Investigating Virtual Reality Locomotion Techniques with Blind People

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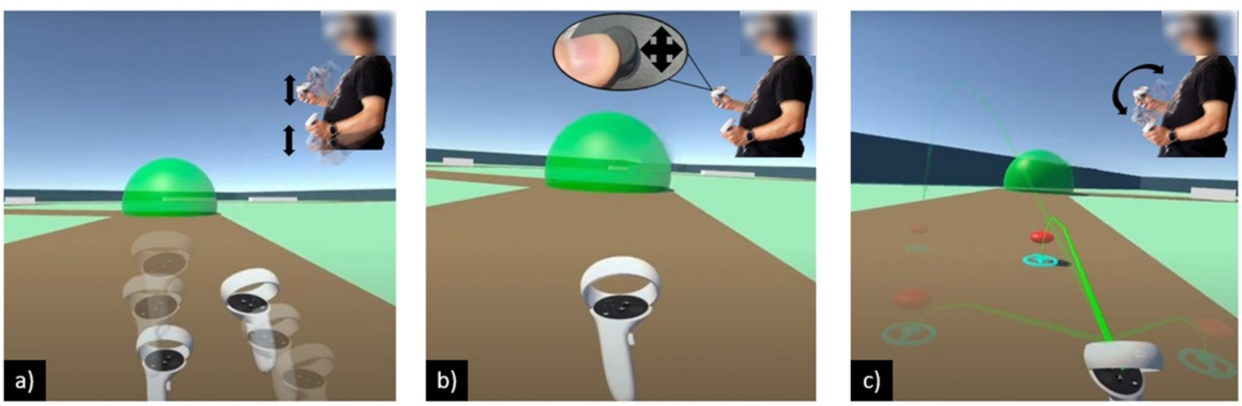

Figure 1: Three popular VR locomotion techniques implemented and augmented with audio and haptic cues for accessibility: a) Arm Swinging - uses the movement of the arms (up/down) while standing in place and pressing the trigger buttons; b) Linear Movement - relies on the controller's thumbstick to indicate the walking direction and speed; and c) Point & Teleport - uses the controller's direction and inclination to select the location, and the trigger button to Teleport. All techniques use the headset orientation to infer head orientation.

ABSTRACT

Many Virtual Reality (VR) locomotion techniques have been proposed, but those explored for and with blind people are often custom-made or require specialized equipment. Consequently, it is unclear how popular techniques can support blind people's VR locomotion, blocking access to most VR experiences. We implemented three popular techniques — Arm Swinging, Linear Movement (joystick-based steering), and Point & Teleport — with minor adaptations for accessibility. We conducted a study with 14 blind participants consisting of navigation tasks with these techniques and a semi-structured interview. We found no differences in overall performance (e.g., completion time), but contrasting preferences. Findings highlight the challenges and advantages of each technique

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and participants' strategies. We discuss, among others, how augmenting the techniques enabled blind people to navigate in VR, the greater control of movement of Arm Swinging, the simplicity and familiarity of Linear Movement, and the potential for efficiency and for scanning the environment of Point & Teleport.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; **Accessibility**; **Virtual reality**.

KEYWORDS

Point and Teleport, Linear Movement, Arm Swinging, Visual Impairment, Navigation, Virtual Reality.

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1 INTRODUCTION

Locomotion plays a key role in Virtual Reality (VR), allowing users to navigate and explore the virtual world. Multiple techniques have been proposed and implemented [6, 13, 18], ranging from familiar digital interactions (e.g., analog joystick) to magical (e.g., teleport) options or to mimic real-world movement (e.g., a treadmill or arm swinging). This variety of locomotion techniques provides a range of experiences with different levels of immersion, comfort, and freedom of movement [18, 43]. In addition, the different interaction mechanisms satisfy different abilities (e.g., using the controllers, legs, or even posture to walk), potentially increasing the accessibility of VR experiences. Still, little is known about the accessibility of locomotion techniques, particularly for visually impaired people.

Visual feedback is the primary means of interaction in current VR experiences, posing significant challenges for blind people to both understand and navigate the environment. Prior research in accessible VR for blind people has focused on developing and evaluating custom-made applications, for instance, to support Orientation and Mobility training [19, 38, 55, 58]. In particular, locomotion approaches often mimic real-world behavior leveraging prior skills and experience– e.g., by augmenting a white cane [41, 56, 62]. While these novel, specialized approaches provide valuable contributions to the field, they are generally unavailable in current VR applications – for instance, due to the need for additional equipment, and/or because the prototypes are used in research contexts alone. In addition, designers often carefully choose the locomotion method as it affects the experience [11, 12], meaning specialized techniques could be complex (or sometimes unfit) to integrate into existing experiences – e.g., walking with a white cane significantly differs from Teleport. For these reasons, VR applications are currently deeply tied to the locomotion techniques selected by their designers. Understanding the potential that the most popular locomotion techniques have to support accessible experiences may increase and diversify blind people's access to (mainstream) VR experiences.

In this paper, we investigate how three common locomotion techniques support blind people navigating VR environments: 1) **Arm Swinging**, which uses body movement (arms) similar to real-world walking; 2) **Linear Movement**, which relies on the controller's thumbstick; and 3) **Point & Teleport**, which instantly moves the avatar to a specific location. We then augmented each technique when necessary with haptic and auditory cues to ensure accessibility (e.g., the sound of footsteps and haptic/sound of collisions), as suggested by prior work (e.g., [2, 21, 27]). Our main goal was to understand how these techniques support, or not, blind people navigating VR environments. In particular, we wanted to answer the following research questions:

- What are the differences among Arm Swinging, Linear Movement, and Point & Teleport in terms of performance and user preference?
- What are the relative advantages of each technique, and how do users' interactions and strategies impact performance?

We conducted a user study where 14 blind people were asked to complete VR navigation tasks using the three locomotion techniques. We evaluated the effectiveness (reaching the objectives) and efficiency (completion time and travel distance) of the three techniques in each scenario, performed a brief questionnaire, and conducted a semi-structured interview to better understand user strategies and preferences.

Our findings showed that most participants could complete the navigation tasks with the three locomotion techniques. However, they showed no statistically significant differences among techniques in performance nor self-reported ease of use, fun, comfort, efficiency, and accessibility. This is likely because performance and preferences varied widely among participants, as did their interactions and strategies. Linear Movement was often mentioned as comfortable, familiar, and fun by regular and occasional gamers, but boring and uncomfortable by others. Arm Swinging provided greater awareness of movement and enabled more participants to reach the five objectives, but Point & Teleport resulted in the fastest trials (e.g., by performing quick, consecutive teleports). In addition, some behaviors were transversal to all techniques, such as using body rotation to better align with the objectives. Finally, we discuss lessons learned from our study to inform accessible VR locomotion design, particularly the effect of augmented audio and haptic cues, and each technique's advantages, drawbacks, and affordances.

2 RELATED WORK

This section discusses 1) the numerous locomotion techniques implemented and studied with sighted people, 2) research efforts for accessible virtual environments for blind people, and 3) locomotion for blind people in VR.

2.1 Locomotion in VR

Locomotion is an essential aspect of VR design and is vital to the overall user experience [18]. It enables users to engage with virtual environments in previously impossible ways, such as physically walking, running, or jumping.

Prior research has extensively studied the numerous locomotion techniques proposed and implemented in commercial and academic contexts. Many literature reviews, taxonomies, and databases (e.g., [1, 5, 13, 18, 43]) have tried to define existing locomotion techniques and study essential elements such as immersion, ease of use, tiredness, motion sickness, among others.

Literature reviews often assign locomotion techniques into specific categories, creating taxonomies to group similar locomotion techniques together. Martinez et al. [43] relied on known taxonomies [1, 7] to categorize locomotion techniques and understand their exploration in the literature. They found that Walking-based Locomotion (i.e. relies on physical movements and actions) is the most prevalent, followed by Steering-based (i.e. users may continuously specify a direction of travel – e.g., with a joystick) and Selection-based (i.e. select a destination or path to travel to – e.g., teleport). Less common techniques fall under Manipulation-based (i.e. users may manually control their position in the environment, such as dragging to a particular position) and Automated (i.e. the system controls the user's movement).

Similarly, Boletsis [5] found that most VR locomotion techniques rely on physical interaction, harnessing physical motion cues to navigate within VR environments. While these reviews and existing studies comparing a subset of techniques showcase the pros and cons of each technique, they sometimes present contradicting findings. For instance, joystick-based techniques are sometimes found to outperform the others [13], but specific comparisons often find more efficient techniques, such as Point & Teleport [8], or Redirected Walking [40]. These differences support the need to investigate prominent techniques under different scenarios. Still, the accessibility of locomotion techniques is not addressed in prior reviews, despite the known challenges experienced by people with disabilities with VR technologies [17].

An exception is the Locomotion Vault [18], a database and visualization consolidating information on 109 locomotion techniques. It contains a selection of 19 attributes derived from the analysis of the literature and two attributes proposed by the authors - one of which is accessibility ("*how easy is adopting this LT for users with disabilities?*"). Despite the step forward, accessibility is defined in terms of the motor ability required to use the techniques, which is likely due to prior research on VR for people with motor impairments (e.g., [45, 60]). Still, there is very limited knowledge of the accessibility of locomotion techniques for people who are blind.

2.2 Virtual Environments for Blind People

The accessibility of virtual environments is frequently ignored, which is especially relevant for blind people, as interaction usually relies on visual stimuli.

Digital gaming is one of the most active research areas trying to improve blind people's experience in virtual environments (e.g., [3, 21, 47, 48, 57]). NavStick [47], for instance, allows blind gamers to probe their surroundings by scanning a specific direction at a time with the controller joystick. Gonçalves et al., [21] explored how expert blind gamers played mainstream visual-centric games, as well as the strategies employed to successfully navigate the environment. In both works, the importance of sound design is highlighted, as well as the ability to understand the surroundings to be able to navigate therein.

