Virtual Paving: Rendering a Smooth Path for People with Visual Impairment through Vibrotactile and Audio Feedback

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Fig. 1. (A) Examples of problems with tactile pavings: (1) obstructed by permanent constructions, (2) misused as decorations, and (3) obstructed by trash bins and bicycles. (B) The concept of Virtual Paving, a method of rendering a collision-free and smooth path to visually impaired people through non-visual feedback. This work focuses on its feedback design.

Tactile pavings are public works for visually impaired people, designed to indicate a particular path to follow by providing haptic cues underfoot. However, they face many limitations such as installation errors, obstructions, degradation, and limited coverage. To address these issues, we propose Virtual Paving, which aims to assist independent navigation by rendering a smooth path to visually impaired people through multi-modal feedback. This work assumes that a path has been planned to avoid obstacles and focuses on the feedback design to guide users along the path safely, smoothly, and efficiently. Firstly, we extracted the design guidelines of Virtual Paving based on an investigation into visually impaired people's current practices and issues with tactile pavings. Next, we developed a multi-modal solution through co-design and evaluation with visually impaired users. This solution included (1) vibrotactile feedback on the shoulders and waist to give readily-perceivable directional cues and (2) audio feedback to describe road conditions ahead of the user. Finally, we evaluated the proposed solution through user tests. Guided by the designed feedback, 16 visually impaired participants successfully completed 127 out of 128 trials with 2.1m-wide basic paths, including straight and curved paths. Subjective feedback indicated that our

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solution to render Virtual Paving was easy for users to learn, and it also enabled them to walk smoothly. The feasibility and potential limitations for Virtual Paving to support independent navigation in real environments are discussed.

CCS Concepts: • **Human-centered computing → Accessibility technologies**; *Haptic devices*; Empirical studies in accessibility.

Additional Key Words and Phrases: accessibility; visual impairment; tactile paving; path following; vibrotactile feedback; auditory feedback

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1 INTRODUCTION

According to the World Health Organization, an estimated 285 million people worldwide are visually impaired, including 39 million people who are blind [75]. This vast population is faced with daily challenges in mobility tasks, and, as a consequence, more than 30% of people who are blind do not travel outdoors independently [9].

Tactile pavings are a major part of the public infrastructure for visually impaired people, supporting navigation by suggesting a path to follow through haptic cues underfoot [54]. Compared to canes and guide dogs, which only help users avoid nearby obstacles, tactile pavings help users directly find a potentially collision-free path [44, 59]. They have been shown to be effective in helping visually impaired people maintain a stable walking direction, avoid zigzags [50], and navigate through large open spaces or complex pedestrian environments [54].

Tactile pavings have been widely installed throughout the leading cities in Asia and mainly around railway and subway stations in Europe, Pan-America, and Oceania [44]. While, in Japan, 70% of visually impaired people reported using sidewalk tactile pavings [32], in many other countries, their usability is greatly affected by installation errors [22, 44, 45], inconsistent standards [36], and obstructions [80]. Furthermore, tactile pavings cannot be installed everywhere, such as at crossroads or in many indoor areas [45]. Likely due to the above issues, it has been reported that the majority of visually impaired people in China rarely use tactile pavings [80].

In this paper, we propose Virtual Paving, which aims to support independent navigation by "rendering" a safe and smooth path to visually impaired people through non-visual feedback (see Figure 1 (B)). Conceptually, Virtual Paving not only inherits the benefit of tactile pavings, but also saves the cost of physical deployment and maintenance. Moreover, Virtual Paving is not limited to only certain areas and can plan paths with smooth turns.

Virtual Paving relies on three techniques: *sensing*, *planning*, and *rendering* (see Figure 2). These techniques work together as follows: First, environmental data for the users' surroundings are collected in real time through sensors, such as cameras or lidars. Second, a smooth and collision-free path is computed within the free space to avoid any obstacles. Finally, information about this path is provided to visually impaired users through non-visual feedback. This work focuses on designing a user-friendly feedback solution to render Virtual Paving. Design guidelines on sensing and planning are also provided, though not implemented here.

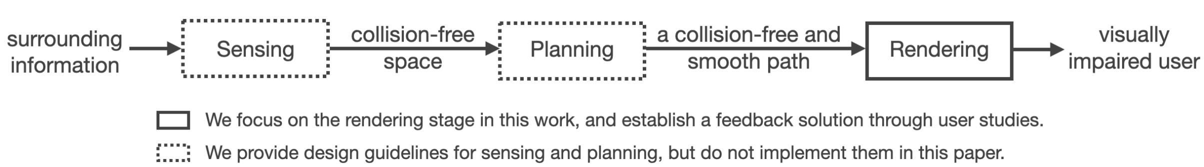


Fig. 2. The system structure of Virtual Paving with the focus of this work highlighted.

In order to optimize the feedback solution, there are several human-factor challenges to be considered, including how to design the path to make it easy to follow and how to provide the information needed by visually impaired users to follow that path. To address these, we conducted three user studies. Firstly, we conducted semi-structured interviews with visually impaired people to understand their current practices and difficulties when using tactile pavings or when completing path-following tasks. Based on the findings from these interviews, we summarized the design guidelines of Virtual Paving and designed a practical method to optimize the feedback solution.

Next, to find a user-friendly feedback modality to render Virtual Paving, we conducted co-design with visually impaired people to explore the design space and tested possible modalities in navigational tasks. Based on the co-design activities and user tests, we designed a multi-modal feedback solution that combines (1) vibrotactile feedback on the shoulders and waist to give readily-perceivable directional cues (e.g. *stop*, *turn left*) and (2) audio feedback to describe road conditions ahead of the user (e.g. *"The road ahead is smooth."*). We also designed the strategy to indicate directional cues, with the goal to enable users to walk smoothly and efficiently. The multi-modal solution was integrated into a wearable backpack for the convenience of daily use.

Finally, we evaluated our multi-modal solution in navigational tasks in a lab environment. Four basic path types were selected for evaluation: straight paths, gentle turns, sharp turns, and continuous turns. Guided by the vibrotactile and auditory feedback on 2.1m-wide basic paths, 16 visually impaired participants completed 127 out of 128 trials. Subjective feedback indicated that our solution was easy for users to learn and enabled them to walk smoothly. Based on the results of our user studies and related literature, we further discussed the feasibility and some potential limitations for Virtual Paving to support independent navigation in real environments.

Our contributions with this paper are three-fold:

- We investigated the current practices and issues of visually impaired people with tactile pavings and path-following tasks.
- We proposed a set of guidelines to design Virtual Paving and an approach to optimize the feedback solution.
- We designed and implemented a multi-modal feedback solution to render Virtual Paving, based on the co-design and evaluation with visually impaired people. Our feedback solution enabled visually impaired users to navigate along paths within 2.1m width smoothly.

2 RELATED WORK

The key task to render Virtual Paving is to guide users along a continuous path smoothly and efficiently. It is, in essence, a path-following task [66]. Therefore, in exploring the literature, we first reviewed existing systems that support path-following tasks for visually impaired people, and, based on these, we identified the research gaps. We also reviewed non-visual feedback techniques that could be adopted to indicate navigational cues.

2.1 Guidance Systems to Support Path-following Tasks for Visually Impaired People

Existing guidance systems primarily support path-following tasks for visually impaired people in two ways: (1) by providing turn-by-turn guidance or (2) by guiding users along a collision-free path.

In turn-by-turn guidance, users are informed along the path where and how to turn (e.g. "turn slightly to the left") [2]. Existing systems have adopted auditory [2, 16, 56] or haptic [3] feedback to provide turn-by-turn guidance. Several studies additionally explored the personalized models of human reaction under turn-by-turn guidance [47, 48]. Unfortunately, turn-by-turn guidance systems rarely help users avoid obstacles, and, guided by these systems, visually impaired users have been found to turn at the wrong locations or in wrong directions [47].

Contrasting the primarily turn-by-turn guidance systems above, another type [15, 33, 34, 39, 45, 72] supports path-following by guiding visually impaired people along a collision-free path. In some systems [34, 45], users were informed of a safe direction; the direction was only computed to ensure *local* safety and could not help users avoid detours. In other systems [15, 33, 39], which modeled the safe path by a series of waypoints and guided users towards each successively, users reported walking in zigzag patterns and easily getting confused by the frequently changing signals for them to correct their orientation [15]. Possible reasons for the latter set of issues include the path being modelled in a piece-wise linear way and the instructional cues being generated based only on the angle between users' heading and the path tangent. Some systems [19, 49] aimed to avoid this unintended zigzag issue when following a straight path but were not yet tested with curved paths.

Overall, although numerous systems have been proposed to support path-following tasks, few existing systems successfully enabled users to follow a continuous path (with both straight paths and turns) smoothly and efficiently. We, therefore, addressed this gap in the literature by establishing a feedback solution to render Virtual Paving in a user-friendly way. A review of electronic guidance systems [18] summarizes seven issues related to their low adoption rate, with three of these being human-factor issues. Specifically, these were problems of systems being invasive, causing cognitive overload, or requiring long period of training. We, thus, carefully designed and validated our feedback solution to overcome these important human-factor issues.

