Investigating Blind People's Route Perception of Complex Pre-Mapped Routes in Virtual Reality

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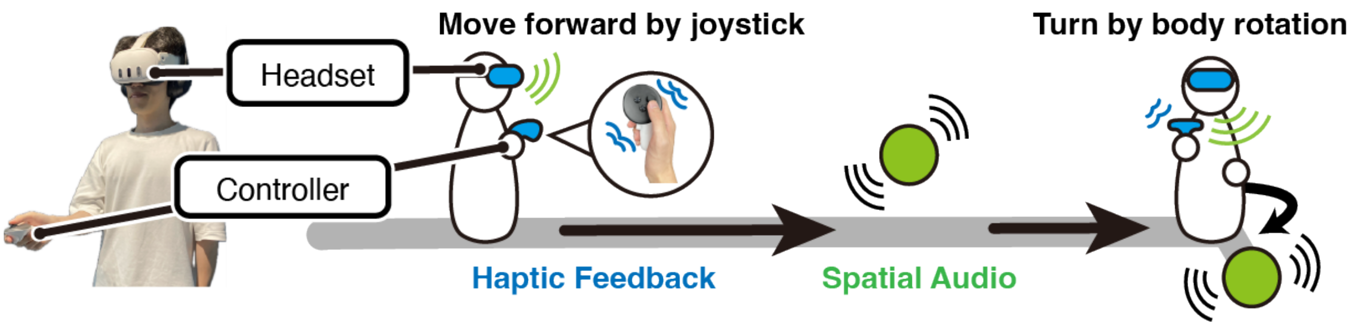

Figure 1: Users navigate the virtual environment using multimodal feedback on pre-mapped routes - a) the user walks forward in the virtual environment by pushing the thumbstick while receiving directional haptic cues; b) spatial audio provides orientation and distance cues as the user progresses; c) physical body rotation reorients the avatar's heading.

Abstract

Virtual reality (VR) offers immersive environments that can support spatial learning and rich exploration experiences. While prior work has enabled blind people to engage with VR through simple paths, there is little to no knowledge about how blind people perceive complex paths, such as those with curved paths and non-perpendicular turns, commonly found in places like museums or shopping malls. In this paper, we propose a VR system that enables blind people to explore using an off-the-shelf VR headset. Rather than free exploration, our system leverages a pre-mapped route to afford a clearer spatial structure and reduce cognitive load during exploration. We conducted a user study with six participants to investigate how they perceive these routes in VR. Findings show that participants were able to perceive routes with up to two non-perpendicular turns and the general shape of curved routes. However, routes involving multiple turns remained difficult to understand.

CCS Concepts

• **Human-centered computing → Accessibility systems and tools**.

Keywords

Blind people, Virtual Navigation, Spatial Learning, Complex Environments

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1 Introduction

We developed a system that enables blind people to learn large, complex routes, such as those with curves and multiple non-perpendicular turns, within a virtual environment using off-the-shelf VR headsets. By allowing users to explore and familiarise themselves with unfamiliar environments in advance through *virtual navigation*, it helps them build spatial understanding prior to their visit.

Prior research has explored blind navigation using devices such as smartphones [5, 6], computer keyboards [2], and joysticks [8], which support route exploration through device gestures or button inputs. However, these interactions do not incorporate body movement or orientation, limiting users' embodied sense of space, particularly in environments with complex, non-linear layouts. In contrast, off-the-shelf VR headsets support advanced interactions through head orientation and hand gestures, enabling richer embodied and natural navigation experiences [3, 9]. For example, prior research on Orientation and Mobility training has introduced VR cane systems that support navigation in virtual environments mapped to real-world spaces, using audio and haptic feedback during physical walking, leveraging users' existing skills and experiences [11, 12]. While these approaches contribute valuable insights, little is known about how blind people perceive navigation in complex routes.

To convey complex paths without physical movement in VR, our key idea is to use a pre-mapped route design, *i.e.*, a path with guided progression, to afford a clearer spatial structure and reduce cognitive load for users during exploration. We adopt this design because comprehension with free movement can be cognitively demanding for blind users in open spaces, even in VR-based environments [7], and it may hinder spatial learning [1].

To gain initial insights into designing a system and to evaluate how blind people perceive VR-based pre-mapped routes, we conducted a user study with six blind participants. We show that participants were able to navigate the routes, relying strongly on spatial audio. While some encountered challenges with environment recognition, these experiences offered insights for refining virtual navigation systems and informing design to better support blind people's spatial learning strategies.