In more immersive VR – e.g., using a Head-Mounted Display (HMD) – prior work has also shown the importance of audio and haptic feedback for understanding virtual environments [34]. Recent efforts include augmenting virtual objects with alternative audio representations using a VR boxing use case [22], and supporting social VR experiences by dividing the social space into different social bubbles while conveying audio feedback accordingly [30].

Another active line of research is the design of virtual environments to support mobility training or gaining spatial knowledge of real-world locations [14, 19, 23, 36, 59]. These and other works also leverage blind people's skills in the real world to support navigating virtual worlds – e.g., using echolocation skills [2]. In addition, for systems with desktop and smartphone implementations, navigation often relies on the keyboard or joystick (e.g., [14]), or the smartphone itself (e.g., [23]). Still, current VR technology now supports more immersive alternatives that blind people may leverage.

The abovementioned research has contributed valuable knowledge to design more accessible virtual environments. In particular, the haptic and audio feedback used in prior work can inform the design of accessible virtual environments and locomotion techniques.

2.3 VR Locomotion for Blind People

Locomotion techniques aiming to create immersion often draw inspiration from real-world settings, translating physical movements from real into virtual environments. An existing approach is to walk in the real world, producing the same effect in the virtual world. This has been used in past work on Orientation and Mobility training [59], and on promoting physical activity [28]. However, the equivalence to real walking imposes constraints as the experience must be designed for small spaces, or a large space is needed for using the device.

A way to deal with physical space restrictions is to use walking-based techniques where users stand in place. Prior explorations with blind people include either a treadmill or trackers to detect steps [25, 33, 35], which require specialized equipment.

Other techniques, exclusively designed for blind people, use their mobility skills and navigation aids to support virtual navigation. In particular, prior work has proposed using a white cane, augmented with haptic, force-feedback to simulate obstacles and real-world navigation [41, 56, 62]. Alternatively, prior work has explored teleporting to specific locations selected from lists of objects, people, or points of interest [4]. Such approaches significantly ease reaching specific destinations but at the cost of freedom of movement through the environment.

Additional works have compared existing locomotion techniques [25, 35]. For instance, BlindWalkVr [35] compared using walking-based techniques (with treadmills or trackers) against the Joystick and found the latter to feel safer, more precise, and intuitive. In addition, participants felt walking on treadmills was unnatural. Still, the evaluation was based on the users' subjective perceptions alone.

Overall, prior research has made significant contributions, frequently relying on custom-made solutions that demand specialized equipment or extensive/unrestrictive spaces. Unfortunately, this specificity often restricts the widespread adoption and implementation of such techniques due to their intricate setup requirements. In this work, we focus on widely popular techniques that lack these demanding prerequisites, aiming to enhance our understanding of approaches more readily accessible to the general population.

Prior research also exploring common techniques (some requiring specialized equipment) has provided interesting insights based on participants' subjective perspectives [35]. Instead, we focus both on objective metrics to understand how each technique impacts performance, and on observations and subjective feedback from semi-structured interviews to gain a deeper understanding of users' perceptions and behaviours.

3 LOCOMOTION TECHNIQUES FOR BLIND PEOPLE IN VR

There have been valuable contributions concerning locomotion techniques for blind people, but there is still little knowledge of how common techniques support blind virtual navigation. In particular, we aim to explore blind people's performance and preferences with the most common types of locomotion techniques – walking, steering, and selection-based [43].

To select the locomotion techniques, we analyzed both the literature (e.g., [6, 13, 18, 43]) and resources available on the market (e.g., [24, 61]). Similarly to prior work [10, 16, 40, 46, 53], we considered techniques that can be used in place (to avoid being constrained by the physical world) and that do not require any specialized hardware besides the HMD and handheld controllers. In addition, we selected techniques that are very different among themselves while also being popular in the literature and commercial VR applications. We also ensure we have represented VR's versatility with techniques that provide a sense of realism or transcend the boundaries of physics (magical) [18].

In this work, we implemented and evaluated three locomotion techniques: Arm Swinging, Linear Movement, and Point & Teleport. We maintained the core implementation of these techniques and augmented them with haptic and auditory cues (e.g., collisions represented with sound and vibrations) to support accessible navigation. In the implementation of these cues, we performed preliminary testing within the research team and one pilot study with a blind participant, who helped refine our feedback cues.

3.1 Arm Swinging

Arm Swinging is a Walking-based technique relying on Partial-Gait locomotion [43], where users are required to move their arms while standing in place and pressing the *trigger* buttons (Figure 2 A1). The velocity of the virtual character depends on how fast users move their arms (Figure 2 A2), and the headset orientation gives the direction. Arm Swinging is the most explored Walking-based technique in the literature, considering those not requiring additional hardware and where the user stands in place [43]. In addition, it is included in many VR applications (e.g., Thief Simulator VR, Creed: Rise to Glory).

We implemented additional cues to ensure the accessibility of this technique based on prior work on accessible virtual environments [2, 21, 27]. These cues include the sound of footsteps that indicate both the walking speed and the type of terrain. Collisions are announced with a bumping sound and the vibration of their controllers. For instance, if the user collides front-facing an obstacle, both controllers vibrate, but if the obstacle is on the right, only the right controller vibrates (and footsteps may continue if the collision – e.g., with a wall – is not stopping the user).

3.2 Linear Movement

Linear Movement (referred to as Joystick-directed Steering in [43]) is the most explored Steering-based locomotion technique in the literature [43] and is available in many VR applications. This technique relies on the controller's thumbstick to indicate the walking direction (with right and left corresponding to lateral movement) (Figure 2 B). Similarly to Arm Swinging, rotation is given by head(set) orientation, meaning the user can still rotate physically. Velocity depends on the force applied to the thumbstick, meaning that slightly pushing it forward would result in walking slowly.

The additional cues implemented in this technique include the sound of footsteps and collisions (as in Arm Swinging). In addition, we included a soft mono audio (wind sound) to indicate when the user is moving straight ahead (within a 10º radius). This was intended to prevent veering due to users slightly tilting the thumbstick to the left/right when trying to move forward, which was observed in preliminary testing.

3.3 Point & Teleport

Point & Teleport is the most explored Selection-based locomotion technique in the literature [43] and one of the most overall (both in the literature and commercial VR applications). Because of its ubiquity in different VR platforms (e.g. Meta Quest) [29], we used the arc-based or parabolic curve aim. This technique relies on the controller to point to a specific destination, instantly placing the user at the intended location after pressing and releasing the *trigger* button (Figure 2 C1)). In addition to the direction (Figure 2 C3)), the user can control the distance of the teleport by pointing the controller upward (further away) or downward (Figure 2 C2)). Head(set) orientation affects the audio feedback received (as if the avatar turns the head in the virtual world), but the controller's position and orientation are what dictate the direction of the teleport.

We implemented additional cues to support users in understanding the outcomes of their actions. To convey both direction and proximity, a sonar-like spatialized sound is emitted from the destination's location when pointing to teleport. To help detect obstacles, a different sound is emitted (e.g., a bumping sound) when pointing to a location where teleportation is impossible (e.g., a wall). For confirmation, a distinctive "whoosh" sound is emitted when teleport is successful. To provide additional feedback on the distance traveled, the length of such sound varies – meaning longer the teleport, longer the "whoosh" sound, and vice-versa. After this sound, one footstep sound is emitted to convey the terrain where the user landed. When trying to teleport to an impossible location (e.g., a wall), a failure sound is emitted. Finally, a subtle vibration on the controller used for pointing is conveyed when reaching the maximum teleport amplitude.

4 USER STUDY

We conducted a user study with 14 blind participants aiming at answering the following research questions:

(1) What are the differences among Arm Swinging, Linear Movement, and Point & Teleport in terms of performance and user preference?
(2) What are the relative advantages of each technique and how do users' interactions and strategies impact performance?

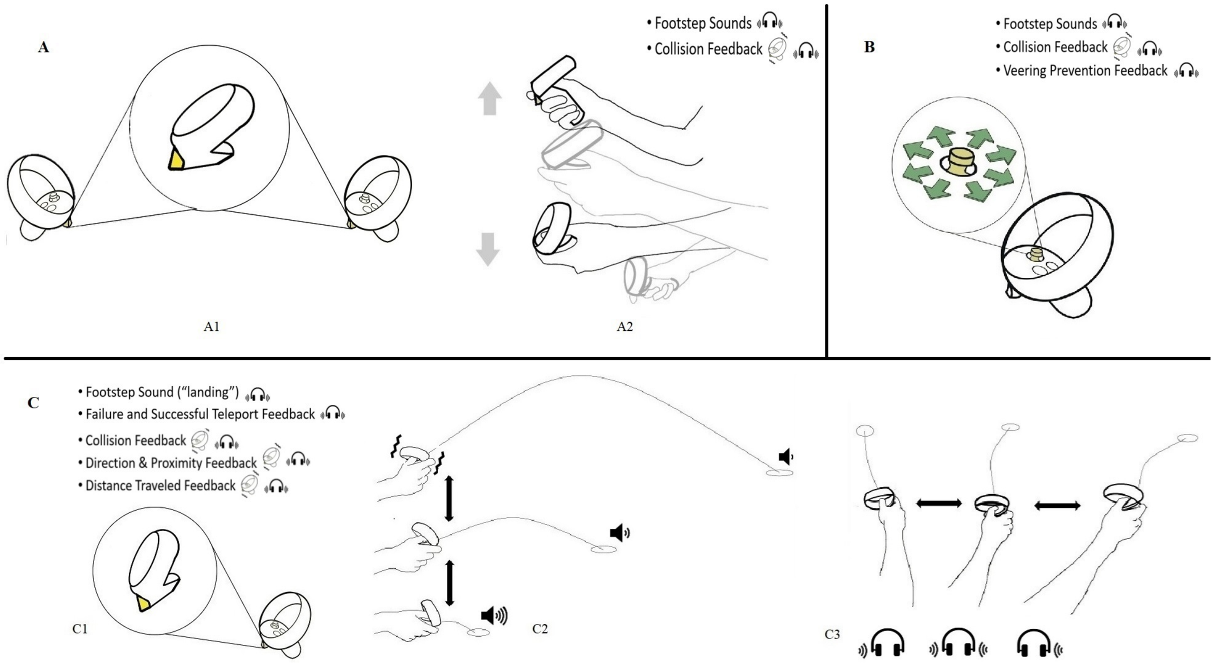

Figure 2: The three popular locomotion techniques with the respective feedback (the icons represent auditory and haptic feedback): (A) Arm Swinging - A1) Trigger buttons of VR controllers to engage the technique; A2) user moving the arms in an up and down motion; (B) Linear Movement input, displaying possible directions to push the thumbstick. The force applied to the thumbstick influences speed; (C) Point & Teleport - C1) Trigger button of VR controller to engage the technique; C2) user controlling the distance of the teleportation alternating the wrist upward to downward, vice versa; C3) user adjusting the direction of the destination.