2.2 Non-visual Feedback Modalities to Provide Navigational Cues

With respect to selecting a feedback solution to render Virtual Paving, important design factors include the modeling of paths, the feedback modality to interface with users, and the strategy for when and how to indicate cues. This work aims to optimize the overall guidance solution based on a feedback modality selected from existing options and does not attempt to propose a novel modality. In prior works, haptic and auditory feedback were the most common modalities through which visually impaired people interfaced with electronic guidance systems [14]. To inspire our design, the capabilities and design considerations of these two modalities are reviewed.

2.2.1 Audio Feedback. In existing navigation systems, audio has been used to convey information in three main ways: spatial audio [1, 6, 29, 31, 35, 40, 43, 55], acoustic patterns [58], and audio descriptions [21, 34]. Both spatial audio and acoustic patterns can be used to provide non-verbal information, but previous research has shown evidence that spatial audio is more intuitive to perceive when indicating directions [14]. Audio descriptions using verbal cues can also provide environmental details, but the level of detail needs to be carefully considered during design [38]. Additionally, there is evidence that many visually impaired people prefer not to use earphones, citing that the earphones might interfere with their perception of acoustic cues from the environment [12, 14, 69]. To address this issue, some work [73] adopted bone conduction headphones to provide auditory feedback.

2.2.2 Haptic Feedback. There are three main forms of haptic feedback adopted in existing guidance systems: on-body vibrations [8, 10, 11, 13, 24, 30, 33, 41, 42, 45, 57, 64, 65, 67, 70, 71, 74], vibrations from handheld devices [7, 23, 37, 68, 72], and braille displays [4, 74]. Among the three forms, on-body vibrations have gained the widest adoption, likely due to its feedback being readily perceivable without occupying the user's hands, its ability to not interfere with user's inherent perception of the environment, and its easy integration into wearable devices.

The selection of body location is a central concern for the design of on-body haptic interfaces. Haptic perception has been shown to vary in resolution and sensitivity among the different body locations, but studies have reported different results [28, 42], an inconsistency which is potentially explained by their differing methods for actuator placement. Prior work has explored the positioning on the back [13, 65], abdomen and waist [11, 24, 30, 33, 67, 72, 74], hand and wrist [41, 42, 61, 62], as well as foot and sole [57, 64, 70, 71] to receive haptic navigational cues. One study [42] compared the recognition accuracy of four distinct cues among waist, wrist, and foot but found no significant differences.

Another important consideration in the design of haptic feedback systems is the mapping between vibration patterns and the intended instructional cues. Several studies [10, 13, 42, 70] have explored wave-like vibration patterns where several motors vibrate in sequence rather than just a single motor vibrating at a single point. However, wave-like patterns are reported to underperform fixed-point stimuli around both the foot [70] and waist [10]. Other studies have tried to divide the area ahead of the user into multiple sub-areas (e.g., five sections in [30], ten in [41], and a four by four 2-D array in [11]) and encode the vibration for each area with different cues. However, when the vicinity is divided into only five sub-areas and encoded with five motors on a belt, the recognition accuracy was shown to be a low value of 83.4% [45].

In summary, the literature review suggests that the principle design concerns of on-body vibrotactile feedback are the selection of body positions, the vibration patterns, and the cue encoding approaches. Since these factors are shown to be interdependent, they should be individually optimized for each design.

3 STUDY 1: INVESTIGATING PRACTICES WITH THE TACTILE PAVING AND PATH FOLLOWING

The ultimate goal of Virtual Paving is to guide visually impaired users along a collision-free path in a user-friendly way. To optimize the user experience, users' current practices and challenges should be investigated. Although prior works provided some insights on the general challenges [53, 63, 76, 77, 79] and information needs [81] of visually impaired users related to mobility, few studies focused on visually impaired people's current practices and limitations in using tactile pavings and in completing path-following tasks. Therefore, we conducted semi-structured interviews with visually impaired people in order to investigate the aforementioned topics.

3.1 Participants

Twelve visually impaired participants were recruited (seven males, five females), with their ages ranging from 19 to 38 (mean = 26.1). Among them, eight participants were completely blind, two (P1, P12) could only sense light, and the remaining two (P6, P10) experienced low vision. As for mobility aids, eight participants used white canes on a daily basis as their only helper tool, two (P3, P4) alternately used white canes and guide dogs, while the two users with low vision (P6, P10) seldom used mobility aids. No participants had ever used any electronic travelling aids in daily life, with only two participants having previous experience testing other devices. Table 3 shows their detailed information. All participants were recruited from a supporting community for visually impaired people in Beijing based on two criteria: being visually impaired and having lived in a city with tactile pavings in the last year. For each potential participant, we conducted a brief phone screening to ensure they met criteria.

3.2 Procedure

We conducted a face-to-face interview with each participant. During the interview, we first collected their demographic information and then encouraged them to discuss their experiences and opinions via the following questions:

(1) *Frequency of Use*: Have you used tactile pavings in the last year? How often did you use them?
(2) *Practices and Issues with Tactile Pavings*: Recall one or more recent experiences during which you used a tactile paving. Could you describe how you used it? What difficulties did you encounter during its use?
(3) *Reasons for not Using Tactile Pavings*: Why have you not used tactile pavings in the last year?
(4) *Practices and Issues with Path-following Tasks*: Recall one or more recent events during which you needed to reach a destination. How did you finish this task? Did any tools or technologies help you finish this task? Did any problems occur during this experience?
(5) *Requirements of Electronic Guidance Devices*: What are your requirements for electronic guidance devices?

To help participants recall previous experiences, we asked about concrete situations, such as, "Have you gone to a bank in the last month? How did you reach it?". When interesting points came up, we followed up with questions about additional details. Each interview lasted from 30 to 45 minutes. All interviews were conducted in Mandarin, recorded by written notes and audio, and later translated into English. All data were classified into the above topics, which informed our findings.

3.3 Key Findings

3.3.1 Reasons to Use or Not Use Tactile Pavings: Concerns about Safety, Ease of Use, and Efficiency. All participants resided in Beijing the year before the interview and were aware that tactile pavings had been installed on most sidewalks. However, only one participant (P7) had used tactile pavings several times a week, four participants used tactile pavings less than once a month, and seven participants never used them the year before the interview. Compared to the 70% of visually impaired people using tactile pavings on sidewalks in Japan [32], tactile pavings in Beijing were used with notably less frequency by our participants. We identified their concerns as follows:

Safety was the primary concern for participants who seldom or never used tactile pavings. Specifically, eleven out of twelve participants stated that they felt unsafe using tactile pavings because of previous accidents during use, predominantly caused by high-hanging (mentioned 7 times), shallow (5 times), or moving (4 times) obstacles.

Besides safety, **ease of use** was also an important concern. For instance, eight participants stated that tactile pavings were hard to find in large open halls (7 times), at crossroads (5 times), or in subway stations (4 times). Six participants also complained that many of the textured tiles on sidewalks were worn out and hard to feel. Therefore, the usability of tactile pavings is greatly limited by the difficulty to find them or to feel the textures.

Additionally, **efficiency** is another factor in determining whether or not to use tactile pavings. Of all participants, only one participant (P7) used tactile pavings on a weekly basis, mostly in the subway station closest to her home, and offered the following reason: *"In that station, the textured tiles just start from the exit of the elevator door, so it's very efficient to follow the paving."* For the four participants (P1, P4, P6, P11) who used tactile pavings less than once a month, subway stations were also the places with highest frequency of use; however, none of these participants intentionally sought out the tactile pavings, and P1 reported the following:

> *"Although it would be easier to follow the tactile paving, I could still navigate without it since I am pretty familiar with the route. However, if I tried to find the tactile pavings on purpose, I might make detours, and it would also be just a waste of time and effort."* (P1)

Altogether, our findings revealed three main concerns affecting the usability of tactile pavings: safety, ease of use, and efficiency. These factors should also be considered to design a system that supports path-following tasks.

3.3.2 Issues with the Use of Tactile Pavings: Deviation Threshold, Path Continuity, and Movement Smoothness. Zero of the five participants who had used tactile pavings in the last year would put both feet on the pavings, and their common reason was that the pavings were too narrow in width. Instead, four participants (P1, P4, P6, P7) walked with a single foot on the paving, and the remaining participant (P11) only used a white cane to feel the textures. The width of tactile pavings acts as a **deviation threshold**, which determines when users will encounter cues to adjust their paths. In the case of current tactile pavings, the threshold was too small; therefore, the users manually enlarged this threshold using their single-foot-on strategy. This issue highlighted the importance of selecting a proper deviation threshold in the guidance systems, which is further discussed in section 4.4.

Besides the deviation threshold, **path continuity** also affects users' experiences during path-following tasks. Specifically, eight participants stated that they easily became confused about the direction in which to walk when the paths were broken halfway. For example, P11 recalled his own experience:

> *"There are many times when I was walking along the tactile pavings, and suddenly there were no more textured tiles ahead. I got really confused and didn't know where to go next."* (P11)

As suggested, discontinuities in paths have the potential to greatly reduce the usability of tactile pavings. This finding emphasizes two design implications for systems that facilitate path-following tasks: the path should be planned in a continuous manner (i.e., without interruption by obstacles), and the direction of travel should be indicated in real time without sudden change. Otherwise, users could potentially get confused.