2 Implementation

Our system was developed in Unity, running on the Meta Quest 3 using its controller for user input and headset for body orientation. The virtual environment was created by manually designing a pre-mapped route composed of straight segments, 30°, 45°, 60°, and 90° turns, and curved sections.

Users navigate in the environment by physically turning their bodies and pushing the controller's thumbstick forward to move. As shown in prior research, adding appropriate auditory and haptic cues can improve accessibility in virtual navigation [4, 10]. **1)** To convey a sense of movement, a continuous footstep sound is emitted while in motion; and **2)** similar to bumping sounds used in earlier systems, an error beep is emitted when the users' head or controller face a non-navigable direction, alerting that movement is not possible. Additionally, we added:

Spatial Audio: To indicate the direction of travel, a spatialized sound is emitted from the target direction (*i.e.*, louder sounds indicate closer targets). On straight paths, the sound is typically emitted from the next turning point; on curved paths, it is emitted from a closer position along the path to provide more continuous guidance.

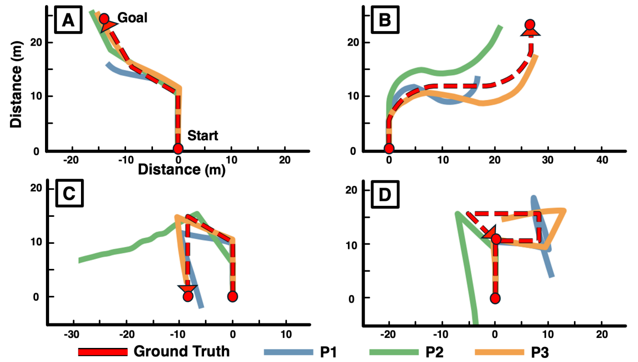

Figure 2: Comparison of the ground truth route with route navigated during the Reconstruction phase by three participants, referr to as P1, P2, and P3.

Haptic Feedback: Spatial audio alone may lack directional precision, so we complement it with haptic cues. When the controller points in a navigable direction, a brief pulsed vibration is delivered every second; otherwise, continuous vibration is applied.

3 User Study

We conducted a user study with 6 blind participants (3 male, 2 female, 1 non-binary; ages 19–51), which took 120 minutes each on average. We designed eight paths in the virtual environment, each containing at least two intersections, turns, and curved segments. After a tutorial session, the participants completed eight tasks, each consisting of two phases:

1) Guided Navigation, participants navigated a predefined path using our system (spatial audio, haptics, footstep sounds);

2) Reconstruction, participants re-navigated the path they had just navigated by moving with a joystick and rotating their bodies, guided only by footstep sounds in an open virtual space. This phase assessed how well they could recall and reproduce the spatial layout using only auditory and proprioceptive cues.

4 Result and Discussion

This section presents the results in two key themes.

Natural movement helps with complex route understanding, but to a limit: Fig. 2 shows examples of the trajectory results from participants. Analysis of think-aloud verbalizations and trajectories revealed that blind participants recognized turns up to 90° (Fig. 2-A), and were able to capture the general curvature, but not always precisely (Fig. 2-B). On the other hand, turns exceeding 90° were often misrecognized (Fig. 2-C). In more complex paths containing four turns, all participants produced reconstructions with only three turns (Fig. 2-D). Interview comments suggest that smaller turns can be handled with a single, continuous body rotation, while larger turns require multiple rotations, leading to spatial disorientation, e.g., *"Once I rotate my body from its original facing direction (and then rotate again), I lose track of how much I've actually turned."* This highlights the difficulty blind participants face in encoding and recalling virtual environment layouts, even for relatively simple, corridor-like paths. We can improve our system by implementing functions that notify users of large turns in advance and provide a summary of the navigated path.

Navigation is better when feedback modalities match the task and user preference: Participants actively changed between spatial audio and haptic feedback according to the navigation task. Spatial audio was preferred for general orientation, *e.g., "I knew where to head because the sound came from that direction"*, while haptic cues were used for fine-tuning directions *e.g., "I used the controller to find the spot where the vibration stopped"*. This complementary design enabled, to some extent, effective and confident navigation, suggesting the value of multimodal strategies in VR navigation systems for blind people *"With spatial audio, I could perceive the general position and distance, and with the vibration, I got the precision—the finer details, so to speak."*.

5 Conclusion

We developed a VR system that supports blind people in exploring complex, large environments via pre-mapped routes. Our study showed that participants could perceive routes with up to two non-perpendicular turns and general curvature, but struggled with multiple turns over 90°. Future work includes adding route summaries for large routes.

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