m-wide door. Thus, the two paths were considered to be the same according to [65].

We used blue stickers to label the start point, the four turning points, and the destination of each path. During the experiment, one experimenter followed each participant five meters behind, and controlled the target direction θ_t through an iOS application, which communicated with the feedback device (LightGuide or HapticBag) via bluetooth. The iOS app was built with two user interfaces: (1) a knob for swift direction control and (2) a slider for subtle adjustment (see Figure 12(c)). The experimenter was well-trained to use the iOS app, such that the target direction could be controlled quickly and accurately with a unified strategy. An IMU (inertial measurement unit) sensor was connected to the feedback device to compute users' current orientation θ_c in real time. The feedback device then determined the directional cue according to $\theta_g = \theta_t - \theta_c$, and indicated the cue through lights or vibrations. During the experiment, a second experimenter followed the participant one meter behind to ensure the participant's safety.

7.2 Design and Procedure

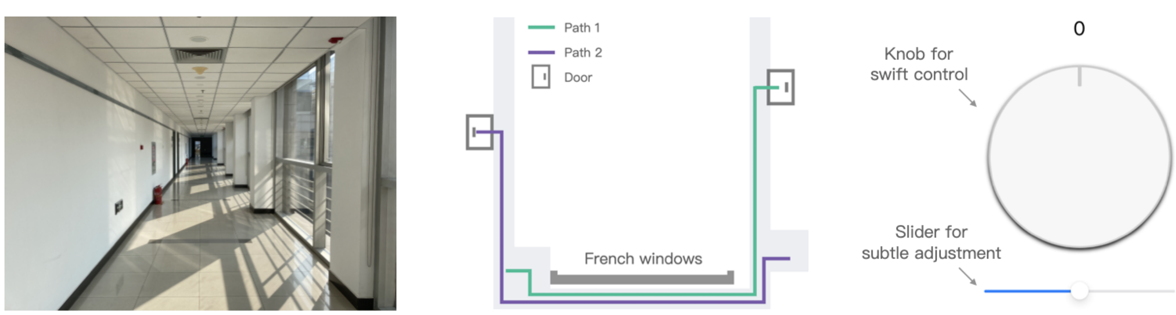
Study 3 adopted a between-subject design, where the two techniques were counterbalanced among the twelve participants. Each participant completed one trial with each technique, and the two paths were randomly paired with the two techniques, such that the participant would not walk along the same path in more than one trial.

During the experiment, participants were allowed to use their mobility aids. As a result, two participants (P5, P11) used the white cane for both techniques, and the other ten participants did not use any other aids. During each trial, if the participant was likely to collide with obstacles (e.g., walls, pedestrians, or doors), we immediately alerted them and brought them back to the closest point on the path centerline (i.e., the centerline of the corridor or the doorway). Two metrics were recorded for each trial: (1) *completion time*: the time it took for the participants to reach the destination (excluding the time it took to bring the participant back on the path). (2) *danger rate*: the number of potential collisions. After the two trials, we conducted an interview with each participant to collect their subjective ratings (as shown in Table 2) and qualitative feedback on the two techniques.

7.3 Results and Findings

A total of 24 trials were conducted, with 12 trials for each technique. Based on the quantitative data and users' qualitative feedback, we have the following findings.

7.3.1 Task Performance. All participants completed the tasks within four minutes when using LightGuide, while the longest completion time for HapticBag was 8.4 minutes (see Figure 13). The mean task completion time for LightGuide (M=186.7s, SD=30.6) was significantly shorter than HapticBag (M=261.5s, SD=114.1) (t_{11} = 2.569, p =



(a) French windows in the experimental site (b) Two experimental paths (c) iOS app to control the target direction

Fig. 12. Apparatus of Study 3.

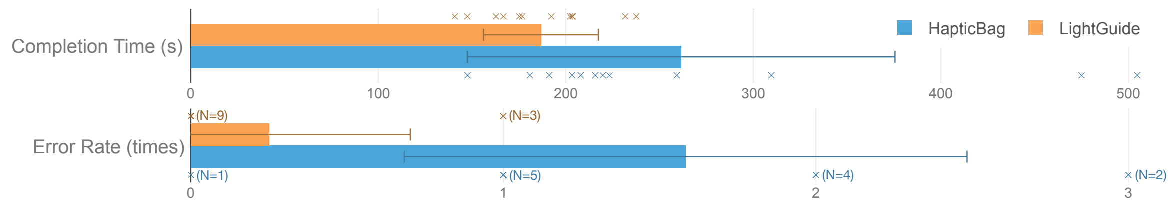


Fig. 13. Task performance in Study 3. Error bars indicate standard deviation. Markers "×" indicate original data.