Moreover, three participants (P4, P5, P11) expressed their common hope to be able to walk smoothly "like sighted people." For example, P4 recalled one unpleasant experience during the use of tactile pavings:

> *"While I was standing on a warning [turning] block and probing for the correct direction to turn to, several boys ran by me and laughed at me, saying: 'Look! That man walks just like a robot!' I felt quite annoyed but also ashamed. I just wish I could walk like sighted people one day."* (P4)

3.3.3 Information Needs for Path-following: A Safe Direction of Travel, and Awareness of Surroundings. The **safe direction of travel** is the most vital information needed to support safe path-following tasks, and the lack of directional cues in large open areas (mentioned 7 times) make path-finding especially difficult. For example, P1 stated the difficulty as follows: *"I entered an open hall and tried to find an elevator. However, there were hardly any indications, and I didn't know where to walk."*

In addition to directional cues, **awareness of surroundings** was a need commonly indicated by participants. Specifically, eight participants expressed their requirements to be informed of complex situations, including surface level changes (mentioned 7 times), uneven surfaces (5 times), complex pedestrian environments (3 times), and complex obstacles (2 times). Even if existing tools were able to help manage these situations, an awareness of surroundings could have better prepared them mentally. For example, P8 stated:

> *"Passing by a row of bicycles was especially difficult. The space was narrow.... Although I could eventually manage with my cane, it still took time for me to figure out what situation I had been in. I wish I could have known it beforehand."* (P8)

There are two key information needs to support path-following tasks. First, it is fundamental to indicate a safe direction of travel that is collision-free and leading to the destination. Second, to enhance users' awareness of surroundings, environmental descriptions could be additionally provided in complex situations.

3.3.4 Requirements of Assistive Guidance Systems. During discussions, participants expressed several consistent requirements for assistive guidance devices, including reliability (mentioned 12 times), unobtrusiveness (12 times), portability (12 times), ease of use (11 times), ease of learning (11 times), comfort (9 times), endurability (7 times), and duration of battery life (6 times). The following statements specifically exemplify the participants' common desire for the assistive system to be unobtrusive:

> *"In my opinion, the device must not be conspicuous. Once I tested a pair of head mounted glasses (as navigation aids), but it was just too heavy and eye-catching, and I would never wear it."* (P10)
>
> *"I hope I could use the system without a white cane ...... Some people were just mean and impolite, and they made fun of me when I used the cane."* (P9)

4 DESIGN GUIDELINES OF VIRTUAL PAVING

From our findings in study 1, we extracted the key design goals of Virtual Paving in the following four aspects:

- **Safe**: The system should ensure safety by avoiding nearby obstacles and warning about potential hazards.
- **Smooth**: The system should enable users to walk smoothly (i.e., to not slow down or stop during walking).
- **Efficient**: The system should enable users to walk efficiently (i.e., to not detour or walk in zigzag patterns).
- **Supporting Ordinariness**: The system should be unobtrusive in appearance and also capable of supporting visually impaired users in walking smoothly, like sighted people.

Based on the above goals and findings, we summarize the design guidelines in the subsequent sections.

4.1 Selection of Sensing Techniques

In this section, we provide the design guidelines on the selection of sensing techniques. The implementation of the sensing stage is not covered in this work.

To support safe navigation, the selected sensing technique should be effective in detecting obstacles commonly encountered by visually impaired users, including (1) high-hanging and chest-level obstacles, such as branches and billboards, (2) low obstacles, such as puddles, (3) hollow obstacles, such as fences and wire nettings, (4) moving obstacles, including pedestrians and vehicles, and (5) surface level changes, such as curbs or stairs.

Furthermore, for the system to work accurately in real time, the sensing technique should fulfill the following requirements: low delay, high resolution, high accuracy, and high robustness. Prior work in sensing adopted a wide range of devices, such as infrared sensors, sonars, lidars, and RGB-Depth cameras [30]. Recently, progress in computer vision has also provided several solutions for obstacle detection and motion planning [20, 27, 52, 78], which could be further adopted in the sensing stage of Virtual Paving.

4.2 Path Characteristics for Planning

Based on our findings in section 3.3.2, we distilled **path continuity**, **path smoothness**, and **path width** as three path characteristics to be considered during path planning. Their possible design options are illustrated in Figure 3. We summarized the criteria used to select these characteristics as follows: First, the path should be planned in a collision-free manner (i.e., not interrupted by obstacles) so that users can walk without extra tools for obstacle avoidance. Second, the path should be planned smoothly to support smooth movements of users. Specifically, the path should avoid sudden changes in direction and have a minimum number of sharp turns. Third, the path width should be selected to fit within the collision-free space and also to be compatible with the designed feedback solution, which is further explained in section 4.4.

4.3 Feedback Solutions for Rendering

To reach a proper feedback solution to render Virtual Paving, the main issues to be considered are as follows:

First, the **instructional cues** should be designed to fulfill the **information needs** of visually impaired users during path-following tasks and also to avoid cognitive overload. Based on our findings in section 3.3.3, it is essential to provide *directional cues* that indicate the safe direction of travel. Additionally, to enhance users' awareness of surroundings, the system could optionally provide *environmental cues* in complex situations, such as, "a row of bikes on your left" or, "uneven roads ahead, take care."

Second, to provide the instructional cues, an appropriate **feedback modality** (e.g., haptic/auditory feedback) should be selected under the following requirements: (1) easy to learn, (2) requiring low cognitive load, (3) able to provide readily perceivable cues, and (4) able to be integrated into unobtrusive and portable devices. These requirements are distilled from the findings in section 3.3.4. The first two requirements have also been frequently summarized in prior works [12, 18].

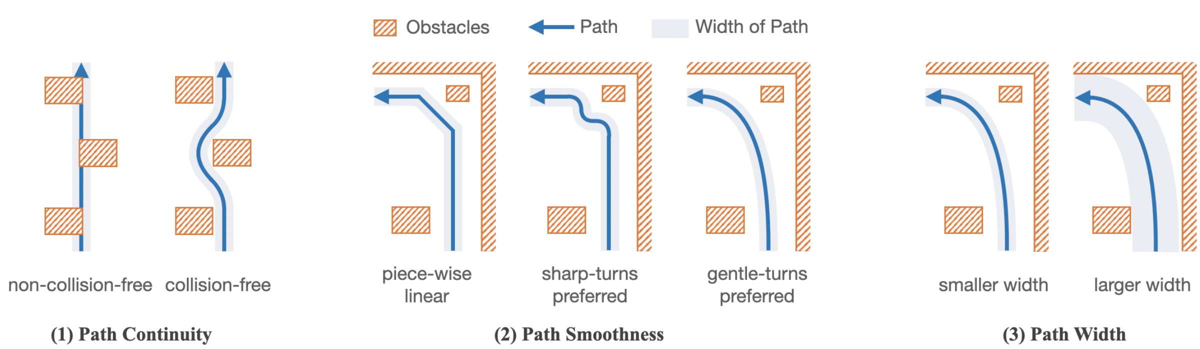


Fig. 3. Demonstrations of the path characteristics of Virtual Paving to be considered during path planning.

Third, the **cue generation strategy** on when and how to provide the instructional cues should be designed with the goal to enable users to walk smoothly and efficiently within the planned path. The concrete approach to design the cue generation strategy is detailed in section 4.4.

4.4 A Practical Method to Optimize the Feedback Solution

The above guidelines provide some general rules on the design of Virtual Paving. In this section, a practical method is provided to establish a feedback solution that ensures safety, smoothness, and efficiency.

Any guidance system has its safety limit. For example, if a system has only been validated in its ability to guide users to walk within a 1.2m wide path, then this system might not ensure safe navigation through a 1.0m wide corridor. Therefore, to design Virtual Paving for real world usage, designers need to first specify the expected **safety limit** W_{safe} of the system, which is defined as the minimum width of the area from which the users will not deviate when guided by the system. A system with a smaller safety limit could ensure safe navigation through narrower spaces, and, therefore, could be generalized to other applications.

To fulfill a given safety limit, a proper cue generation strategy should be established. To clarify the design considerations, we adopted the following naive strategy as an example: If users walked outside of an area with a width of W_{thres}, they would be instructed to turn left/right. Otherwise, no instructions would be provided. In this strategy, it is crucial to select a proper deviation threshold W_{thres}. First, W_{thres} should be selected to fulfill the safety limit W_{safe}. It was assumed that when guided by the strategy, users could be kept within an area with a width of W_{bound}. W_{thres} must be selected so that $W_{\text{thres}} < W_{\text{bound}} \leq W_{\text{safe}}$. Second, the selection of W_{thres} will also affect users' walking smoothness and efficiency. With a small W_{thres} (e.g., 0.5m), users might be instructed to adjust their orientations more frequently, resulting in low smoothness and efficiency. In contrast, with a large W_{thres} (e.g., 10m), users could walk smoothly; however, there would also be a high probability that users would deviate from the path, leading to low efficiency. Therefore, to ensure both smoothness and efficiency, a moderate value of W_{thres} should be selected. Overall, **the design rule of the cue generation strategy** is to optimize users' walking smoothness and efficiency under the strict safety constraints: $W_{\text{bound}} \leq W_{\text{safe}}$. Note that the above naive strategy was used for demonstration only. In actual design practices, the strategy could be a function of different user states (e.g., the strategy in section 6.1), and the optimal strategy could be approximated to by fine-tuning and validation through iterative user tests. The procedure to establish a proper strategy in this work is summarized in section 8.

Based on the above analysis, we derived a method to establish an appropriate feedback design as follows:

(1) Specify the expected *safety limit* W_{safe} of the Virtual Paving system.
(2) Find the proper *feedback modality* and *cues* so users can readily perceive and react to the cues.
(3) Establish a proper *cue generation strategy* through user tests with the goal of optimizing users' walking smoothness and efficiency under the strict safety constraints $W_{\text{bound}} \leq W_{\text{safe}}$.

