Enhancing Virtual Mobility for Individuals Who Are Blind or Have Low Vision: A Stationary Exploration Method

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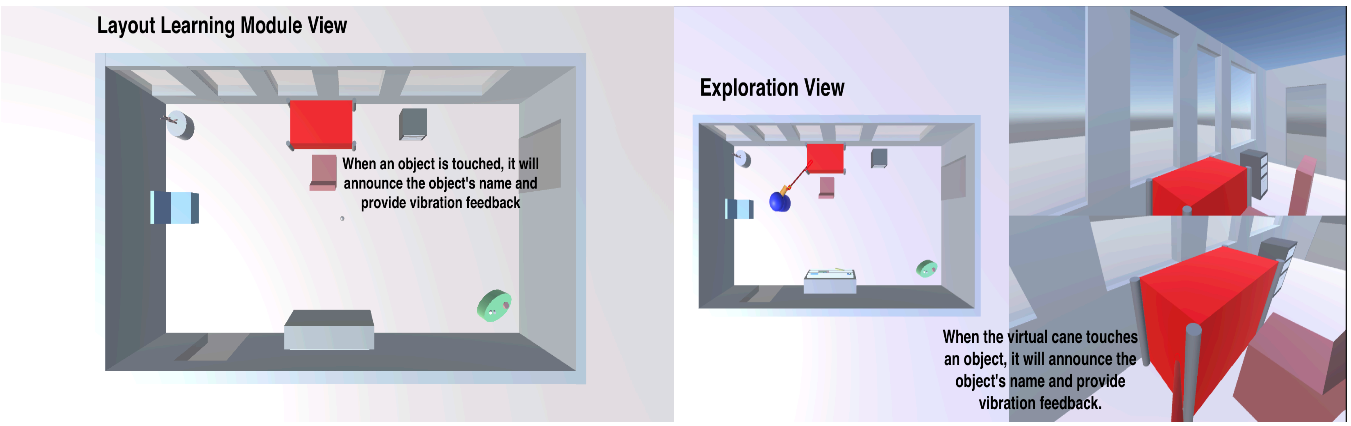

(a) Layout Learning Module

(b) Exploration Room

Figure 1: (a), an example of the layout learning module, an object's color turns to red and the app provides audio and vibration feedback when a BLV user's finger touches it; (b), an example of the in-place exploration module, an object's color turns to red and the app provides audio and vibration feedback when a BLV user's virtual cane touches it.

Abstract

Designing accessible locomotion methods for individuals who are blind or have low vision (BLV) is a complex challenge, particularly in mobile VR environments with limited interface options. In this paper, we propose a novel locomotion technique on mobile VR that enables users to control a virtual character's movement while staying stationary or within a small physical area. The technique utilizes the phone's gyroscope for movement control, while providing spatial audio and vibration feedback to enhance virtual exploration for BLV individuals. Our study examines how BLV individuals acquire spatial knowledge in mobile VR environments. A user study is conducted to assess the effectiveness of the proposed approach.

CCS Concepts

• **Human-centered computing** → **Virtual reality**; • **Computing methodologies** → *Perception.*

Keywords

Mixed Reality, Mobile Application, Blind and Low Vision, Spatial Knowledge, Virtual Exploration, Haptic Feedback, Audio Feedback, Gyroscope

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1 Introduction

Exploring and understanding new environments poses a significant challenge for blind and low-vision (BLV) individuals. The mixed reality (MR) Cane [4, 6], by simulating the function of a white cane, aims to assist BLV individuals in better exploring and understanding new environments. The simulated cane offers numerous applications for BLV individuals, including orientation and mobility training, as well as virtual environment exploration. However, the current need for 1:1 scale real-world spaces in testing virtual environments presents practical limitations, which hinder the advancement and application of many research initiatives.

The objective of this study is to develop a stationary exploration method as an innovative solution, enabling BLV individuals to achieve virtual mobility within a confined physical space. This method can effectively reduce the dependence on large physical spaces, thereby allowing for more flexible testing and application. By facilitating the exploration of virtual environments within a small area, this study aims to enhance the independence of BLV individuals and provide valuable practical experience and data support for the further development of related technologies.

This research utilizes the phone's gyroscope to control VR avatar's movement, and a headset with spatial audio to track head rotation, creating an in-place control method for virtual character exploration. Combined with a Learning Layout Module that utilizes haptic and auditory feedback, the system assists users in building mental maps of virtual environments. User studies with BLV participants will evaluate the effectiveness of this approach in improving spatial knowledge acquisition and usability. The anticipated results include enhanced virtual exploration capabilities, improved spatial awareness, and increased user satisfaction, contributing to the broader application of mobile VR technologies to BLV individuals.