.026), implying that the participants reached the destination significantly faster with LightGuide. Compared to HapticBag, users' subjective ratings (see Table 2) for LightGuide were also significantly higher on efficiency ($Z = -2.232, p = .026$) and smoothness ($Z = -3.017, p = .003$), implying that LightGuide enabled participants to walk more smoothly (with fewer zigzags) and efficiently (with the pace more close to daily walking speed).

Participants also walked with significantly lower danger rate ($Z = -2.859, p = .004$) when using LightGuide (M=0.25, SD=0.45) compared to HapticBag (M=1.58, SD=0.90). Among the 12 trials with LightGuide, nine trials were completed without any potential collision, while the other three participants had one potential collision. In contrast, as for HapticBag, only one participant (P4) reached the destination without any potential collision. All of the other eleven participants encountered at least one potential collision during walking (see Figure 13). These results indicated that LightGuide enabled participants to walk more safely in real world environments.

7.3.2 Reasons for Potential Collisions. The reasons for potential collisions were different for the two techniques. For HapticBag, most potential collisions occurred while the participants were walking through the 0.9m-wide door (10 times) or when the participants over-adjusted their orientations in the 2.4m-wide corridor (9 times). In contrast, for LightGuide, no collision happened in the corridor, while all three potential collisions occurred when the participants failed to follow the path accurately through the 0.9m-wide door due to their fast walking speed. These findings suggest that LightGuide effectively helped the participants to avoid veering off straight paths and to turn left and right in wide corridors. However, the current design of LightGuide might fail to guide users through narrow spaces (e.g., 0.9m-wide door) safely, because users did not know when to slow down.

In fact, the current design of LightGuide only indicated a safe direction of travel without any alarm of danger. As a result, users might walk too fast in complex situations. To address this issue, alarm of dangerous situations is necessary. Moreover, two participants (P4, P6) also suggested that the directional feedback of LightGuide could be combined with the audio descriptions of the surrounding environment (e.g., "A door three meters ahead on your right" or "Narrow path ahead, take care"), so that they could get better prepared for the upcoming situations.

Table 2. Subjective ratings. (1 = Strongly Disagree, 7 = Strongly Agree)

Metrics	Participant Statements	LightGuide	HapticBag	Significance
Learnability	Technique was easy to learn.	6.83 (SD=0.39)	6.75 (SD=0.62)	$Z = -.577, p = .564$
Low Cognitive Load	Technique required low concentration and mental efforts.	4.17 (SD=1.27)	4.00 (SD=1.54)	$Z = -.364, p = .716$
Smoothness	Technique helped me walk smoothly without zigzags.	6.67 (SD=0.49)	5.25 (SD=0.75)	$Z = -3.017, p = .003$
Efficiency	Technique helped me walk with the same pace as in daily life.	6.75 (SD=0.45)	5.83 (SD=1.26)	$Z = -2.232, p = .026$
Convenience	The cap/backpack would be convenient for daily use.	6.92 (SD=0.29)	6.50 (SD=1.00)	$Z = -1.289, p = .197$
Low Social Concern	I have no concern about being stigmatized using the technique.	6.67 (SD=0.65)	6.83 (SD=0.39)	$Z = -1.000, p = .317$
Willingness to Use	I hope to use the technique in daily life.	6.83 (SD=0.39)	6.58 (SD=1.00)	$Z = -.816, p = .414$

7.3.3 Learnability and Cognitive Load. Subjective ratings on learnability were both high for LightGuide (M=6.83, SD=0.39) and HapticBag (M=6.75, SD=0.62), indicating that both techniques were easy to learn. Most participants agreed that the direction indication of LightGuide was very intuitive (mentioned 10 times) and was similar to their way-finding strategy using lights in real life (4 times).

Interestingly, however, the twelve participants rated differently on the cognitive load of the two techniques, most likely due to their different trust on the visual and haptic information. Five participants (P2, P3, P6, P8, P11) contended that LightGuide required less cognitive load than HapticBag, because "visual cues were more intuitive and reliable" (mentioned 4 times) and "LightGuide indicated the specific turning angle and therefore required less attention to find the target direction" (2 times). In contrast, another five participants (P1, P5, P9, P10, P12) claimed that LightGuide required more cognitive load, because they needed to "stare at the light closely" (mentioned 3 times), to "take time to confirm the direction of the light because visual cues were not always trustworthy" (1 time), and to "distinguish the light from LightGuide and from environments" (1 time). Overall, the cognitive load of LightGuide tended to be lower for participants with higher trust on visual cues.