After establishing a feedback solution using the above method, the **valid range of the path width** during planning could be formulated as $W \geq W_{\text{safe}}$, where W is the width of the planned path.

4.5 Methodology of the Following Studies in this Work

The method in section 4.4 is adopted in the following studies of this work. Considering that the minimum width of indoor corridors in Chinese standard is 2.1m [46], we selected $W_{\text{safe}} = 2.1$m in this particular work, with the goal to ensure safe navigation through indoor corridors built with Chinese standards.

The objectives of the subsequent user studies are as follows: In Study 2, we aimed to find a proper feedback modality to render Virtual Paving. Next, we presented the overall feedback solution, including the *feedback modality* and the *cue generation strategy* that optimizes walking smoothness and efficiency. Finally, in Study 3, we aimed to validate the designed feedback solution and report its safety limit.

5 STUDY 2: EXPLORING PROPER FEEDBACK MODALITIES TO RENDER VIRTUAL PAVING

The aim of this study was to determine the ideal *feedback modalities* to render Virtual Paving. To this end, a rapid-prototyping co-design workshop was conducted with visually impaired people. This resulted in the identification of four promising modalities which were tested for performance in navigational tasks.

5.1 Pilot Study: Finding Promising Feedback Modalities in a Rapid-Prototyping Co-design Workshop

5.1.1 Participants and Apparatus. Three researchers and five visually impaired users (see Table 3) participated in the workshop. To provide on-body vibrotactile feedback, four modular prototypes were developed (see Figure 4). In each, a coin-sized motor was used to provide vibrations. The vibrations were triggered wirelessly from a mobile phone. For auditory feedback, a mobile application was developed with Unity 2019, which was capable of playing both synthesized spatial audio and non-spatial verbal audio through either earphones or speakers.

5.1.2 Procedure. First, the participants tested vibrations on the various body positions, accommodated by our modular prototypes, and listened to the spatial audio through earphones. Second, we brainstormed with the users on the following topics: (1) the advantages and disadvantages of haptic and audio feedback in their daily life, (2) the possible body positions for on-body vibrations, (3) the design of instructional cues that might facilitate the smooth walking experience, and (4) the promising feedback modalities to provide the instructional cues. From this brainstorming, we proposed six feedback modalities (see Table 1). Next, we tested the recognition accuracy of cues provided by all six modalities. This test adopted a within-subject design with randomized partial counterbalancing. In each trial, a visually impaired participant was asked to first stand at a fixed position then move according to a cue randomly selected from the four directional cues. The cue encoding for each modality is specified in Table 1. Each trial was marked as positive if the participant moved correctly within 4 seconds. For each modality, we conducted 100 trials (20 trials × 5 users) and reported the Accuracy = $\frac{\text{Count of positive trials}}{\text{Count of all trials}}$ (Table 1). Finally, we collected the participants' opinions and preferences of each modality. The workshop lasted around 4.5 hours. Based on audio recordings and written notes from the design stages, we established four promising feedback modalities. Their design specifications are reported in section 5.2.

5.2 Design Specifications of Four Promising Feedback Modalities

Four modalities were identified as the most promising: (1) verbal audio feedback and vibrotactile feedback on the (2) shoulders, (3) wrists, and (4) ankles. In this section, design specifications of each modality are clarified.

5.2.1 Instructional Cues. In all modalities, the 4-directional cues (i.e., *walk straight*, *turn left*, *turn right*, and *stop*) were adopted due to high recognition accuracy (see Table 1). Although multi-directional cues have the potential to indicate more detailed directions, prior research has reported a limited recognition accuracy of 83.4% for 5-directional cues indicated on a haptic belt [45]. Therefore, the 4-directional cues were selected to ensure

Table 1. The six proposed feedback modalities in the pilot co-design workshop. Four promising modalities are marked with *.

	Vibrotactile Feedback				**Audio Feedback**	
	Shoulders*	**Wrists***	**Ankles***	Abdomen	Spatial Audio	**Non-spatial Verbal Audio***
Accuracy	100% (100/100)	100% (100/100)	97% (97/100)	92% (92/100)	89% (89/100)	94% (94/100)
Cue Encodings	(1) In vibrotactile feedback, "*turn left*" and "*turn right*" are encoded with vibrations on various lateral body positions, while "*walk straight*" and "*stop*" are always encoded with vibrations on the front/back of the waist. (2) In spatial audio feedback, virtual audio sources are generated at the front, back, left, and right of the user. (3) In verbal auditory feedback, the directional cues are verbalized as "*turn left*," "*turn right*," "*walk straight*," and "*stop*."					

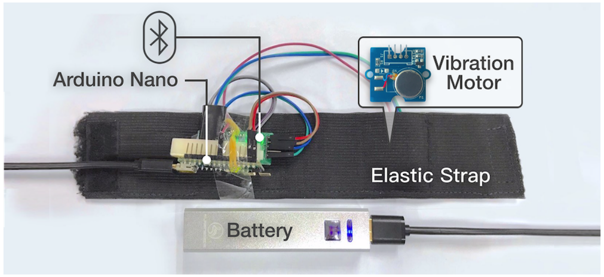


Fig. 4. Prototype for on-body vibrations in Study 2.

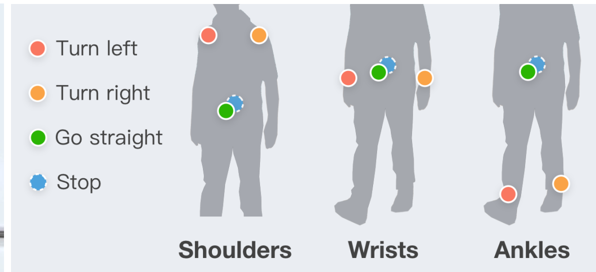


Fig. 5. Cue encoding for three on-body vibrotactile modalities.

that the cues could be correctly and readily perceived. In this paper, "*turn left*" and "*turn right*" will be used interchangeably with "orientation-adjusting cues."

5.2.2 Three Vibrotactile Modalities. As shown in Figure 5, three on-body vibrotactile modalities were selected with the following design considerations:

(1) *Vibration Pattern and Intensity*: The vibration pattern and intensity adopted in the three vibrotactile modalities were confirmed by all participants to be easily-perceivable and comfortable. Specifically, the motor was periodically turned on for T_{on} = 500ms with a pulse-width modulated signal of duty cycle D_{on} = 50% and then turned off for T_{off} = 500ms. All future references to a haptic feedback used the above-mentioned pattern.

(2) *Use of the Waist to Receive "Walk Straight" and "Stop" Cues*: As preferred by all five participants in the workshop, these two cues were intuitively encoded with vibrations on the front/back of the waist, so that the two cues could be distinctly recognized and would not be confused with orientation-adjusting cues.

(3) *Use of Shoulders, Wrists, and Ankles for Orientation-Adjusting Cues*: These three positions were selected to receive "*turn left/right*" for two reasons: First, vibrations on these positions could be readily perceived with high recognition accuracy (see Table 1), allowing users to adjust their orientations smoothly. Second, these positions allowed feedback from easily wearable devices.

(4) *Continual Application of Orientation-Adjusting Cues*: To support the smooth movements of visually impaired users, the vibrotactile cues for"*turn left*" and "*turn right*" are designed to be continually applied (with the above-mentioned vibration pattern) until the target direction is reached. With this design, users would not need to stop to find the target direction but could, instead, adjust their orientations while continuing to walk.

5.2.3 Verbal Audio Feedback Modality. In addition to the haptic feedback, the 4-directional cues were directly verbalized as: "*walk straight*," "*turn left*," "*turn right*," and "*stop*." Compared to spatial audio, verbal audio cues could be recognized with higher accuracy (see Table 1). They could also be supported by devices with a single speaker, such as mobile phones, an especially useful feature when considering that of the five visually impaired users in our workshop, all expressed their unwillingness to wear earphones during navigation.

5.3 Experimental Design: Testing the Four Modalities in Navigational Tasks

5.3.1 Test Paths and Environment. Four types of basic paths for daily navigational scenarios were adapted for our experimental tasks: *straight paths*, *gentle turns*, *sharp turns*, and *continuous turns* (see Figure 6 (a)). While these four types may not cover all scenarios, they are highly representative of many daily routes. With the rationale stated in section 4.5 for selecting an expected safety limit, participants were expected to follow the paths in all tasks within a 2.1m-wide zone.

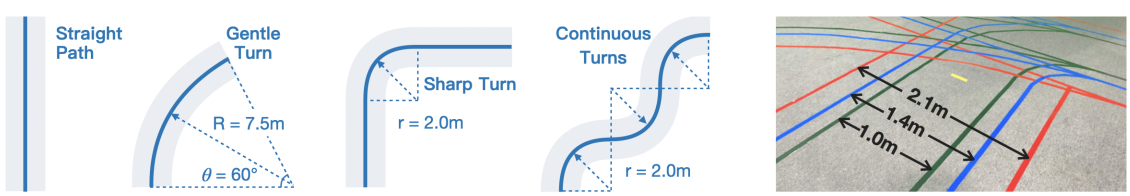
The specifications of the various paths used in Study 2 were as follows: The *straight paths* were 10m long. The *sharp turns* and *gentle turns* had centerline radius of $R = 7.5m$ and $r = 2.0m$ respectively, and each came in left and right turn variations, which were counterbalanced between the participants. *Continuous turns* consisted of three sharp turns with alternating directions (see Figure 6).