2 Related Work

In-place virtual exploration using treadmills has been a significant research area within virtual reality (VR) systems[3], particularly for enhancing immersive experiences. Treadmills allow users to walk naturally in confined physical spaces while exploring expansive virtual environments, offering both a sense of presence and physical activity. However, their utility for blind and low-vision (BLV) individuals is limited. Traditional treadmills rely heavily on visual feedback, making independent and safe navigation challenging for BLV individuals.

To address accessibility challenges in VR, various intuitive control mechanisms have been proposed for BLV individuals. One such approach involves smartphone-based virtual white cane systems, where users control avatars through thumb movements and gestures[5]. However, this method has led to confusion among participants, indicating the need for simpler and more intuitive control schemes.

Another promising avenue is the use of 3D audio to create immersive virtual environments for BLV individuals[1, 7]. Auditory cues can effectively convey spatial information, helping users navigate and interact with virtual objects. Despite these advances, providing a complete and intuitive sense of space remains a challenge.

There is a clear need for more accessible and effective in-place virtual exploration systems for BLV individuals. Improving control design, spatial awareness, and feedback mechanisms can make virtual environments more user-friendly and enhance spatial cognition skills, potentially benefiting real-world navigation.

3 Methods

3.1 Layout Learning Module

A layout learning module is a foundational tool that helps users build a spatial mental map of an unknown environment, which is crucial for effective navigation and orientation prior to detailed exploration. This module is an indispensable part of the research methodology as it can enhance the spatial awareness of BLV individuals.

Interaction and Exploration

- `Touch Interaction`: Users can explore the room layout through intuitive touch gestures on the screen. They are instructed to move their fingers from top to bottom and from left to right of the phone screen to ensure they do not miss any objects. This tactile interaction method allows them to understand the spatial layout of an environment and the distribution of objects within it.
- `Auditory Feedback`: This module provides real-time feedback on the room layout using auditory cues, alerting users to the presence of objects as they explore. This auditory guide improves the user's understanding of their environment.
- `Haptic Feedback`: Integrated vibration feedback enriches the tactile experience, enabling users to perceive subtle spatial differences, such as room dimensions and object distances. This haptic feedback mechanism plays a crucial role in enhancing spatial awareness within the environment.

By combining these interactive elements, the layout learning module not only aids in the initial understanding of the environment but also supports continuous spatial orientation, making it an important part of the research methodology aimed at improving exploration aids for BLV individuals.

3.2 In-place Exploration Module

The design of this in-place motion control method aims to enhance the navigation experience of BLV individuals in virtual environments by integrating auditory and tactile feedback. Using ubiquitous mobile devices such as smartphones and wireless headphones, it simulates real-world navigation tools to make user interactions in virtual environments more natural and intuitive. This approach not only improves the interactive capabilities of BLV individuals in virtual environments but also provides a safe and effective means of orientation training. Here are specific features and implementation details:

Activation and Movement:

- When the user swings the phone downwards, the virtual character starts moving, simulating a step forward in the virtual environment. This design mimics walking actions in reality, providing an intuitive way to start, reducing the learning curve for users.

Directional Control:

- The direction of the virtual character's movement is determined by the orientation of headphones with a spatial audio feature, utilizing devices users are already familiar with and minimizing learning costs.
- When users turn in place, the virtual character changes its direction accordingly, simulating natural turning actions in the real world for intuitive and easy direction control.

White Cane Simulation:

- The smartphone simulates the functions of a white cane. Users can swing the phone left or right to adjust the direction of the virtual cane. This approach takes advantage of users' existing familiarity with traditional cane usage, making the virtual tool more intuitive and accessible for BLV individuals. Through the phone's gyroscope, the system accurately detects swinging motions and updates the direction of the virtual cane in real time.

Feedback Mechanisms:

- `Auditory Feedback`: The application provides various sound cues to help users understand their surroundings. For example, footsteps sound corresponds to the character's movement[2], providing continuous movement feedback to help users understand their motion status. When the virtual cane encounters obstacles or objects, audio signals announce their names, such as "This is a chair" or "wood table," enabling users to understand the environment in real time.
- `Tactile Feedback`: When the virtual cane encounters an obstacle or object, the phone generates vibration feedback. This tactile feedback simulates the feeling of collisions in reality, enhancing the interaction experience between users and the virtual environment, allowing users to better perceive the position of obstacles and objects in the virtual environment.