Participants completed navigation tasks using the three techniques in a VR environment, followed by a semi-structured interview to gather a comprehensive understanding of strategies and preferences. The study protocol was approved by the University's Ethics Committee.

4.1 Implementation of VR Prototype

Our VR prototype was developed using Unity3D, running on the Meta Quest 2 VR system, with the Rift software and the Oculus Integration package. Meta Quest 2 includes a Headset and two controllers. In addition, we used the Oculus Spatializer Plugin for sound spatialization, Narakeet for TTS (Text-to-Speech), and the Firebase realtime database to log all user interactions. The implementation of the virtual environments and of the three locomotion techniques is available at https://git.lasige.di.fc.ul.pt/raribeiro/vr-locomotion-blind-people.

4.1.1 Virtual Environments. We built two environments for the user study: a learning environment (180x180 meters) to introduce participants to the technique and to the VR application and a study environment (260x200 meters, with three possible layouts) to perform the study tasks.

Learning Environment. This environment introduces new elements iteratively, allowing participants to learn new features gradually. It starts as an open, no-boundary space with two different types of terrain, to understand how to move with a given technique and the feedback of footsteps (velocity and sound of each terrain). Then, a wall is introduced to explain how collisions work. Finally, an objective element producing sound is added to better explain spatialized audio, and participants are tasked to reach it.

Study Environment. This environment features a boundary space, with grass terrain, and a gravel path with varying angles. Both the grass and gravel terrains include obstacles. This environment also features five objective elements that produce a looped piano sound[1], to convey target location in space. We designed three equivalent layouts (Figure 3) to be used in the study tasks.

4.1.2 Locomotion Techniques. When possible, we used the native assets provided by Unity3D and the Oculus Integration package for the locomotion techniques. Below, we detail the implementation of each technique.

Arm Swinging. Since Arm Swinging is unavailable in the Oculus Integration package, we based our implementation on prior examples of this technique. In particular, the Arm Swinger technique[2] described in the Locomotion Vault [18], and a prior implementation described online[3].

[1] Piano Sound - https://pixabay.com/sound-effects/67634/ (last visited on February 2nd, 2024)
[2] Github repository - https://github.com/ElectricNightOwl/ArmSwinger (last visited on February 2nd, 2024)
[3] Unity VR XR Toolkit Development (Walking In Place, Arm Swing) Tutorial - https://youtu.be/Eipi6rNPz9U (last visited on February 2nd, 2024)

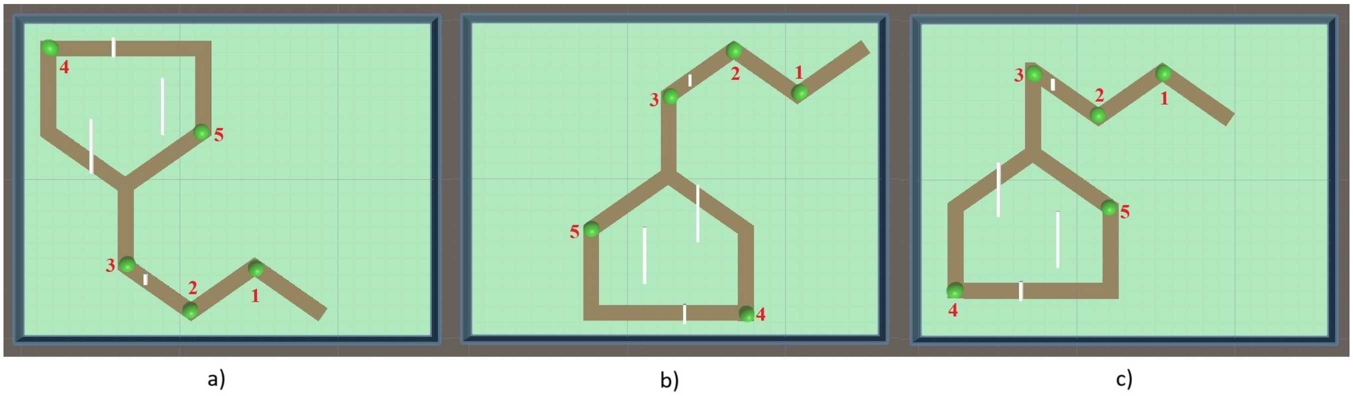

Figure 3: Study Environment with the three possible layouts (a, b, and c), and all the objectives (and corresponding sequences)

We used the velocity of movement of the VR controllers, to understand how fast the user was moving. To ensure that the velocity aligns accurately with the user's perspective, the velocities (of each controller) were converted to world space where the maximum velocity is 2.5 m/s. This value was based both on prior studies that used 2 or 3 m/s [6, 39] and on experimentation to ensure realistic footstep rhythm.

Linear Movement. We used the implementation available in the Oculus Integration package. We changed the speed threshold to ensure a velocity range similar to Arm Swinging, with a maximum of 2.5 m/s. In addition, we added the footstep and collision feedback, and the wind sound to prevent veering.

Point & Teleport. We adapted the implementation from Oculus Integration package to support the audio and haptic cues previously described. The orientation of the controller indicates the direction of Teleport, and the maximum range is approximately 8 meters.

4.2 Participants

We recruited 14 blind participants (Table 1) through a local training institution for people with visual impairments. Participants were between 26 and 63 years old (M=41.5; SD=10.4). Thirteen participants were totally blind or had light perception at most, while one (P11) had residual vision in one eye[4]. We excluded P11 from the quantitative analysis due to a higher level of residual vision, as well as P4, who completed only one of the tasks due to fatigue but considered their comments in the qualitative analysis. Most participants rated themselves as somehow experienced with technology but less experienced with virtual environments. Seven participants had never tried VR, while six tried it once or twice. In particular, four participants experimented with VR in a prior research study, while the others did not specify their prior experience.

4.3 Apparatus

We used the above VR prototype, running on a laptop with compatible system graphics (NVIDIA GeForce RTX 3070). The wired connection gave more control over the experience, enabling the researcher to set/switch the environments and techniques as needed and have visual feedback. During the study tasks, participants were instructed to use headphones to enhance spatialized audio. The data from the study (e.g. task completion, time) was saved in Firebase.

The study was conducted in a room at the training center (P1-P13) or a location chosen by the participant (P14), ensuring enough space and low noise levels.

4.4 Methodology

The study had a within-subjects design, where all participants executed a navigation task with three different conditions – the three locomotion techniques. The order of each condition was counterbalanced, using the latin-square design. Our methodology revolves around quantitative analysis, involving participants' task performance and self-reported ratings (e.g., comfort, fun), and qualitative analysis based on semi-structured interviews and observation.

4.4.1 Navigation Task. Participants performed three navigation tasks, one with each technique and layout (Figure 3). These tasks mimic traditional A to B navigation, which is common in many contexts where users know where they want to go (e.g., in Social VR or in games). We selected simple tasks (e.g., similarly to [20, 26]) due to the lack of knowledge about the accessibility of these techniques. For each task, participants were asked to reach five objectives as quickly as possible. These objectives emit a spatialized sound, enabling participants to understand their location. The objectives appear sequentially (from 1 to 5), meaning there is only one active objective at each time. An objective appears right after reaching the previous one or after a time limit of three minutes (for that objective) to avoid fatigue and frustration. If unsuccessful, a corresponding mono sound would play, and the avatar would be positioned on the objective location, ensuring all participants start from the same position when seeking the next objective.

We started with simple scenarios (from A to B, without obstacles nor other users), moving to slightly more complex ones (e.g., including walls to cope with collisions). When starting, the avatar is misaligned with the first objective (90 degrees to the left or right) to require reorientation (Figure 3). Objectives **O1** and **O2** only require reorienting and moving straight. **O3** requires moving straight but

[4]While recruitment was directed to people with no to very little residual vision, P11 reported having residual vision when starting the study, which enabled him to perceive some elements in the virtual environment.

Table 1: Participant demographics, with experience (technology and virtual environments) rating from 1 (Not Experienced) to 7 (Very Experienced).