Previous research has reported the effects of environmental factors on navigational performance [25]. To avoid covariant effects, a 15m × 15m empty indoor space was chosen for the test environment. The limitations of the test environment are discussed in section 9. The designed test paths were labeled on the floor of the space using thin colored tapes, (see Figure 6 (b)) for which all participants confirmed that no tactile difference could be felt. Three concentric paths with the widths of 2.1m, 1.4m, and 1.0m were labeled along each course in order to explore the appropriate threshold to trigger directional cues.

5.3.2 Participants. Five visually impaired participants (2 females and 3 males, aged from 19 to 27) were recruited for Study 2. Their demographic information is shown in Table 3. Among participants, two were blind, while the other three had very low vision. It was confirmed that all participants were unable to see or feel the tactile difference of the tape. While two participants were previously interviewed in Study 1, none had participated in our pilot co-design workshop. One participant (P4) had some experience testing other electronic traveling aids (ETA), but none had real-life experience with any ETA. To eliminate the impact of other navigation tools, the participants did not use canes or dogs during the test.

5.3.3 Apparatus. The devices to provide vibrotactile feedback were identical to those used in the pilot study (see Figure 4). For verbal auditory feedback, a Bluetooth speaker was used to play pre-recorded cues. To quickly simulate a computer controlled device, the appropriate vibrotactile and auditory cues were wirelessly triggered by a mobile phone, which was controlled by an experimenter. Both the position and orientation of the user were considered in determining which directional cues to send. The experimenter was trained to best fit the following strategies: (1) to keep the user within the 1.0m-wide area (so that users never walk out of the 2.1m-wide zone) and (2) to avoid interfering with the user by frequently triggering orientation-adjusting cues.

5.3.4 Procedure. Study 2 utilized a within-subject design, in which the presentation order of four modalities to each participant was determined by a 4×4 Latin Square. The order of (a)shoulder-(b)wrist-(c)ankle-(d)audio was implemented twice (P1, P5), and the other three orders ("b-c-d-a," "c-d-a-b," and "d-a-b-c") were implemented once. For each modality, four tasks were presented to each participant in random orders to avoid learning effects. The procedure was as follows: First, we briefly introduced the devices and the meaning of 4-directional cues. Next, the participant was assisted in putting on the device and was given time to become familiar with the vibrotactile cues. Subsequently, the experiment began. One experimenter led the participant to the entrance of each path and provided directional cues while another experimenter video recorded the process. After the experimental phase,



(a) Four basic paths used for experiment tasks (b) Paths were labeled by colored thin tapes

Fig. 6. Four basic paths selected as experiment tasks and labelled by colored tapes.

all participants were asked to indicate their level of agreement on six statements (see Table 2) using a 7-point Likert scale. Finally, all participants engaged in a focus group discussion.

5.3.5 Performance Metrics. We adopted the following metrics: (1) *Task Completion Time*, which quantifies the walking efficiency and (2) *Out-of-Area Frequency (OAF)*, which quantifies the walking smoothness. OAF is defined as the number of times participants walked out of the three areas with widths of 2.1m/1.4m/1.0m. The unit of OAF is number of times. In Study 2, all performance metrics were manually acquired from video playback.

5.4 Results and Findings

A total of 80 trials (4 tasks × 4 modalities × 5 participants) were conducted, with 20 trials for each modality. All participants completed each trial successfully without exiting the 2.1m-wide zone.

5.4.1 Task Performance. The task completion times and OAF are illustrated in Figure 7. The mean task completion time for vibrotactile cues on shoulders (20.57s, SD=5.63) was lower than on wrists, on ankles, and with auditory cues. In regards to OAF, the participants walked outside of the 1.0m-wide area 0.5 times on average with vibrations on the shoulders or the wrists, which was lower than with vibrations on the ankles or with auditory cues. Regarding the 1.4m-wide area, the mean OAF dropped to 0 for wrists and 0.05 for shoulders. No participants walked out of the 2.1m-wide area in any task.

5.4.2 Subjective Feedback. Subjective ratings are shown in Table 2. A Wilcoxon Signed-Rank test showed that vibrations on shoulders outperformed vibrations on wrists ($z = -2.04$, $p < .05$), vibrations on ankles ($z = -2.06$, $p < .05$), and auditory feedback ($z = -2.04$, $p < .05$) in terms of convenience in daily use. Regarding overall user satisfaction, vibrations on shoulders outperformed vibrations on ankles ($z = -2.12$, $p < .05$) and auditory feedback ($z = -2.07$, $p < .05$). No significant differences were found among the four feedback modalities on the

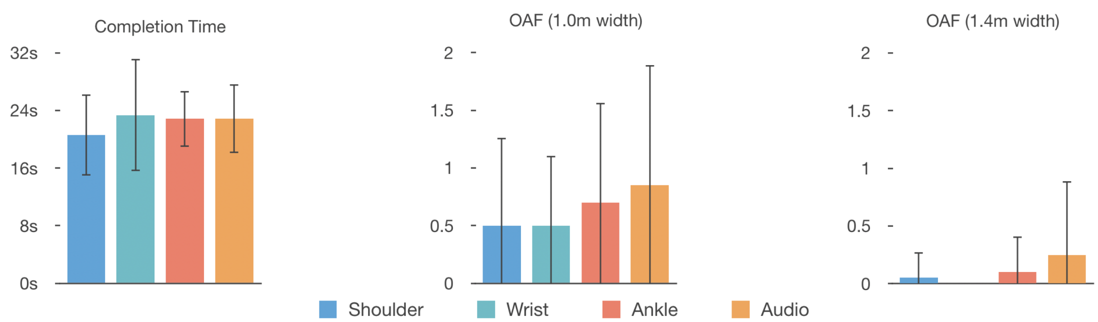


Fig. 7. Task performance in Study 2. The unit of OAF is number of times. Error bars indicate standard deviation.

Table 2. Subjective ratings in Study 2 and Study 3. (1 = Strongly Disagree, 7 = Strongly Agree)

Subjective Metrics		Study 2				Study 3	
Metrics	**Participant Statements**	**Shoulder**	**Wrist**	**Ankle**	**Audio**	**Vibration Only**	**Vibration+Audio**
Sensitivity	Vibrations or audio could be easily sensed.	6.4 (SD=0.89)	6.4 (SD=0.55)	5.8 (SD=1.10)	6.6 (SD=0.55)	6.63 (SD=0.62)	6.56 (SD=0.63)
Low Cognitive Load	Technique required low concentration.	6.4 (SD=0.55)	6.2 (SD=0.84)	5.6 (SD=1.52)	4.4 (SD=1.82)	6.81 (SD=0.54)	6.69 (SD=0.60)
Learnability	Technique was easy to learn.	6.0 (SD=1.00)	6.0 (SD=1.00)	6.0 (SD=1.00)	6.2 (SD=1.30)	6.94 (SD=0.25)	6.94 (SD=0.25)
Smoothness	Technique helped me walk smoothly.	6.4 (SD=0.89)	6.2 (SD=0.45)	5.6 (SD=1.14)	5.0 (SD=1.41)	6.00 (SD=0.97)	6.38 (SD=0.62)
Convenience	Technique would be convenient for daily use.	6.6 (SD=0.55)	4.6 (SD=1.14)	4.8 (SD=0.45)	2.8 (SD=0.84)	5.94 (SD=0.85)	5.94 (SD=0.85)
Overall Satisfaction	Technique was overall satisfactory.	6.6 (SD=0.55)	6.2 (SD=0.45)	5.4 (SD=0.55)	4.0 (SD=0.71)	5.94 (SD=0.68)	6.31 (SD=0.60)

metrics of sensitivity, low cognitive load, learnability, and smoothness, although the mean values differed slightly. During the test, qualitative feedback was also collected from participants through focus group discussions. Based on all collected data, our research has provided the following findings:

(1) *Learning Time:* Before the trial, participants were given time to learn the directional cues. Three participants acquired the directional cues in less than two minutes, while the remaining two participants completed the task in five to seven minutes. At the beginning of the training, both of the two participants misinterpreted the orientation-adjusting cues to mean move left/right without changing orientations, thus explaining the relatively long learning process for these participants.

(2) *Cognitive Load:* All participants reported that vibrotactile cues required lower levels of concentration than auditory cues. One participant (P2) stated the following: "With audio cues, I needed to listen carefully to confirm that I understood it correctly." Among the three on-body positions, vibrations on shoulders were the most intuitive to perceive, as indicated by P1 and P3. These participants provided the rationale that shoulders were always in the same orientation with the body.

(3) *Convenience in Daily Use:* Regarding on-body positions, all participants indicated that the convenience in daily use was especially important. Four out of five participants reported that vibrations on wrists were inconvenient for the following reasons: First, hands are frequently used to sense the environment (e.g., touching a handrail or finding a chair). Second, vibrations on wrists conflict with daily tasks, such as carrying bags. Three participants indicated that vibrations on ankles would affect their sensing of ground textures using their feet.