Through this design, users can utilize their familiar devices and movements to obtain a VR exploration experience similar to the real world. This method not only provides an effective virtual navigation tool for BLV individuals but also brings new possibilities for their training. The integrated feedback mechanism ensures that every action of the user in the virtual environment has corresponding feedback, enabling them to explore the virtual world more confidently.

4 User Study

4.1 Participants

Due to the challenges of recruiting BLV individuals for the study, we recruited 3 BLV participants and 12 sighted participants for our user study. The BLV participants had varying degrees of visual impairment, ranging from light perception to complete blindness, and all had experience using a white cane. The sighted participants were instructed to close their eyes during the experiment.

4.2 Virtual Room

The virtual room is about 10 meters long and 5 meters wide, contained seven virtual objects, including a wooden table, two chairs, a bookcase, a trash can, a filing cabinet, and a potted plant, as illustrated in Figure 2. There were two doors, one on the south wall and one on the east wall. The virtual character's initial position is in front of Door1, facing north.

4.3 Experiment

In the experiment, we provided participants with an overview, including the technologies used and how the Layout Learning Module and the method of in-place control for moving the virtual character work. We then began the instructional tutorial, which primarily focused on teaching participants how to use their phone as a virtual cane, similar to a real cane, and how to rotate the virtual character to change direction.

After completing the tutorial, we proceeded to the Layout Learning Module experiment. Participants were given 3 minutes to explore the room, or they could end the test early if they became

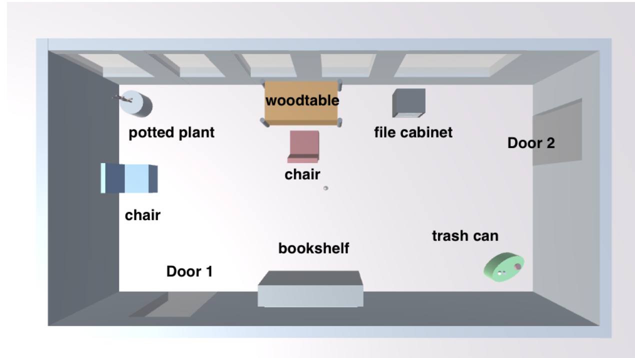

Figure 2: Virtual Room

familiar with the virtual room's layout. After exploration, participants were asked to briefly describe the layout of the virtual room and name the virtual objects.

Following the Layout Learning Module experiment, participants used the Swing method to control the virtual character's movement and freely explore the virtual room. They were given 10 minutes for exploration. When they discovered an object, we asked about the location of another object and had them point out the direction and control the virtual character to find it. At the end of the experiment, we asked participants to complete a post-experiment survey.

5 Results and Analysis

Our study investigated three key aspects of user interaction in a virtual environment: the intuitiveness of control movement method, ease of virtual cane control, and effectiveness of the Layout Learning Module. We present our findings for each of these areas.

5.1 The Intuitiveness of Control Movement Method

To evaluate the intuitiveness of the swing gesture to initiate character movement in virtual environments, we conducted a user study with 15 participants. Each participant rated the intuitiveness of the gesture on a 5-point Likert scale, where 1 represents "Not intuitive" and 5 represents "Very intuitive". We compared two groups:

- BLV participants (n = 3): Mean score = 2.00
- Sighted participants (n = 12): Mean score = 3.42

To better understand the distribution of ratings for sighted participants, we created a frequency table:

Rating	Frequency
1	0
2	3
3	3
4	4
5	2

Table 1: Frequency distribution of intuitiveness ratings for sighted participants

The results suggest that while sighted participants found the swing gesture relatively intuitive, there is a noticeable disparity in perceived intuitiveness between BLV and sighted participants. This difference highlights the importance of considering diverse user groups when designing interaction methods for virtual environments.

5.2 Ease of Control in Virtual Cane Movement

We investigated the ease of controlling a virtual cane by swinging a phone left or right. Participants rated the ease of control on a 5-point Likert scale (1 = Very difficult, 5 = Very easy). We compared two groups:

- BLV participants (n = 3): Mean score = 3.00
- Sighted participants (n = 12): Mean score = 4.42

These results suggest that sighted participants found the virtual cane control easier than the BLV participants. However, the small sample size, particularly for the BLV group, limits the generalizability of these findings.

5.3 Effectiveness of the Layout Learning Module

We evaluated the Layout Learning Module's effectiveness by measuring participants' ability to find and correctly place objects in a virtual environment. In Table 2, data were collected from 9 participants.