ID	Age	Gender	Technology	Virtual Environments	VR Experience
P1	63	M	4	4	1-2 times
P2	55	M	7	4	None
P3	38	F	6	4	None
P4	29	F	4	1	None
P5	39	M	5	1	1-2 times
P6	38	F	5	5	None
P7	26	F	7	5	None
P8	40	M	5	3	1-2 times
P9	49	F	4	3	None
P10	55	M	4	5	>5 times
P11	38	M	3	1	None
P12	35	M	5	3	1-2 times
P13	41	F	5	4	1-2 times
P14	35	M	6	4	1-2 times

includes an obstacle in the middle of the gravel path. In these objectives, a gravel terrain represents the shortest path. While this may work as a hint, participants were not informed and were completely unaware of the environment, as we wanted to grasp if participants leveraged these differences. Objectives **O4** and **O5** had obstacles in the gravel path and along the shortest path. These intend to force collisions to better understand how each technique supports such scenarios. To compare users' performance using each locomotion technique, we collected data regarding the number of objectives successfully reached, completion time and distance traveled.

After completing the task with each technique, we asked the Single Ease Question [54] where participants had to rate task ease from 1 to 7 (1- Very Difficult, 7- Very easy). We also used 7-point Likert Items about the efficiency, fun, comfort, and accessibility of each technique (from 1- Strongly Disagree to 7- Strongly Agree).

4.4.2 Semi-Structured Interview. We conducted a semi-structured interview, focusing on understanding the rationale behind participants' preferences and each technique's relative pros and cons. In addition, we asked about the preferred way to navigate virtual environments in VR, and we tried to understand participants' perceptions of the accessibility of the environment and specific elements (e.g., collisions with walls). We audio-recorded the interview for later transcription and analysis.

4.4.3 Procedure. Sessions took on average 84 minutes (minimum 69, maximum 112). All sessions were conducted by two to three researchers, where the first author conducted the study, and the others observed, took notes, and facilitated the experience (e.g., moving the cable if needed).

Introduction. Each session started with a short overview of our research and its main goals. Participants were informed about their rights and signed a consent form, followed by a questionnaire focused on demographics and experience with technology and VR. The audio of the whole session was recorded after consent. Participants were then introduced to the VR equipment, where the researcher gave a brief explanation of its components while participants explored them with their hands to learn their size, weight of the headset and overall button position on the controllers. Then, participants were assisted in wearing the Meta Quest 2 hardware.

Study Trials. Participants were then asked to experiment with the three locomotion techniques in sequence. When starting with each technique, participants entered a learning environment, where features were introduced sequentially by the researcher, who provided detailed explanations about the feedback and interactions of each technique, followed by a TTS message from the system. After each message, participants could experiment with the technique and clarify questions with the researcher. After completing the learning phase and making sure participants did not have doubts about the technique, the researcher started the navigation task, where a TTS message indicated the goal. After each task, we asked participants to rate the five 7-point questions and asked if participants wanted to take a short break.

Debriefing. After completing the tasks with all conditions, we asked participants to rank the locomotion techniques according to their preference and performed the semi-structured interview. Finally, we thanked participants for their time and insights. All participants received a 10€ gift voucher for their participation.

4.5 Data Analysis

We ran the Shapiro Wilk test to assess the normality of the task performance metrics: number of objectives reached, completion time, and distance traveled. The completion time variable had a normal distribution for all techniques, while the remaining variables did not. To compare the three locomotion techniques, we used the ANOVA repeated-measures test for Completion Time, which involved a single factor (locomotion technique) with three levels, and the (non-parametric) Friedman test for the remaining variables. Similarly, we ran the Friedman test to compare the Single Ease Question and Likert Items results among the three techniques.

We transcribed all semi-structured interviews and conducted a mixed deductive-inductive thematic analysis, described as a codebook approach by Braun & Clarke [9]. The initial codebook was created based on our concepts of interest (for instance, the locomotion techniques, fun, efficiency, and accessibility) and our familiarity with the data, complemented by notes taken during the study. Then, three researchers independently coded the same two interviews, adding new codes as necessary (e.g. orientation, real movement). They met to discuss the resulting codebooks to refine and ensure all relevant topics were captured. Then, the remaining interviews were split between the first three co-authors. The themes presented in the findings result from multiple discussions and iterations over a live document with sense-checking by all authors.

5 RESULTS

We present our findings supported by a quantitative analysis of performance and participants' self-reported ratings, and a qualitative analysis based on participants' feedback and observations of their navigation tasks.

5.1 Performance Analysis

There was no significant difference (p=0.17) in **the number of objectives reached**. Eleven participants reached all five objectives with Arm Swinging (M=4.92, SD=0.29), while seven reached all with linear Movement (M=4.33, SD=0.98) and eight with Point & Teleport (M=4.25, SD=1.48). One participant did not reach any objective with Point & Teleport, while on average, participants reached 13.50 objectives across the three techniques (and six reached all fifteen objectives).

As for **completion time** (Figure 4), participants on average took less time with Arm Swinging (M=233.00, SD=87.89), but no significant differences (p=0.301) among techniques were found when compared with Linear Movement (M=297.50, SD=209.90) and Point & Teleport (M=320.67, SD=230.99). There were also no significant differences when comparing the time to complete each objective individually. Looking at the time spent on each objective, O5 was where participants took longer on all techniques, which was expected due to its complexity.

One participant reached all objectives with Point & Teleport within 46s, showcasing its potential for efficiency, while the minimum for the other two was close to 120s. On the other hand, Point & Teleport also represents the longest completion time (900s, for the participant unable to reach any objective with this technique), showcasing its greater complexity.

Finally, for the **distance traveled**, participants walked less with Arm Swinging (M=520.79, SD=143.56), with no statistically significant difference (p=0.097). The averages of the other two were close to 800m with high variance (Linear Movement M=765.84, SD=450.23; Point & Teleport M=837.42, SD=455.65). It was also with Arm Swinging that a participant walked the minimum of 414.17m, across all three.

5.2 Self-Reported Ratings

Through the debriefing, participants ranked their favorite techniques, showing a balanced result with varied preferences (Table 2). Linear Movement was the most preferred, but not by far (5 participants preferred it, against 4 and 3 of Arm Swinging and Point & Teleport, respectively). On the other hand, Linear Movement was also the one most mentioned as least preferred (5 participants).

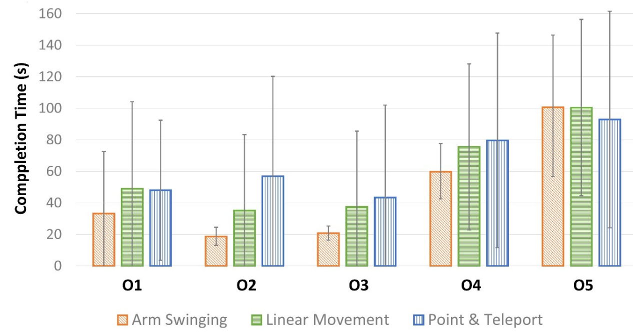

Figure 4: Average completion time per objective [O1 - O5] (in seconds) by all participants, for each technique. Error bars represent standard deviation.

Table 2: Frequency of participants' order of preference for each locomotion technique

Locomotion Techniques	First	Second	Third
Arm Swinging	4	5	3
Linear Movement	5	2	5
Point & Teleport	3	5	4

After finishing each task, participants were asked to evaluate the respective technique according to its Ease of Use, Efficiency, Fun, Comfort, and Accessibility. We found no statistically significant differences among the three techniques in any parameter. Overall, the tasks were marked as **Easy** to complete by most participants for all techniques (Figure 5). In addition, all techniques had high, similar values for **Efficiency**, **Fun**, **Comfort**, and **Accessibility**.

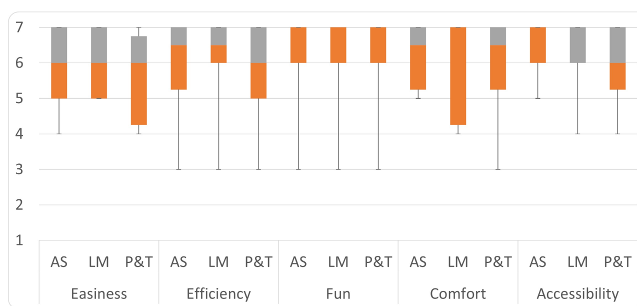

Figure 5: The Box Plot Graph demonstrates the variation of the answers from 1 to 7, according to the Likert Scale to different aspects of the Locomotion Techniques (AS - Arm Swinging; LM - Linear Movement; P&T - Point & Teleport) tested by the participants.

5.3 Findings from Qualitative Analysis

In this section, we present the findings divided into five main themes: preferences, dealing with direction, controlling movement, feedback cues and understanding the environment, and body language. All quotes were translated from Portuguese to English.

5.3.1 Preferences. Participants often justified their preferences when asked to justify their ranking. As reported above, preferences varied widely among participants as each technique significantly impacts the overall experience, by affording specific advantages for a subset of the participants. For instance, those very keen to exercise would like the physical activity of Arm Swinging, while others would prefer less tiring options.

> "*The arms require the person to move more and when the distances are long they have to swing their arms a lot*" - P1

It is this physical activation, however, the main factor for those preferring Arm Swinging:

> "*It makes it more interactive and we are more aware of the movement (...) if we want to accelerate we move our arms, it's not something we have to press a button.*" - P13

> "*For me, for my gaming experience, I like it better when it is more physically demanding, let's say... That it involves more movement, real.*" - P14

On the other hand, participants who enjoyed being physically active, described Linear Movement as uncomfortable or not as engaging:

> "*What I didn't like about the joystick was that you have to press a button all the time to move forward (...) it's a bit more uncomfortable.*" - P3

> "*I don't find it difficult at all, I just don't find it as stimulating, as much, as much fun*" - P14

Linear Movement was often preferred due to its simplicity and familiarity among occasional gamers. P1 stated that "*the joystick was the most fun [technique] and the easiest to learn*", while P8 referred to his familiarity with buttons in reference to gaming.