(4) *Movement Smoothness:* Four of the five participants reported walking smoothly during the experiment. However, P2 suggested that the signal changes were slightly too frequent on straight paths. Through video playback, we confirmed that the turning angle per step of P2 was around $40°$ during orientation adjustment, which was larger than the other four participants (around $20 - 30°$), causing her to frequently over-adjust. Therefore, to better support the smoothness during walking, individual differences in *turning angle per step* (around $20 - 40°$ in Study 2) should be considered when designing the strategy to indicate directions.

5.5 Discussion: Selection of the Feedback Modality and Issues to be Further Addressed

5.5.1 Selection of the Feedback Modality: Vibrotactile Directional Cues and Audio Environmental Descriptions. In Study 2, vibrotactile feedback on the shoulders and waist outperformed the other three modalities, having lower cognitive loads, higher convenience in daily use, and higher overall satisfaction. As a result, in our final feedback solution, we selected vibrations on the shoulders and waist to indicate directional cues. Moreover, all participants indicated that verbal auditory feedback could be additionally employed to describe road conditions ahead of the user, such as, "Low obstacles two meters ahead on your left." (P3). They stated that such environmental descriptions would make them feel safe, which also echoed our findings from Study 1. Therefore, we also included the audio descriptions of road conditions in our final feedback solution.

Overall, our feedback solution combined the following two modalities: (1) **vibrations on shoulders and waist to indicate 4-directional cues** and (2) **verbal audio feedback to describe road conditions ahead of the user.** The haptic feedback specifications in this solution were consistent with section 5.2.

5.5.2 Issues to Address in the Next Study. We identified three issues to address in the next study. First, we needed to evaluate if the multi-modal design in section 5.5.1 could support a better navigation experience than a design that only provides directional cues. Second, we needed to formulate the cue generation strategy for precise and automatic control by computing devices and to evaluate whether or not the designed strategy could fulfill the safety limit of 2.1m. Third, we needed to enhance the training process to help all users acquire the cues without the misinterpretation stated in section 5.4.2 (1).

6 FEEDBACK SOLUTION TO RENDER VIRTUAL PAVING

We specified the multi-modal design in section 5.5.1, and, in this section, we present two additional design factors of the solution: the strategy to indicate directional cues and the integration of hardware into a wearable backpack.

6.1 The Strategy to Generate Directional Cues

Our goal was to enable users to navigate safely, smoothly, and efficiently along a continuous path. However, in existing electronic traveling aids, directional cues are generated based on the angle between a user's current heading and the direction from that user's position towards a target waypoint [33, 72]. Such a design targets guiding the users towards a series of waypoints rather than along a smooth path. Therefore, in our design, both the orientation and (importantly) the position of users (see Fig 8 (a)) are considered.

As explained in section 4.4, the cue generation strategy should be designed to keep users within the safety zone, and also to optimize users' walking smoothness and efficiency. Precisely, we need to find a cue generation strategy F to trigger directional cues V with the following two goals: (1) minimize the possibility p for the user to walk out of the safety zone in order to ensure safety and (2) minimize the expectation $E(X)$ of the frequency to trigger orientation-adjusting cues in order to support the walking smoothness and efficiency. The optimization problem is formulated as: Find $V = F(x, \theta)$, $s.t.$ min $I = \iint_{(x,\theta)} E(X|x, \theta)p(x, \theta)\mathrm{d}x\mathrm{d}\theta$, where x is the distance from the user's position to the path centerline, and θ is the angle between the user's heading to the tangent of the path centerline. Both x and θ are illustrated in Figure 8 (a).

In this work, we approximated the appropriate strategy based on user performance observed in Study 2. First, we defined the region where $|x| < 1.05m$, $|\theta| < 120°$ as the *safe region*, which could guarantee that the user would be walking towards the correct direction within the 2.1m-wide zone. Second, we selected the positional threshold to trigger orientation-adjusting cues based on the following finding in Study 2: When the experimenter attempted to keep users within the 1.0m-wide area, four out of five participants walked smoothly, while one participant reported that the adjusting frequency was interfering. Therefore, we fine-tuned the positional threshold from 1.0m to 1.2m. Third, to balance between walking smoothness and efficiency, we designated two states: *smooth state* (s_1) and *adjusting state* (s_2). In the *smooth state*, if the user walked within the 1.2m-wide *optimum zone*, we avoided interfering with the user unless his/her orientation deviated too much. If the user stepped out of the *optimum zone*, the user's state would shift to the *adjusting state*. In the *adjusting state*, the thresholds were set to be less tolerant than in the *smooth state* in an attempt to make the user return to the *optimum zone* as quickly as possible. Fourth, we fine-tuned the angular threshold with respect to different positional deviations (x) so that

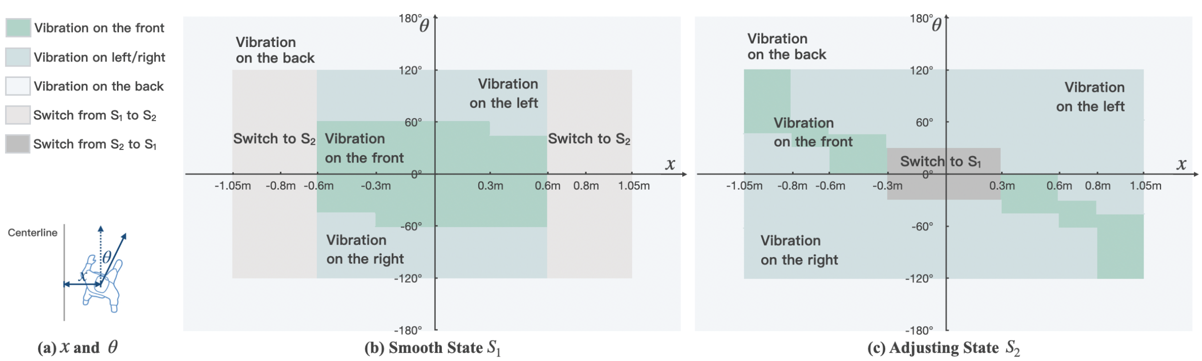


Fig. 8. Strategies to generate directional cues for paths with low curvature (straight paths and gentle turns).

users could easily follow the cues to return from the *adjusting state* and move to the *smooth state*. The angular threshold was fine-tuned based on the finding in Study 2, which illustrated that a user's turning angle per step was approximately $20 - 40°$ during orientation adjustment. Fifth, to effectively guide users in the completion of sharp turns, the cue generation strategy F was modified to accommodate different shapes of upcoming paths. For paths with low curvature (i.e., *straight paths* and *gentle turns*), the cue generation strategy F_l is illustrated in Figure 8. For paths with high curvature (i.e., *sharp turns* or *continuous turns*), the cue generation strategy F_h is adjusted by $F_h(x, \theta) = F_l(x, \theta + 20°)$ for left turns and $F_h(x, \theta) = F_l(x, \theta - 20°)$ for right turns.

6.2 Integrating the Feedback Solution into a Wearable Backpack

The designed feedback solution was integrated into a wearable backpack (see Figure 9 (a)) considering convenience in daily use. A backpack was chosen because it is comfortable to wear, does not occupy users' hands, and is already widely used for outdoor mobility to help users transport items. To provide vibrotactile feedback, the left and right vibration motors were placed inside the shoulder straps of the backpack, with the front motor on the buckle in front of the user's chest and the rear motor at the bottom of the back pad, close to the user's back. To provide auditory feedback, a Bluetooth speaker was placed inside the backpack.

7 STUDY 3: EVALUATION OF THE FEEDBACK SOLUTION

In Study 3, we evaluated the performance of our multi-modal feedback solution and reported its safety limit.

7.1 Objectives and Methodology

The primary objective of Study 3 was to evaluate the multi-modal solution in order to ascertain if it could facilitate a better navigation experience than a single-modal system that only provides directional cues. In the multi-modal solution, directional cues were indicated through vibrations, and, therefore, *vibration-only* feedback was selected as the condition for comparison. An additional goal of Study 3 was to evaluate the designed feedback solution in order to identify if it could fulfill the expected safety limit $W_{\text{safe}} = 2.1\text{m}$.

7.2 Experimental Design

7.2.1 Test Paths and Environment. The four types of test paths in Study 3 were identical to those in Study 2 (see Figure 9 (b)), with the exception that the length of *straight path* was extended to 15m from the original 10m. The experiment was conducted in a 34m×17m empty indoor space.

(a) Placement of motors on the Wearable Backpack **(b) Four types of test paths in study 3** **(c) Path Boundary Detection**

Fig. 9. Apparatus and Experimental Setup for Study 3.

7.2.2 Apparatus and Feedback Specifications. The backpack in section 6.2 was chosen as an apparatus. As stated in section 7.1, two conditions were selected for evaluation: *vibration+audio* and *vibration-only*. In both conditions, the vibration specification is the same as it is in section 5.5.1. In *vibration+audio*, the audio descriptions of different paths were designed as follows: (1) *straight path*: "The road ahead is smooth," (2) *sharp/gentle turn*: "A sharp/gentle turn two meters ahead to your left/right," and (3) *continuous turns*: "Continuous turns two meters ahead."

7.2.3 Recognizing the Labeled Path for Evaluation Purposes. To evaluate our feedback solution independently of human bias, we adopted two Intel RealSense D435 depth cameras for environmental sensing and developed a computer vision (CV) module to compute users' positions and orientations relative to the labeled path (see Fig 9 (b)). This CV module was used for evaluation only. In an implementation of Virtual Paving for actual use, there would be no labels, and the paths would be planned based on real-time environmental data.