Measure	Mean	SD	Min	Max
Objects Found	6.56	0.88	5	7
Objects Correctly Placed	5.89	1.27	4	7

Table 2: Descriptive Statistics for Layout Learning Module Performance

Participants demonstrated high performance in both tasks, finding an average of 6.56 out of 7 objects (93.7%) and correctly placing an average of 5.89 objects (84.1%). These results indicate that the Layout Learning Module is effective in facilitating spatial learning in virtual environments, with participants showing good spatial awareness and memory.

6 Discussion

This study explored a novel stationary exploration method that aims to provide virtual mobility for BLV individuals within a confined physical space. Our results reveal several key findings worthy of further discussion.

Our study on the intuitiveness of the swing gesture for character movement in virtual environments revealed significant differences between BLV and sighted participants. These findings have important implications for the design of inclusive virtual reality (VR) experiences.

Disparity in Perceived Intuitiveness:

- The substantial gap in mean scores between BLV participants (2.00) and sighted participants (3.42) suggests that the swing gesture may not be equally intuitive across different user groups. This disparity underscores the critical need to consider diverse user needs in VR interface design.

Potential Reasons for Differences:

- Sighted participants might have more exposure to similar gestures in other technologies, such as smartphones or gaming consoles, which could influence their perception of the gesture's intuitiveness. This familiarity could make the gesture feel more natural to them.

Although the swing gesture shows promise for sighted participants, there is a clear need for further refinement and the exploration of alternative methods to create truly inclusive VR experiences that ensure accessibility and ease of use for BLV individuals.

The ease of virtual cane control showed marked differences between BLV and sighted participants. The participants in sight reported significantly less difficulty in control compared to the BLV participants (mean scores of 4.42 and 3.00, respectively). This disparity likely reflects the unique challenges faced by BLV individuals in adapting to new virtual exploration tools. Importantly, this difference may be attributed to the existing habits and experiences of BLV individuals with real cane usage. In real-world scenarios, BLV individuals typically swing their canes with minimal lateral movement. This finding underscores the critical importance of designing with BLV individuals' established navigation habits and preferences in mind. Future iterations of our system should aim to more closely mimic the subtle movements characteristic of real-world cane usage, potentially by increasing sensitivity to smaller movements or offering customizable control settings. By tailoring the virtual experience to match the familiar physical experience of cane users, we can potentially reduce the learning curve and enhance the overall usability of the system for BLV individuals.

The effectiveness of the Layout Learning Module was encouraging. Participants demonstrated excellent performance in finding and correctly placing virtual objects, locating an average of 93.7% of objects and correctly placing 84.1%. These results indicate that our approach is highly effective in helping users build spatial cognition in virtual environments. This high level of performance highlights the potential of combining haptic and auditory feedback to significantly enhance users' spatial awareness.

Nevertheless, we acknowledge some limitations in our study. Particularly, the small sample size of BLV participants ($n = 3$) limits our ability to draw broad conclusions from their experiences. Additionally, while our study primarily focused on short-term spatial learning and exploration, the long-term impacts of using such a system remain to be explored.

7 Conclusions and Future Work

This study developed a novel stationary virtual exploration method for individuals who are blind or have low vision (BLV), integrating the phone's gyroscope and a headset with spatial audio to capture head and device movements for virtual navigation within a limited physical space. Our results indicate significant potential in enhancing spatial cognition and usability.

The high efficacy of the Layout Learning Module highlights the value of multimodal feedback in enhancing spatial understanding of virtual environments. However, the difference in virtual cane control difficulty between BLV and sighted users emphasizes the need for further interface optimization to meet the specific needs of BLV individuals. And future research should investigate the factors contributing to the divided user opinions and explore potential modifications to the gesture to increase its overall intuitiveness.

Despite these positive outcomes, several areas remain for future research:

(1) **Expanded Sample Size:** Future studies should increase the number of participants, especially BLV individuals, to improve the reliability and generalizability of results.
(2) **Longitudinal Studies:** Conduct long-term studies to assess the impact of prolonged system use on spatial cognition abilities and user satisfaction.
(3) **Personalized Interfaces:** Explore the possibility of adaptive interfaces that adjust control sensitivity and feedback intensity based on individual user needs and preferences.
(4) **Real-world Application Assessment:** Test the system in practical settings, such as virtual museum tours or city navigation training, to evaluate its practicality.

In conclusion, this study presents a promising solution for virtual mobility among individuals with BLV. By continuing to refine and expand this technology, we have the potential to create more accessible and inclusive virtual experiences for people with BLV, thus improving their independence and quality of life.

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