Conversely, participants felt that Point & Teleport was the hardest to master (e.g., "*But as I say, I had more doubts about using this technique than the others, but it went well.*" - P1). Its main advantages were its ability to move faster and afford a different experience:

> "*For a matter of … imagination (...) for an environment a bit different. And different in the sense that it is not natural, right? To human beings ... teleporting.*" - P14

Despite participants' preferences, the three techniques were generally rated positively and seen as appropriate for this setting:

> "*It's only because I have to choose one. Because for me they're all easy, all good. I liked them all.*" - P13

Other participants argued that techniques could be more appropriate for specific scenarios while sometimes also referring to possibly combining them depending on the challenge. For instance, P11 mentioned:

> "*In an entrance, I'm on the 2nd floor and want to teleport to the entrance of the building. Maybe it would be better for me to go downstairs in one click (...) but now, if I wanted to go to the office, it would be easier with my arm, to be sure of the path I'm taking*"

P14 agreed on the advantages of having all techniques available or even combining them in the context of a game:

> "*I think that the fact that I prefer the first one [Arm Swinging] doesn't mean that the player can't choose one of the three, and even go on to combine them. Let's suppose the game has levels. I may want to use a Teleport level in the first scenario because it is less difficult, so I can reach the objectives quickly. In the following levels, I may want to move more cautiously, slowly.*"

5.3.2 Dealing with Direction. The three techniques rely on the headset to convey the head's virtual orientation. All participants relied mostly on full-body rotation to align themselves with the objectives and then move forward in their direction. For participants, it was intuitive to use their bodies to face the intended targets, sometimes forgetting there were alternatives:

> "*As I was told that I would therefore walk forward when the joystick was in that direction, I always tried to use the movement of my body, I didn't even think.*" - P1

Interestingly, when rotating their bodies to try to locate the sound of the objective, four participants always rotated to the same side (e.g., only turning right) to grasp differences in sound spatialization. In addition, some participants performed occasional head (e.g. P9, P10, P11) or torso movements (e.g. P3, P11) to try to understand the objective's location.

Moving in other directions – other from forward – intentionally was very rare, even though both Linear Movement and Point & Teleport allowed movement in all directions without changing head orientation. The rare occasions included, for instance, P6 pointing to the side with Point & Teleport while maintaining fixed body orientation.

Unintentionally veering occurred multiple times and was the main reason for taking longer to reach the objectives. This was mostly caused by a mismatch of head orientation and input direction, sometimes leading to continuous circular patterns around the objective (Figure 6). Such behaviour was more common with Point & Teleport, as participants would slightly deflect the controllers when teleporting without realizing they were not pointing straight ahead. With Linear movement, the cause was usually a slight right/left movement with the thumbstick. In both cases, participants were often continuously moving and adjusting the orientation as they went, passing right next to the objective and then readjusting while moving. Participants, however, did not always understand what was happening in such scenarios.

The wind feedback was intended to prevent veering in Linear Movement, but the major focus on the objective led most participants to miss (or ignore) it:

> "*I'll be honest, I didn't use it. I really felt it, but I was so focused on the goal that I didn't pay attention.*" - P1

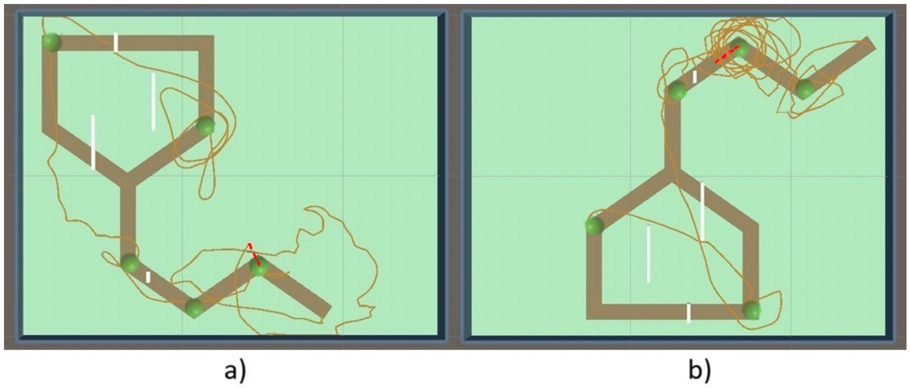

Figure 6: Top view of the environment with participants' trial trajectories, showing circular patterns - a) P9 (Linear Movement) on O5; and b) P6 (Point & Teleport) particularly on O2. Orange solid lines represent the path traveled by the participant and red dashed lines indicate the automatic repositioning when the time limit was reached for a given objective.

Exceptions include P11 and P14, who referred to the importance of the wind feedback to prevent them from veering.

5.3.3 Controlling Movement. Each technique required specific interactions to control movement, which resulted in variations in performance and preference for each participant, despite the overall lack of significant differences in these criteria. The proprioception of Arm Swinging gave participants a feeling of being in movement:

"*The arm movement really is as if you were walking.*" - P5

"*It feels that I am really moving [when] using my arms.*" - P11

In addition, having greater control of movement may result in more precise interactions:

"*As the movement of the technique is slower (...) the arm technique allows for more constant control of the movement you are making.*" - P1

However, most participants did not vary the swing speed, keeping a constant (often the maximum) speed throughout the trial. This may be explained, in part, by the lack of feedback when the maximum speed is reached, meaning participants could vigorously swing their arms without producing differences in speed:

"*In this technique, I didn't know the maximum speed. That regardless of swinging my arms quickly, the speed wouldn't increase*" - P1

Overall, the style and speed of swinging varied among participants with some vigorously swinging their arms, and others swinging them gently, resembling a soft jog. Still, both P1 and P14 referred to Arm Swinging as slower than the others (despite having the same maximum speed as Linear Movement) and suggested increasing the maximum speed when Swinging vigorously. With Linear Movement, participants usually moved forward at maximum speed, as they could easily push the thumbstick until its limit. This resulted in a simpler interaction that was valued by participants (e.g., "*It's just your fingers, the button on the side, to the left and up, it didn't take much work*" - P12). Still, it also provided less control and notion of speed (P11, P14), contrasting with Arm Swinging:

"*I know that it's all .. down, at maximum speed but I don't feel the speed itself, it's as if there's no movement that would lead me to conclude that I'm really at maximum speed*" - P11

Alternatively, a few participants controlled movement by giving small pushes on the thumbstick, resembling clicking a button and assessing their next move continuously. In addition, participants referred to the freedom of movement given by the thumbstick, which resembles locomotion in video games:

"*Is the movement of the joystick. It's that thing where you can have freedom... (...) The joystick allows you to move from side to side, make diagonals, play... with the game, you know?*" - P8

However, most participants only pushed the thumbstick forward, with very few occurrences of lateral walking. Just pushing forward lets participants focus only on body rotation to reach the objectives, which may also cause a feeling of observer as pointed by P1 (whose favorite technique was Linear Movement):

"*It's curious because while in the others I was aware that I was moving, when I was using the joystick technique I seemed to be more concerned with directing myself towards the goal and more 'in that goalkeeper position waiting for the ball to arrive'.*"

Point & Teleport differs from the others in the lack of continuity of movement, which is impossible to replicate in the real world. This caused uncertainty in understanding how to interact with this technique, even for those who performed the best.

In addition, this technique included additional auditory cues, which may have raised unique barriers to participants. P6 referred to greater difficulties using this technique:

"*I don't know if I'd say it was a disadvantage, but I sometimes had a hard time getting to the sound.*"

Some participants referred to Point & Teleport as the most efficient:

"*It's faster. In one click you're right where you want to be (...) And at the same time, you can make the jump to*

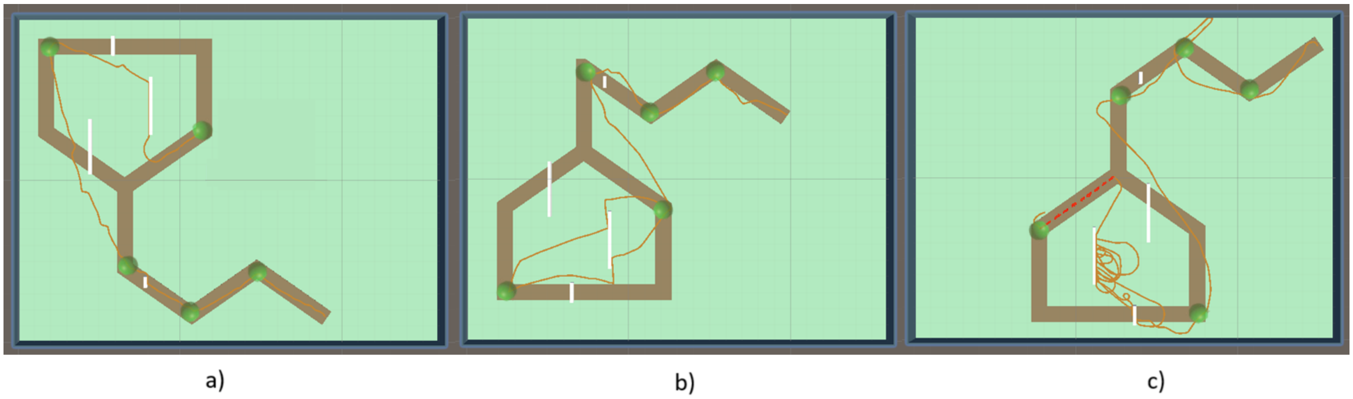

Figure 7: Top view of the environment with participants' trial trajectories - participants using obstacles as a guide: a) P1 (Arm Swinging); b) P14 (Linear Movement); and c) P7 not finding the limit of the obstacle (Linear Movement). Red dashed lines represent the repositioning of the avatar after passing the time limit.

return, which means I can jump to the other side and back in two clicks" - P11

Still, interactions with this technique were different among participants. The most efficient ones usually performed "consecutive jumps", pressing quickly to teleport, while making minor orientation adjustments. P1 was the most extreme case as he took 46 seconds to complete the navigation task with Point & Teleport, while the fastest trials with Arm Swinging (122s, P3) and Linear Movement (116s, P1) were much slower. Other participants, would reassess the auditory feedback of the objective after teleporting, taking longer to complete the trials. Participants also varied their use of teleport amplitude and scanned the surroundings. While some participants always used maximum amplitude, others reduced the length of their teleport when getting closer to the objective, showing awareness of proximity and fear of over-shooting.