7.3.4 Convenience in Daily Use. In this work, we implemented LightGuide in the form of a cap, which gained the subjective rating of 6.92 regarding its convenience. Participants mentioned several strengths of caps, including sheltering the sunlight (mentioned 4 times) and protecting the head from collision (1 time). However, caps also had weaknesses, such as blocking users' upper visual field (mentioned 4 times), making some users felt oppressive (3 times), or messing users' hairstyle (1 time). Besides, one participant also mentioned the unwillingness to wear caps with brims. To address these weaknesses, six participants proposed the form of sunglasses, which could shelter users from sunlight without blocking their visual field or making them feel oppressive.

As for social concerns, one participant (P10) whose vision degenerated in the recent three years was worried about the glowing lights being conspicuous and wished the light to be seen only by herself. In contrast, the other eleven participants consistently expressed that they had absolutely no concern about LightGuide being obtrusive. Their primary reason was that "safe mobility is far more essential than being discreet". Moreover, participants stated that the glowing cap could remind other people to take care (mentioned 2 times) and could be fashionable (3 times). Overall, results showed that most participants had no social concern about using LightGuide in real life.

7.3.5 Light Feedback in Real World Environments. In Study 3, all participants were able to easily distinguish the light of LightGuide from lights in the environment, including the automatic ceiling light and the sunlight through French windows. As stated by P1, "the light of LightGuide was relative to my body, while other lights in the environment were anchored in the world. So I could easily distinguish them by slightly turning my head". Participants also rated their willingness to use LightGuide in real life as high (score=6.83).

However, we found three main concerns about light feedback for further investigation: (1) *Fatigue*: After using LightGuide continuously for around half an hour, two participants (P2, P6) felt tired and one participant (P5) felt dizzy. (2) *Interference with Visual Cues from the Environment*: Four participants (P6, P7, P10, P11) were concerned that light feedback might interfere with their environmental perception from visual cues, such as identifying the stairs. (3) *Confusion with Other Lights*: Two participants (P6, P10) also worried that they might confuse the light of LightGuide with other lights in complex environments, such as car lights at night (2 times) or extremely bright sunlight in summer (1 time). To address this, participants proposed that the brightness of lights should be automatically adjusted according to the environment. Overall, these concerns underlined the need to further evaluate the performance of light feedback after long time use and in different real world environments.

7.4 Discussion on LightGuide in Real World Environments

In Study 3, all participants were able to distinguish the light of LightGuide from the sunlight and ceiling lights in the real world environment. Compared to HapticBag, LightGuide enabled users to walk more efficiently (with shorter time and with the pace closer to daily walking speed), smoothly (with fewer zigzags), and safely (with lower danger rate). Subjective feedback indicated that LightGuide was easy to learn and intuitive to use. Moreover, most participants expressed that they had no concern about the glowing cap being obtrusive in daily use.

We found several limitations of LightGuide. First, LightGuide did not alarm users of dangerous situations, and as a result, users might walk too fast in complex environments. Second, LightGuide might cause fatigue after long time use. Third, LightGuide might interfere with users' environmental perception from visual cues. Moreover, further evaluation is needed to assess whether the light of LightGuide could be easily distinguished from other lights in complex environments (e.g., car lights at night).

8 DISCUSSION ON LIGHTGUIDE

Our work proposed a novel feedback design for visually impaired people with light perception and demonstrated its effectiveness through three user studies. In this section, we summarize the strengths and weaknesses of light feedback and discuss several ways to improve the feedback design.

8.1 Visual Conditions Suitable to Use LightGuide

Based on our participants, we report the conditions suitable to use LightGuide in the following aspects:

(1)*Light Perception*: The primary condition to use LightGuide is that the user should be able to perceive the direction of a light. In our studies, all the twelve participants were legally blind, but they could still distinguish the direction of a light, and therefore performed well with LightGuide. LightGuide is also expected to work for people with low vision, because they have better functional vision than people who are blind. However, further investigation is needed to explore whether the light would cause discomfort or fatigue for people with low vision.

(2) *Visual Field*: Another factor affecting the effectiveness of LightGuide is users' visual field. Among the twelve participants, the broadness of their visual field was quite different (see ID_l and ID_r in Table 1), but these participants were all able to use LightGuide as long as they could distinguish whether the light was on their left, front, or right. For example, although P12 could only perceive the light from three LED pixels on his left, he achieved the shortest completion time for complex paths among all participants (see Figure 10(c)).