The CV module worked as follows: First, thin, red tapes were selected to label the boundaries of the 1.2m-wide *optimum zone* along the path and used yellow and blue tapes to mark the entrance and exit of the path. Second, two D435 cameras (see Figure 9 (a)) were used to collect the real-time RGBD data, both ahead of the user and around the user's foot. Third, with the collected data, the path labels were detected in HSV space by the Sliding Window Method (see Figure 9 (c)), and the 3D coordinates of path labels in the camera coordinate system were computed. Fourth, the plane equation of the floor in the camera coordinate system was fitted. Finally, two values were computed as outputs, including (1) the distance (Δx) from the user's projection on the floor to the boundary of the 1.2m-wide optimum zone and (2) the angle difference (θ) between the user's orientation and the tangent of the boundary. Using the outputs from the CV module, instructional cues were generated according to the strategy in Figure 8 and, finally, transmitted the cues to vibration motors and to the speaker via Bluetooth communication. In our implementation of the CV module, the localization error was ±3.46% in root mean square value based on 1000 independent trials to calculate the length of a 1.2m-long line (ground truth = 1.2m).

7.2.4 Participants. We recruited 16 visually impaired participants (3 females and 13 males) aged from 20 to 41 (mean = 26.44). Their information is detailed in Table 3. Among participants, eleven were blind, while five were visually impaired with low vision. It was confirmed that all participants were unable to see the tapes on floor or feel the tactile difference. Only one participant (P14) had previous experience in testing electronic traveling aids. Four participants were included in Study 1, and none had participated in Study 2. To avoid the effect of other tools, the participants did not use canes or dogs during the experiment.

7.2.5 Procedure. Study 3 adopted a within-subject design, in which the two modalities were counterbalanced among 16 participants. For each modality, the order of tasks for each participant was randomized to avoid learning effects. The training process was as follows: (1) We introduced our backpack to participants, including its function and how to interact with it; (2) The participants put on the backpack and learned how to adjust their orientations according to the cues; (3) They tried to walk along our four basic paths, and the researcher corrected their behavior if needed. After training, the test phase began. Finally, all participants were asked to give their ratings on the six statements in Table 2 and were encouraged to provide any comments or suggestions.

7.2.6 Performance Metrics. The following metrics were computed to evaluate task performance: *task completion time*, *out-of-area frequency* (OAF), *optimum proportion* (OP), and *user's trajectory*. In this study, the OAF was defined as the number of times the participant walked out of the 1.2m-wide optimum zone. Optimum proportion was defined as $OP = \frac{T_{optimum}}{T_{total}}$, where $T_{optimum}$ was the time within the optimum zone, and T_{total} was the total time in one trial. These metrics were computed based on the RGBD data collected by RealSense cameras using the computer vision module in section 7.2.3.

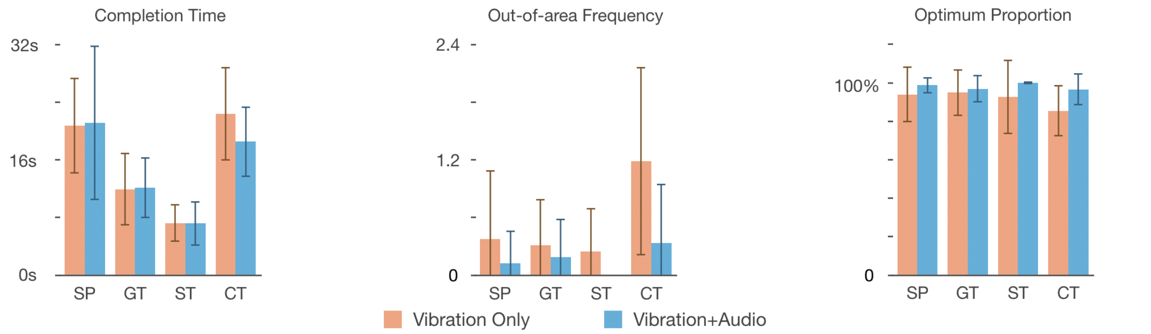


Fig. 10. Task performance in Study 3. SP = Straight Path, GT = Gentle Turn, ST = Sharp Turn, CT = Continuous Turns. Error bars indicate standard deviation.

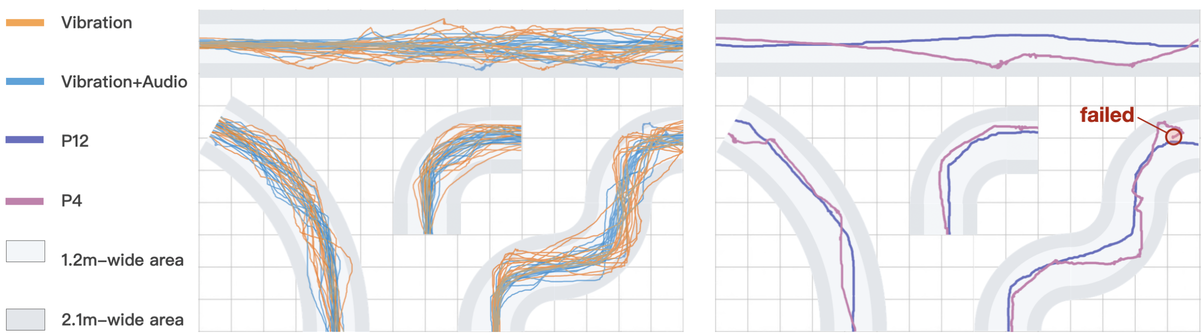


Fig. 11. Trajectories in Study 3. Left: trajectories of all participants. Right: trajectories of P4 and P12. Turns with opposing directions (left/right) were counterbalanced among participants and are superimposed by mirroring for visualization above.

7.3 Results and Findings

A total of 128 trials (2 modalities × 4 tasks × 16 participants) were conducted, with 64 trials for each modality. The results and findings are detailed as follows:

7.3.1 Task Performance. Participants completed 127 out of 128 trials successfully within the safe region ($|x| < 1.05m$, $|\theta| < 120°$). One trial failed with *vibration+audio* because the participant (P4) over-adjusted his orientation and turned back to the opposite direction of the path, triggering an emergency stop ($|\theta| > 120°$). The trajectory of the failed trial is shown in Figure 11 (right). Also shown were the trajectories of P12, who completed all tasks with the smallest mean completion time of 9.83s. It can be seen from the trajectories that, compared to P12, P4 tended to adjust his orientation with a larger turning angle and walked in zigzags more easily.

The performance metrics for the two modalities were calculated for each type of path and are shown in Figure 10. Users' trajectories in all trials are illustrated in Figure 11 (left). RM-ANOVA showed the following significance: *Vibration+audio* outperformed *vibration-only* in OAF for a *sharp turn* ($F_{1,15} = 5.0$, $p < .05$) and for *continuous turns* ($F_{1,15} = 14.607$, $p < .01$). Regarding OP, *vibration+audio* outperformed *vibration only* for *continuous turns* ($F_{1,15} = 16.728$, $p < .01$). It can also be seen from Figure 11 that, compared with *vibration-only*, the trajectories of *vibration+audio* were more convergent and close to the path centerline for *sharp turn* and *continuous turns*. Based on the above results, we could deduce that *vibration+audio* outperformed *vibration-only* in keeping users within the 1.2m-wide optimum zone.

7.3.2 Subjective Feedback. Subjective Ratings are shown in Table 2. Based on the ratings and other data recorded during the experiment, we report the following key findings:

(1) *Learnability*: Subjective ratings for learnability (6.94) were high for both modalities, indicating that our prototype was easy to learn. Specifically, all participants learned our prototype in less than 10 minutes (mean=5.04, SD=1.88). After training, all participants acclimated to adjusting their orientations according to the cues, and none misinterpreted the cues as moving left/right without changing their orientations.

(2) *Smoothness and Overall Satisfaction*: A Wilcoxon Signed-Rank test on the subjective ratings shows that *vibration+audio* outperformed *vibration-only* on metrics including smoothness ($z = -2.121$, $p < .05$) and overall satisfaction ($z = -2.121$, $p < .05$). Notable consistent comments included the following: "I could walk smoothly under the guidance of the device" (mentioned 5 times) and "I felt gradually adapted to the device over time" (4 times). Nine out of sixteen participants also expressed their willingness to test Virtual Paving in real environments.

7.3.3 Safety Limit of the Feedback Solution. In all trials (including the one failed trial), zero participants walked out of the 2.1m-wide zone, indicating that our feedback solution was able to keep users within the expected safety limit W_{safe}=2.1m. Therefore, the designed feedback solution could ensure safe navigation in environments where the collision-free space is wider than 2.1m, such as the indoor corridors built to the Chinese standard [46].

7.3.4 Conclusion. Both *vibration+audio* and *vibration-only* have been shown to achieve the expected safety limit of W_{safe}=2.1m. Moreover, *vibration+audio* outperformed *vibration-only* in keeping users within the 1.2m-wide optimum zone and gained higher ratings on walking smoothness and overall satisfaction. Based on this empirical data, we conclude that our multi-modal solution could facilitate a better navigation experience than a single-modal solution that only provides haptic directional cues.