5.3.4 Feedback Cues and Understanding the Environment. The environment and the techniques have feedback mechanisms encompassing different audio and haptic cues. All participants agreed on the accessibility of the environment and of the techniques, showing that minor adjustments and careful (but simple) audio and haptic design enable blind people to use these popular techniques. Overall, participants were aware of all elements in the environment, as portrayed by P14's comment:

"*In terms of terrains, it had three types, as I understood, clay, grass, and water. Ahh, then we had the walls, which were perceived with the vibration of the controllers and with the sounds of .. beating, almost percussive. And in terms of sound, we had a human voice singing and a piano. And in the third [Linear Movement], we had the wind, the sound of wind to help with orientation.*"

The spatialization of sound was important for participants to understand the direction and proximity to the objective. The sound of footsteps was relevant to understanding movement and speed, but the different terrains, despite being noticed, were somehow ignored by participants, who did not grasp their potential relevance to the task.

Multimodality was valued on collision feedback (vibrations and bumping sounds), as the vibrations gave an additional cue to what was happening:

"*The question of vibration was very important when we hit the wall, because it's different information, there you go, when we're listening to the music, we're listening to the footsteps, the wind (...) we can see that something strange has happened there.*" - P3

All participants tried to identify the objective's location and moved toward it except when blocked by obstacles. Herein, the locomotion techniques afford different strategies to surpass them. With Arm Swinging and Linear Movement, participants often walked alongside the wall using it as a guide until there was an opening to the objective (Figure 7, a) and b)). Still, as there is no length indication, participants often felt uncertain about the best strategy to surpass the obstacles:

"*I couldn't understand at first if the walls were continuous, or if they were just... a sort of barrier... well, shorter, with a beginning and an end. No, I couldn't understand that and I had some difficulty.*" - P14

In such cases, some participants tried to get further from the obstacle and then tried again, but sometimes circled and went back to the same obstacle (Figure 7, c)).

Point & Teleport afforded a different strategy as participants could sweep their arm and scan for obstacles to understand when there is none anymore. This allowed participants to bypass obstacles and make efficient trajectories. Still, when too close to an obstacle, participants' trajectories would often resemble those of the other techniques as participants were required to go around it.

Participants' focus on the objectives sometimes led to confusion. For instance, some participants felt overwhelmed when dealing with the last obstacle:

"*I knew I had to move, but there was the noise of hitting the wall and the noise of the music and I was*

Figure 8: Top view of the environment with participants' trial trajectories - Example of aimless exploration: a) P8 reorienting trajectory (Point & Teleport); and b) P2 using wall to explore (Linear Movement). Red dashed lines represent the repositioning of the avatar after passing the time limit.

> *like, well and then I suddenly just (...), 'you have to go around because you're hitting the wall'.*" - P3

This can be explained, in part, by the lack of occlusion in the environment, where the obstacle in front was not occluding the objective sound. In such cases, a few participants ignored the collision feedback, describing that the sound was right in front of them:

> "*I was so focused on the sound that it seemed like the sound was already there.... That I'd already located the sound and it was right in front of me (...) but at the same time I could hear the noise of the wall and the remote vibrating a lot.*" - P11

In extreme cases, participants maintained the same behaviours and continued colliding with the obstacle until the time limit was reached. When asked how each technique supports understanding the environment, most participants considered all equally able. Arm Swinging was sometimes considered the one with the greatest potential due to proprioceptive feedback. On the other hand, P1 and P11 mentioned that the lack of continuity in Point & Teleport can bring new challenges in gaining awareness of the space traveled and mapping the environment:

> "*I'm going to a space, but I don't know exactly which one, it's not me making the path, it's as if I'm appearing and disappearing.*" - P11

> "*[With Teleport] the person goes from one place to the other, but the space traversed by the jump ceases to be explored*" - P1

A few participants occasionally deviated from the objective, leaving the range where the sound is audible. In such cases, participants continued an aimless route until finding an obstacle e.g., the walls limiting the environment - (Figure 8) and then reorient their trajectory in an attempt to get closer to the objective.

Overall, and despite being aware of all the feedback cues, participants' focus on the objectives resulted in little knowledge about the spatial arrangement of the environment. One exception was P3, who described the three layouts as identical despite their subtle differences:

> "*The environments of the three techniques were identical. They started with a straight, very simple route, then, if I'm not mistaken, a more diagonal one, and a third that you had to turn to the left, and always go more or less straight ahead.*"

5.3.5 Body Language. We explained how to interact with the VR application and hardware, ensuring participants could perform the actions required comfortably and effectively. Still, we did not force a specific posture or way of interacting with the system. This led to differences in how participants controlled their movement, especially in Arm Swinging where the "swings" varied from pulling (e.g. front to back), using circular motions, or using only one arm up and down. In addition, P14 performed as instructed but suggested a motion close to cycling:

> "*Instead of up/down, it could perhaps be a different technique: front/back (...) In fact, it could even combine the two issues, which is, this almost rotational movement (...) which, in the end, is probably even closer to walking (...) so maybe this is a more bicycle-like movement.*"

In Arm Swinging, participants also unconsciously started walking in the real world, expressing difficulties in suppressing this movement when first introduced to the technique. P1 referred to this tendency to move, especially with Arm Swinging, but also with the other techniques.

> "*The most challenging thing for me was really being able to control the movement of my body, specifically to direct myself in the right directions and then even with the other techniques, I was able to inhibit that tendency to move forward, I think control of position is important.*"

Participants also held the controllers in different ways. For instance, some participants kept them close to their chest in all techniques, as a way to prevent accidental collisions with real-world objects. Still, some hit both controllers against each other or even with the headset (especially with Arm Swinging).

Point & Teleport has also created unexpected behaviours, as many participants would sweep their surroundings (especially facing forward), sometimes resembling a white cane. P7 actually referred to its similarity with a white cane during the learning phase. P6, on the other hand, would keep a relatively stable head orientation while teleporting in the direction of the sound, which contrasted with the body posture of the other participants who would try to align their heads with the objective.

Linear Movement observed a similar posture among participants, independently of how they held the controller (e.g., either closer or further their bodies). An exception is P9 who would actually point the controllers in the direction of where she intended to move.

6 DISCUSSION

We investigated if and how three popular locomotion techniques support blind people navigating VR environments. Results show that most participants could complete the navigation tasks successfully, suggesting that the core implementation of these techniques augmented with careful but simple audio and haptic design (e.g., using footsteps, collisions, and teleport feedback) enables blind people to navigate in VR experiences. In this section, we answer our research questions by summarizing the main results of the user study, and we discuss the lessons learned from our analysis, aiming to inform the design of accessible VR experiences and locomotion techniques.

6.1 RQ1. What are the differences among Arm Swinging, Linear Movement, and Point & Teleport in terms of performance and user preference?

Our quantitative analysis revealed no significant differences among techniques in the performance metrics - number of objectives reached, completion time, and distance traveled. These results differ from the participants' subjective ratings in BlindWalkVR [35], who perceived joystick-based interaction as more precise than three walking-based techniques (that rely on treadmills or feet trackers), and faster (along the Omni Treadmill) than the others. In addition, prior studies with sighted participants report faster completion times with Teleport- than with Joystick-based techniques [49]. However, our study revealed that participants' performance was highly user-dependent as, for instance, Point & Teleport resulted in both the fastest and the slowest trials.

Similarly, preferences were balanced across users and were often aligned with performance – but not always (e.g., P1 preferred Linear Movement, but was much faster with Point & Teleport). Regarding Ease of Use, Efficiency, Fun, Comfort, and Accessibility, participants' self-reported ratings showcase very positive ratings but, again, balanced across techniques. Prior comparisons performed with sighted people found differences in related aspects. For instance, Joystick and Arm Cycling (similar to Linear Movement and Arm Swinging, respectively) were classified as more enjoyable than Teleport (among others) [16]. Another study reported an overall preference for Teleport (and redirected walking) over joystick-based interaction [40]. In contrast, our study showed different, but balanced preferences among blind participants, while all conditions were perceived as equally fun.

6.2 RQ2. What are the relative advantages of each technique and how do users' interactions and strategies impact performance?

Each locomotion technique afforded specific interactions, providing different advantages to participants. For instance, the proprioceptive feedback of Arm Swinging provided greater control over mobility, while Linear Movement was mostly praised for its familiarity and simplicity. On the other hand, Point & Teleport has the potential for efficiency and for inspecting the environment.

These advantages promoted different strategies by some participants (e.g., scanning for obstacles with Point & Teleport, and trailing the wall – a common strategy in the real world [37] – to surpass it with the others), which impacted overall performance.

6.3 Lessons Learned

We extend the answers to our research questions by discussing the lessons learned from the findings of the user study.