However, we found that users with depressed central vision had difficultly distinguishing the light in the home direction. For example, three persons were ineligible during the on-site screening for this reason. However, for another three participants who could distinguish the color of lights (P5, P10, P12), the design of *color home indicator* (i.e., the light color in the home direction was different from other directions) effectively compensated for their depressed central vision. In fact, *color home indicator* only required the ability for users to distinguish the difference in two colors, rather than requiring normal color vision of the user. For example, P5 was color blind, but could still tell the difference between two colors.

(3) *Home Direction*: LightGuide also worked well for users who do not perceive the light right in front of their body to be in the center of their visual field (e.g., P9). For these users, the *home direction calibration* in section 3.3.3 effectively solved the above problem.

8.2 Light Feedback Compared to Haptic Feedback

Through three user studies, we explored users' reactions to light feedback when turning in place, when following a path, and when navigating in real world environments. When turning in place, most participants were more sensitive (i.e., with smaller reaction time) to the vibration on shoulders than light feedback. However, as indicated by the settling time and overshoot, LightGuide enabled participants to reach the target direction more quickly and smoothly. In path-following tasks, LightGuide outperformed HapticBag in efficiency (with shorter task completion time and trajectory length), accuracy (with smaller deviation), and smoothness (with fewer zigzags and more even pace). Moreover, LightGuide also helped participants to navigate in real world environments more efficiently (with shorter time) and safely (with lower danger rate). Users' subjective feedback indicated that LightGuide was easy to learn and intuitive to use.

However, compared to haptic feedback which is suitable for almost all visually impaired people, light feedback only works for people with light perception, and has several requirements on users' visual conditions as listed in 8.1. Note that the visual condition of visually impaired people is reported to change over time. Moreover, light feedback also has other weaknesses in that it might cause fatigue after long time use, and might be confused with lights in the environment. These limitations must be considered in further applications of light feedback.

8.3 Further Improvements of LightGuide

Based on our findings in user studies, we report the following directions to improve the design of LightGuide.

(1)*Provision of Additional Warnings when Users Walk Wrongly with Light Feedback*: As indicated by three user studies, visual feedback is not always reliable for all visually impaired users. Study 1 showed that users might turn to the wrong directions at first when the light is in users' peripheral visual field. In Study 2, we found that users with constricted visual field might lose track of the light and walk in wrong directions, resulting in large deviation from path centerline. Study 3 also suggested that users might collide with obstacles when walking too fast through narrow spaces (e.g., the 0.9m-wide door) when using LightGuide.

The above findings highlighted the importance of providing additional alarms through other modalities when users fail to respond correctly to the visual feedback. For example, the sensitive haptic cues at the back of the head could be employed to indicate an emergency stop. Moreover, as suggested by the participants, LightGuide could be combined with the audio descriptions of the complex environment (e.g., "A door three meters ahead on your right" or "Narrow path ahead, take care"), so that users could be well prepared for these complex situations, which also echoed the multi-modal feedback design in [61].

(2) *Improvement of the External Appearance*: The participants mentioned several weaknesses of caps, such as blocking the visual field or making users feel oppressive. To address these, participants suggested the form of sunglasses. However, sunglasses are usually closer to users' eyes than the brim of the cap, which brings up other design questions, such as the proper density and brightness of LED pixels.

(3) *Automatic Brightness Adjustment*: To help users distinguish the light of LightGuide more clearly and also to avoid the light being dazzling in dark environments, the brightness of lights could be automatically adjusted according to the environment, and the effectiveness of such a design needs further evaluation.

(4) *Exploitation of Other Visual Information*: In LightGuide, we utilized the light direction and the light color (for three participants) to indicate directional cues. We also found that some participants could distinguish the shape or size of the light source or recognize the twinkling pattern of the light. These visual information might be further employed to indicate other cues, such as the walking speed.

8.4 Integrating LightGuide into Navigational Systems for Practical Use

This work focuses on exploring light feedback as a new direction indication technique, which could be adopted for practical use in the following ways:

First, LightGuide could be integrated into electronic guidance systems that adopt sensing techniques to plan a safe path and then indicate the path to users through feedback techniques, such as the system in [61]. Given current technology status, SLAM (simultaneous localization and mapping) is considered as the most practicable positioning and path planning solution to integrate with our feedback. SLAM could plan a local safe path in real time and compute users' position and orientation relative to the local path at centimeter level [7, 36]. Given these information, LightGuide could indicate the local safe direction of travel through lights in an intuitive way.