7.4 Discussion on How to Manage Split Attention in the Multi-Modal Design

As suggested in [26, 51], multi-modal feedback might suffer from the split-attention effect. In contrast, our multi-modal solution has been shown to facilitate a better navigation experience than a single-modal feedback through user tests. In our solution, split attention is managed by employing two modalities to provide two types of *useful* information that are *independent* of each other. With a single-modal haptic feedback that only indicates the local safe direction of travel, users could still walk safely but have little awareness of the environment. By comparison, the audio descriptions could help users build a mental model of the environment and effectively prepare for the upcoming situations. The coexistence of these two types of information could support a better navigation experience (as validated in Study 3), rather than suffering from split attention.

In future work, verbal audio could be designed to provide information relating to a variety of situations (such as surface level changes, complex obstacles, or other situations summarized in section 3.3.3). Based on our design in Study 3 and existing works on the design of verbal navigational cues [16, 17], we summarize several rules that have the potential to manage split attention in the future design of multi-modal solutions: (1) *Avoid Redundancy*: The auditory feedback should provide useful information not provided by directional cues; (2) *Be Simple and Concise*: The verbal cues should be concise and easy to understand in order to minimize users' cognitive loads. Overall, the audio descriptions of environments should be designed to fulfill users' specific informational needs and should be validated through user tests.

8 DISCUSSION ON THE DESIGN OF VIRTUAL PAVING

Based on Study 1, we identified four key design goals to optimize the user experience of Virtual Paving: safety, efficiency, smoothness, and supporting ordinariness. Among them, the needs to be *smooth* and to *support* *ordinariness* are inspired by the common desire of visually impaired participants to walk smoothly, like sighted people, which has not been mentioned or explored as prevalently in prior works. We, therefore, highlight them as two important considerations for future research on navigation systems for visually impaired people.

Through Studies 2 and 3, our proposed feedback design to render Virtual Paving was evidenced to be effective in supporting visually impaired users in walking smoothly. We summarized three key points behind our design: First, limited research has been conducted on the shoulder as a body part to receive haptic directional cues. Compared to the wrists and ankles, we found shoulders to be more sensitive to vibrations. Therefore, cues on shoulders can be readily perceived. Second, when users need to change their orientations, the orientation-adjusting cues are continually applied (with the vibration pattern specified in section 5.2.2) so that users do not need to stop in order to find the target direction. Third, our strategy to indicate directions is designed to minimize both the likelihood of users walking into the danger zone and the frequency to trigger orientation-adjusting cues. Therefore, users could walk safely and smoothly without the need to adjust their orientations frequently.

In this particular work, we designed the strategy through iterative user tests. First, in Study 2, we collected users' ratings on walking smoothness under the 1.0m positional threshold and observed users' behavior during orientation adjustment. Next, based on the findings in Study 2, we formulated the cue generation strategy with fine-tuned positional and angular thresholds in section 6.1. Finally, in Study 3, findings indicated that the designed cue generation strategy supported the participants in walking smoothly within the 2.1m wide area. Overall, our design was empirically established and validated based on iterative user studies. The limitations of this empirical approach are discussed in section 9.

9 LIMITATIONS AND FUTURE WORK

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

There are several limitations to the experimental designs in Studies 2 and 3. In both studies, the noise level in the test environment was below 40 decibel. As a result, the effectiveness of the feedback solution under distractions of high decibel noise is unknown and needs further evaluation. Also, in Study 2, the number of participants was five (not a multiple of 4), so we did not have an even distribution on the 4×4 Latin Square. The reader should interpret the quantitative results of Study 2 with the imbalance in mind. Moreover, in Study 3, the mean task completion time was 12.60s for three female participants (24 trials), which is lower than 16.10s for 13 males (104 trials). Although no reliable inference could be reached due to the unbalanced sample size, the potential gender difference in task performance should be addressed in future work.

The cue generation strategy in this work was established using an empirical approach, which has the following limitations: First, we only explored the proper strategy to guide users within the 2.1m safety limit. In future work, to support safe navigation through narrower spaces, the cue generation strategies that fulfill smaller safety limits should be explored using the same iterative approach. Second, the empirical approach heavily relies on further iterative design and user tests to better approximate the optimal strategy, which would require great research efforts. To minimize efforts, a quantitative model for optimization would be beneficial, although it is not yet available due to the lack of prior knowledge on the precise relationship between the cue generation strategy and users' walking smoothness/efficiency. This relationship is a promising direction for future research and has the potential to help the system adaptively select a strategy according to the free space in different environments.

In future work, the multi-modal feedback to render Virtual Paving could be improved in the following ways: First, the set of verbal audio descriptions could be expanded to provide information on more environments with the design considerations discussed in section 7.4. Second, to facilitate the smooth movements of users, one possible solution would be to indicate more detailed directional cues (e.g., turn 12° to the left) than the 4-directional cues. The primary difficulty would be finding an appropriate feedback modality so the detailed-directional cues could be readily perceived with high accuracy. Possible modalities to be explored include the spatial auditory feedback with bone conductive headphones [73] and force feedback from shape-changing devices [60].

We did not implement sensing and planning techniques in this work. However, after establishing the feedback solution to fulfill the safety limit W_{safe}, we were able to provide the following potential solution to the problem of sensing and planning: Plan a collision-free path with its width no smaller than W_{safe}, based on the real-time environmental data collected through sensors. This problem would require great research efforts but is likely solvable considering recent progress in computer vision [20, 27, 78] and will be addressed in future work.

In this work, we only validated the ability for Virtual Paving to support independent navigation along 2.1m-wide basic paths in the lab environment. Ideally, the ultimate goal of Virtual Paving is to enable visually impaired users to navigate independently in real environments so that their mobility will not be limited by the availability of human guides, guide dogs, or public infrastructures. To evaluate whether this goal is achievable, several research gaps remain to be addressed. First, the safety limit and user experience of the guidance system in real environments need to be evaluated, with the sensing and planning techniques fully implemented. Second, prior work [5] suggests that assistive devices might lead to awkward social interaction and low adoption rate due to social concerns. Therefore, users' acceptance of using Virtual Paving in real life should be further examined with long-term longitudinal studies. Overall, Virtual Paving aims to give users more options and flexibility relating to mobility. For the same reason, a full implementation of Virtual Paving should not replace traditional tactile paving, considering that some users (especially elderly users) might not be able to adapt to assistive devices easily [18]. Moreover, as suggested by the interdependence frame in [5], the guidance of electronic devices could be combined with other information sources in order to further facilitate mobility. As a result, further research on how to provide effective guidance when Virtual Paving is being used in combination with other tools could be a possible direction for future work.

10 CONCLUSION

We present Virtual Paving to guide visually impaired people along a collision-free and smooth path in a user friendly manner. Our work focused on optimizing the feedback design to render Virtual Paving. Based on a series of user studies with visually impaired users, we suggested design guidelines of Virtual Paving to optimize user experience, and we established a multi-modal feedback solution to render Virtual Paving, which enabled visually impaired participants to smoothly navigate along basic paths with 2.1m width. We hope this work will provide useful insights on the human-factor considerations to support mobility for visually impaired people and also inspire researchers to propose more effective and user-friendly implementations of Virtual Paving.

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A DEMOGRAPHIC INFORMATION OF THE 27 VISUALLY IMPAIRED PARTICIPANTS

Table 3. Demographic information of the 27 visually impaired participants from all studies. All information was self-reported. **Exp with ETA** = experience with electronic travelling aids.

No.	Age	Gender	Visual Condition	Tactile Paving	Canes or Dogs	Exp with ETA	Study 1	Study 2(pilot)	Study 2	Study 3
1	29	M	weak light perception visual acuity=20/400	< once a month	daily cane user	no	P1	P1		
2	28	F	blind	never	daily cane user	no	P2			P3
3	29	F	blind	never	alternately use canes and dogs	no	P3	P2		
4	38	M	blind	< once a month	alternately use canes and dogs	only tested a haptic belt	P4	P3		
5	23	F	blind	never	daily cane user	no	P5		P3	
6	24	M	low vision visual acuity=20/100	< once a month	seldom cane user	no	P6			P8
7	26	F	blind	3-4 times a week	daily cane user	no	P7	P4		
8	30	M	blind	never	daily cane user	no	P8			P6
9	22	M	blind	never	daily cane user	no	P9			P13
10	19	M	low vision visual acuity=20/100	never	seldom cane user	only tested head-mounted glasses	P10		P4	
11	22	M	blind	< once a month	daily cane user	no	P11	P5		
12	23	F	weak light perception visual acuity=20/200	never	daily cane user	no	P12			
13	24	M	weak light perception visual acuity=20/200	< once a month	daily cane user	no			P1	
14	23	F	blind	never	daily cane user	no			P2	
15	27	M	weak light perception visual acuity=20/200	never	daily cane user	no			P5	
16	26	M	blind	never	daily cane user	no				P1
17	33	M	weak light perception visual acuity=20/200	< once a month	daily cane user	no				P2
18	41	M	blind	never	daily cane user	no				P4
19	28	F	blind	never	daily cane user	no				P5
20	24	M	blind	never	daily cane user	no				P7
21	28	M	blind	< once a month	daily cane user	no				P9
22	23	M	blind	never	< once a month	no				P10
23	22	M	blind	never	daily cane user	no				P11
24	20	M	low vision visual acuity=20/100	< once a month	seldom cane user	no				P12
25	25	M	blind	1-2 times a week	seldom cane user	only tested a smart cane				P14
26	23	F	weak light perception visual acuity=20/400	never	daily cane user	no				P15
27	26	M	low vision visual acuity=20/100	never	seldom cane user	no				P16