Arm Swinging, Linear Movement, and Point & Teleport can support accessible VR Experiences (with appropriate audio and haptic design). The three techniques were augmented with audio and haptic cues that provide crucial feedback for users to perceive their movement and the surroundings. Feedback of footsteps, collisions, different terrains, or to indicate the objectives have been suggested or implemented in the literature related to virtual environments for blind people [21, 35]. Findings have shown participants' ability to (almost always) reach the objectives with all techniques in a relatively simple task. VR designers may use these findings to select and implement popular locomotion techniques that support accessible experiences with little to no additional effort – e.g., many experiences already include a sound for collisions and footsteps – and leverage our adaptations as a starting point for their techniques and experiences. One may speculate that similar techniques (e.g., other walking-based techniques) would also result in overall positive performances, meaning that – with careful audio and haptic design – most locomotion techniques available can potentially support accessible VR experiences for blind people.

That being said, further research is needed to understand how each technique supports different scenarios, especially if considering more complex tasks and experiences. For instance, prior work has investigated differences in spatial understanding, suggesting that a VR treadmill was more effective in remembering routes but less effective in remembering obstacles than VR trackers (walking-in-place) [25]. In our study, participants referred that, while Point & Teleport could be used to quickly reach a destination, Arm Swinging could be used when more caution or precision is needed. Experiments under different scenarios and complexities can help further understand the pros and cons of each technique.

Body Rotation makes interactions even simpler. Participants took advantage of the proprioceptive feedback afforded by VR and the locomotion techniques. Body rotation is important for spatial orientation [42, 52] and prevailed over other orientation techniques, such as rotating the head alone, or moving sideways with Linear Movement (or Point & Teleport), as participants usually moved straight ahead. This was more evident in Linear Movement due to its simpler and familiar interaction with the thumbstick

[35], which was further simplified by participants who relied on body rotation to deal with direction, using the thumbstick only to move forward – or diagonal-forward, sometimes unintentionally (veering). Such behaviour suggests VR designers may rely on body rotation as the main orientation factor. This is also relevant in Linear Movement where participants' mode of interaction questions the need for a typical thumbstick for input – in such cases a single button for navigation could suffice, complemented by head orientation to steer (e.g., similarly to the Lazy Mode in the RIP Motion technique [18]). Still, designers should consider that such simplification would affect the freedom of movement that would allow other types of interactions.

Arm Swinging is perceived to provide greater awareness and control of movement. Arm Swinging, as a walking-based technique, adds the proprioceptive feedback of walking by swinging the arms. This technique resulted in mixed opinions regarding the physical activity required – those keen to it enjoyed it, while others found it tiring – a fact also observed in the literature [6]. Some participants reported having greater awareness and control of movement with Arm Swinging, despite the lack of differences in overall performance metrics. Also, most participants moved at a constant, maximum speed (which also happened with Linear Movement). This suggests that their perceived control may not have been reflected in the virtual environment, likely due to a low maximum speed threshold. Designers and future research may increase such values to provide greater speed variations, potentially improving actual control over movement. However, despite the lack of reports of cybersickness in VR for blind people, special attention must be given to the sound of footsteps to keep them natural and accurately convey speed.

In addition, our tasks and metrics did not focus on participants' spatial representations of the environment, but anecdotal evidence suggests loss of information when using Point & Teleport since this space is not traveled, and a reduced perception of speed when using Linear Movement. While this suggests that designers may use walking-based techniques when such spatial representation is important (as also hinted in [40]), further research is needed to evaluate how each technique supports building mental representations of VR environments.

Point & Teleport has great potential for efficiency but may require additional training. Prior studies on VR locomotion for blind people have focused on continuous walking through the virtual environment with either walking- or steering-based techniques [25, 35, 56]. To our knowledge, this is the first work studying Selection-based (specifically, Point & Teleport) with blind people and comparing it with other techniques. This technique contrasts with the automated ones sometimes found in digital games, which impact users' sense of agency [21], but enables users to quickly move to a desired destination within a specific range, in any direction. Some participants leveraged this by performing rapid consecutive teleports until reaching the destination. P1 spent less than half the time with this technique than the fastest participants in the other two techniques. This links to findings of prior studies with sighted people [8, 49], suggesting designers may consider Point & Teleport an appropriate choice both for blind and sighted people when efficiency is key.

Despite its potential, findings also showed that Point & Teleport was the most efficient technique only for a small subset of participants. This was mostly caused by its greater complexity, which is also a drawback for sighted people [29, 44] who benefit from experience with the technique [49]. Designers may leverage this knowledge to create mechanisms (e.g., through practice or tutorials) to speed up learning when needed. In addition, Point & Teleport required additional feedback cues to give a sense of distance. Future research may seek ways both to reduce complexity while maintaining its advantages and to investigate how blind people's continuous experience with this technique (and the others) impacts performance.

Point & Teleport can be designed to support scanning the surroundings. Point & Teleport offered the unique option to scan the surroundings without moving in the virtual environment. In our study, this feature could detect obstacles and assess their distance, supporting participants' decision-making through more efficient trajectories around obstacles. A parallel can be made with spatial awareness tools developed in the contexts of digital gaming [48], in particular, NavStick [47], which allows blind gamers to inspect what is around them.

This feature may gain further relevance in more complex environments where the user's avatar may incur damage (or worse) by moving to a specific location (e.g., to a hole, cliff, or lava terrain). In such cases, upfront feedback may give further knowledge about the environment, which may provide alternatives to preventive strategies (such as constantly saving the game to load in case of hazard [21]) or fail-safe interactions [51], which decrease the challenge and sometimes user's agency. Further research may explore how this kind of feedback can be provided to blind users in walking-based techniques (e.g., as a preview), as the terrain (or its absence) is only perceived after stepping on it.

Specific body language may affect performance. We observed differences in body language linked to the Arm Swinging technique, including a suggestion to perform rotational movements resembling riding a bicycle (which is an existing technique [16]). These differences in body language may be related to blind people's use of the white cane or guide dog, which may prevent this movement in their daily lives or to the absence of prior examples (e.g., by observing others or videos) that are usually presented visually (which also happens, for instance, with gestures[32]). Designers should consider these interactions by ensuring they are accounted for or providing instructions on how to execute them. Another impact of specific body language is the frequent veering, especially in Point & Teleport, where some participants struggled to point the controller straight ahead, negatively influencing their performance as further discussed below.

Veering is also a problem in virtual navigation. Veering was the cause of most cases where participants missed an objective or circled it repeatedly. Veering is also common in real-world locomotion [15, 31], and researchers have proposed systems to either prevent or correct it [50, 55]. In this study, we included a subtle sound in Linear Movement to indicate participants were walking straight, but most participants ignored these due to being focused on the objectives. Future research may explore if more noticeable corrective sounds (or using another modality, such as haptics) have a greater impact in preventing veering while ensuring the experience is not negatively impacted.

We observed that a mismatch between head and input (controllers or thumbstick) orientation often caused veering, both in Point & Teleport and in Linear Movement. In the first, participants would often point the controller with a slight diagonal orientation, while in the latter, the same happened with the thumbstick. In contrast, Arm Swinging relies on head orientation to control direction, causing less veering. This suggests that techniques with movement restrictions – e.g., relying on the head alone to control direction [10] – may prevent veering. Still, this comes at the cost of freedom of movement, since users can only move forward.

6.4 Limitations

Numerous locomotion techniques have been proposed and implemented, each with some possible variations. In our implementations, we tried to use representative examples of each technique but were required to make decisions that may impact the results. For instance, the decision on maximum speed was defined based on prior work and on experimentation, but there is no standard available. Faster locomotion could, for instance, be perceived as unnatural or influence the performance results.

We also made decisions regarding the haptic and audio feedback provided, which were needed to convey information about what was happening in the environment but may have influenced the results. Such feedback was carefully introduced based on prior research and current practices. For instance, footsteps and collision feedback are common in virtual environments, and we used spatialized audio to convey the location and distance of the teleports. However, we note that a different set of cues could result in a different experience and results. In addition, without a baseline consisting of the core implementation of the techniques alone, it is not possible to assess the impact that the audio and haptic cues have on participants' performance, preferences, and behaviours. Still, we believe specifying and making our implementations available online will enable replication and future experimentation.

The tasks and environment used allowed us to understand how these techniques support accessible navigation in simple scenarios, but VR applications are often more complex and dynamic, with multiple objects and users. Further research is needed to understand if and how these techniques should be adapted to cope with the additional information and feedback in such scenarios.

We also note that the study included a relatively small sample of diverse participants, which likely contributed to highly user-dependent results and, consequently, a lack of significant differences in the performance metrics. While we did not observe personal characteristics that could have influenced these performance differences, future research may explore individual differences in-depth. On the other hand, participant diversity enabled us to learn from a broader set of experiences that resulted in rich qualitative findings.

7 CONCLUSION

We implemented three popular VR locomotion techniques and augmented them with auditory and haptic cues for accessibility. We performed a user study aiming to compare the three techniques in terms of performance and preferences, as well as to understand their relative advantages and the strategies they support. Results showed no significant differences in performance but contrasting preferences where both were highly user-dependent. Ultimately, they also showed that popular locomotion techniques prevalent in mainstream VR applications can be accessible to blind people, as long as appropriate audio and haptic cues are included. If considered by design, these cues may pave the way for more accessible VR experiences, while the lessons learned from our work may inform the design of locomotion techniques that improve blind people's experience and performance.