Second, light feedback could also be combined with commercially-available applications that provide remote sighted guidance, such as *Be My Eyes* [16]. In these applications, visually impaired users are grouped with crowd-sourced volunteers who would interpret the video from the users' smartphone camera and provide support through audio feedback. These applications have also been adopted for remote mobility support. However, prior work [29] reported that the effectiveness of remote navigational guidance suffered from inconsistent verbal description strategies. LightGuide can potentially address this problem by providing intuitive directional cues through unified standards. For example, remote volunteers could examine the video from users' smartphone camera, and then control the safe direction of travel with applications similar to Figure 12(c).

Overall, LightGuide has potential to be integrated into several navigational systems, but the actual performance of these systems needs to be evaluated in future work.

9 LIMITATIONS

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

First, Studies 1 and 2 were conducted in a controlled environment with Opti-track, aiming to evaluate the feedback techniques while avoiding errors related to positioning and path planning. However, the performance of both techniques in the controlled environment might be inflated compared to real world environments. Besides, in Studies 1 and 2, users' position was represented by a marker worn on users' head. Heads would shake slightly during walking, which might affect the accuracy of the trajectory length and deviation.

Second, in Study 3, the directional cues were controlled by an experimenter who was well-trained to adjust the cues as quickly and accurately as possible. Although this method did not totally eliminate the imprecision of human control, it was an efficient way to explore users' experience with LightGuide in real world environments before integrating LightGuide with SLAM or other positioning and path-planning systems. Further evaluation of LightGuide when integrated into practical navigational systems is needed.

Third, we only evaluated LightGuide in an indoor real world environment, which leaves the evaluation of LightGuide in outdoor spaces or at night to future work. Moreover, we did not explore the long-term effect of light feedback on users' visual conditions, which should be explored through long-term clinical studies.

Fourth, most of the participants in our user studies were young adults, and we only had one aged participant (P7, aged 64). The effectiveness of light feedback for elder groups needs further evaluation.

10 CONCLUSION

We present LightGuide, a directional feedback technique that indicates a safe direction of travel via the direction of a light within users' visual field. We customized LightGuide to suit users' different visual conditions, and demonstrated the effectiveness of LightGuide in helping users to perceive a direction quickly and smoothly, and to follow a path efficiently, smoothly, and accurately. We hope this work will provide useful insights on visually impaired people's reaction to light feedback in navigational tasks, and also inspire researchers to actively adopt light as feedback in more scenarios.

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A AUTOMATIC COMPUTATION OF THE PERFORMANCE METRICS IN STUDY 1

This section describes how to automatically compute the four metrics in section 5.1, given a user's orientation $\theta_p(t)$ in response to the target turning angle of θ_t.

To automatically compute the reaction time t_r and settling time t_s, we need to quantify the variation of $\theta_p(t)$. Therefore, we introduced $\mathrm{STD}(\tau)$. Given a time τ, $\mathrm{STD}(\tau)$ is defined as the standard deviation of all samples of $\theta_p(t)$ in the last one second before τ. Precisely, $\mathrm{STD}(\tau) = \mathrm{std}(\{\theta_p(t)|t \in [\max(0, \tau - 1), \tau]\})$.

With $\mathrm{STD}(\tau)$ computed for all τ, we then determined t_r and t_s using the following criteria:

(1) Reaction Criterion: t_r is the earliest time τ with $\mathrm{STD}(\tau) > 0.5°$. $t_r = \min\{\tau|\mathrm{STD}(\tau) > 0.5°\}$.

(2) Settling Criterion: t_s is the earliest time τ after t_r with $\mathrm{STD}(\tau) < 2.4°$. $t_s = \min\{\tau|\tau > t_s, \mathrm{STD}(\tau) < 2.4°\}$.

The above 0.5° and 2.4° were determined through pilot tests.

With the settling time t_s known, the steady-state orientation θ_{ss} and steady-state deviation D_{ss} were computed using: $\theta_{ss} = \theta_p(t_s)$, $D_{ss} = |\theta_t - \theta_{ss}|$.

The maximum overshoot OS is computed by: $OS = |\theta_{peak} - \theta_{ss}|$, where $\theta_{peak} = \begin{cases} \max\{\theta_p(t)|t < t_s\}, & \text{if } \theta_t > 0 \\ \min\{\theta_p(t)|t < t_s\}, & \text{if } \theta_t < 0 \end{cases}$.