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REFERENCES

[1] Majed Al Zayer, Paul MacNeilage, and Eelke Folmer. 2018. Virtual locomotion: a survey. *IEEE transactions on visualization and computer graphics* 26, 6 (2018), 2315–2334. https://doi.org/10.1109/TVCG.2018.2887379

[2] Ronny Andrade, Steven Baker, Jenny Waycott, and Frank Vetere. 2022. A Participatory Design Approach to Creating Echolocation-Enabled Virtual Environments. *ACM Trans. Access. Comput.* 15, 3, Article 18 (jul 2022), 28 pages. https://doi.org/10.1145/3516448

[3] Ronny Andrade, Melissa J Rogerson, Jenny Waycott, Steven Baker, and Frank Vetere. 2019. Playing blind: Revealing the world of gamers with visual impairment. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3290605.3300346

[4] Harshadha Balasubramanian, Cecily Morrison, Martin Grayson, Zhanat Makhataeva, Rita Faia Marques, Thomas Gable, Dalya Perez, and Edward Cutrell. 2023. Enable Blind Users' Experience in 3D Virtual Environments: The Scene Weaver Prototype. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–4. https://doi.org/10.1145/3544549.3583909

[5] Costas Boletsis. 2017. The New Era of Virtual Reality Locomotion: A Systematic Literature Review of Techniques and a Proposed Typology. *Multimodal Technologies and Interaction* 1, 4 (2017), 17. https://doi.org/10.3390/mti1040024

[6] Costas Boletsis and Jarl Erik Cedergren. 2019. VR Locomotion in the New Era of Virtual Reality: An Empirical Comparison of Prevalent Techniques. *Advances in Human-Computer Interaction* 2019 (01 Apr 2019), 7420781. https://doi.org/10.1155/2019/7420781

[7] Doug Bowman, Ernst Kruijff, Joseph J LaViola Jr, and Ivan P Poupyrev. 2004. *3D User interfaces: theory and practice, CourseSmart eTextbook*. Pearson Education, USA.

[8] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2016. Point & teleport locomotion technique for virtual reality. In *Proceedings of the 2016 annual symposium on computer-human interaction in play*. Association for Computing Machinery, New York, NY, USA, 205–216. https://doi.org/10.1145/2967934.2968105

[9] Virginia Braun and Victoria Clarke. 2006. Using thematic analysis in psychology. *Qualitative Research in Psychology* 3, 2 (2006), 77–101. https://doi.org/10.1191/1478088706qp063oa arXiv:https://www.tandfonline.com/doi/pdf/10.1191/1478088706qp063oa

[10] Fabio Buttussi and Luca Chittaro. 2021. Locomotion in Place in Virtual Reality: A Comparative Evaluation of Joystick, Teleport, and Leaning. *IEEE Transactions on Visualization and Computer Graphics* 27, 1 (2021), 125–136. https://doi.org/10.1109/TVCG.2019.2928304

[11] Fabio Buttussi and Luca Chittaro. 2023. Acquisition and retention of spatial knowledge through virtual reality experiences: Effects of VR setup and locomotion technique. *International Journal of Human-Computer Studies* 177 (2023), 103067. https://doi.org/10.1016/j.ijhcs.2023.103067

[12] Jorge CS Cardoso and André Perrotta. 2019. A survey of real locomotion techniques for immersive virtual reality applications on head-mounted displays. *Computers & Graphics* 85 (2019), 55–73. https://doi.org/10.1016/j.cag.2019.09.005

[13] Heni Cherni, Natacha Métayer, and Nicolas Souliman. 2020. Literature review of locomotion techniques in virtual reality. *International Journal of Virtual Reality* 20 (03 2020), 1–20. https://doi.org/10.20870/IJVR.2020.20.1.3183

[14] Erin C. Connors, Elizabeth R. Chrastil, Jaime Sánchez, and Lotfi B. Merabet. 2014. Virtual environments for the transfer of navigation skills in the blind: a comparison of directed instruction vs. video game based learning approaches. *Frontiers in Human Neuroscience* 8 (2014), 13. https://doi.org/10.3389/fnhum.2014.00223

[15] Patricia Consolo, Humberto C. Holanda, and Sérgio S. Fukusima. 2014. Humans tend to walk in circles as directed by memorized visual locations at large distances. *Psychology & Neuroscience* 7, 3 (2014), 269–276. https://doi.org/10.3922/j.psns.2014.037

[16] Noah Coomer, Sadler Bullard, William Clinton, and Betsy Williams-Sanders. 2018. Evaluating the Effects of Four VR Locomotion Methods: Joystick, Arm-Cycling, Point-Tugging, and Teleporting. In *Proceedings of the 15th ACM Symposium on Applied Perception* (Vancouver, British Columbia, Canada) *(SAP '18)*. Association for Computing Machinery, New York, NY, USA, Article 7, 8 pages. https://doi.org/10.1145/3225153.3225175

[17] Chris Creed, Maadh Al-Kalbani, Arthur Theil, Sayan Sarcar, and Ian Williams. 2023. Inclusive AR/VR: accessibility barriers for immersive technologies. *Universal Access in the Information Society* (02 Feb 2023), 1–15. https://doi.org/10.1007/s10209-023-00969-0

[18] Massimiliano Di Luca, Hasti Seifi, Simon Egan, and Mar Gonzalez-Franco. 2021. Locomotion Vault: The Extra Mile in Analyzing VR Locomotion Techniques. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 128, 10 pages. https://doi.org/10.1145/3411764.3445319

[19] Agebson Rocha Façanha, Ticianne Darin, Windson Viana, and Jaime Sánchez. 2020. O&M indoor virtual environments for people who are blind: A systematic literature review. *ACM Transactions on Accessible Computing (TACCESS)* 13, 2 (2020), 1–42. https://doi.org/10.1145/3395769

[20] Rachel L Franz, Jinghan Yu, and Jacob O Wobbrock. 2023. Comparing Locomotion Techniques in Virtual Reality for People with Upper-Body Motor Impairments. In *Proceedings of the 25th International ACM SIGACCESS Conference on Computers and Accessibility*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3597638.3608394

[21] David Gonçalves, Manuel Piçarra, Pedro Pais, João Guerreiro, and André Rodrigues. 2023. "My Zelda Cane": Strategies Used by Blind Players to Play Visual-Centric Digital Games. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 289, 15 pages. https://doi.org/10.1145/3544548.3580702

[22] João Guerreiro, Yujin Kim, Rodrigo Nogueira, SeungA Chung, André Rodrigues, and Uran Oh. 2023. The Design Space of the Auditory Representation of Objects and Their Behaviours in Virtual Reality for Blind People. *IEEE Transactions on Visualization and Computer Graphics* 29, 5 (2023), 2763–2773. https://doi.org/10.1109/TVCG.2023.3247094

[23] João Guerreiro, Daisuke Sato, Dragan Ahmetovic, Eshed Ohn-Bar, Kris M. Kitani, and Chieko Asakawa. 2020. Virtual navigation for blind people: Transferring route knowledge to the real-World. *International Journal of Human-Computer Studies* 135 (2020), 102369. https://doi.org/10.1016/j.ijhcs.2019.102369

[24] M.P. Jacob Habgood, David Wilson, David Moore, and Sergio Alapont. 2017. HCI Lessons From PlayStation VR. In *Extended Abstracts Publication of the Annual Symposium on Computer-Human Interaction in Play* (Amsterdam, The Netherlands) *(CHI PLAY '17 Extended Abstracts)*. Association for Computing Machinery, New York, NY, USA, 125–135. https://doi.org/10.1145/3130859.3131437

[25] Sangsun Han, Pilhyoun Yoon, Miyeon Ha, and Kibum Kim. 2022. VR Wayfinding Training for People with Visual Impairment using VR Treadmill and VR Tracker. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, Christchurch, New Zealand, 596–597. https://doi.org/10.1109/VRW55335.2022.00149

[26] Jan Hombeck, Henrik Voigt, Timo Heggemann, Rabi R Datta, and Kai Lawonn. 2023. Tell Me Where To Go: Voice-Controlled Hands-Free Locomotion for Virtual Reality Systems. In *2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. IEEE, Shanghai, China, 123–134. https://doi.org/10.1109/VR55154.2023.00028

[27] Ying Ying Huang. 2010. Exploration in 3D Virtual Worlds with Haptic-Audio Support for Nonvisual Spatial Recognition. In *Second IFIP TC 13 Symposium on Human-Computer Interaction (HCIS)/ Held as Part of World Computer Congress (WCC) (Human-Computer Interaction, Vol. AICT-332)*, Peter Forbrig; Fabio Paternó; Annelise Mark Pejtersen (Ed.). Springer, Brisbane, Australia, 269–272. https://doi.org/10.1007/978-3-642-15231-3_27

[28] Gesu India, Mohit Jain, Pallav Karya, Nirmalendu Diwakar, and Manohar Swaminathan. 2021. VStroll: An audio-based virtual exploration to encourage walking among people with vision impairments. In *Proceedings of the 23rd International ACM SIGACCESS Conference on Computers and Accessibility*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3441852.3471206

[29] M. P. Jacob Habgood, David Moore, David Wilson, and Sergio Alapont. 2018. Rapid, Continuous Movement Between Nodes as an Accessible Virtual Reality Locomotion Technique. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Tuebingen/Reutlingen, Germany, 371–378. https://doi.org/10.1109/VR.2018.8446130

[30] Tiger F. Ji, Brianna Cochran, and Yuhang Zhao. 2022. VRBubble: Enhancing Peripheral Awareness of Avatars for People with Visual Impairments in Social Virtual Reality. In *Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility* (Athens, Greece) *(ASSETS '22)*. Association for Computing Machinery, New York, NY, USA, Article 3, 17 pages. https://doi.org/10.1145/3517428.3544821

[31] Christopher S. Kallie, Paul R. Schrater, and Gordon E. Legge. 2007. Variability in stepping direction explains the veering behavior of blind walkers. *Journal of Experimental Psychology: Human Perception and Performance* 33, 1 (2007), 183–200. https://doi.org/10.1037/0096-1523.33.1.183

[32] Shaun K. Kane, Jacob O. Wobbrock, and Richard E. Ladner. 2011. Usable Gestures for Blind People: Understanding Preference and Performance. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 413–422. https://doi.org/10.1145/1978942.1979001

[33] Julian Kreimeier and Timo Götzelmann. 2018. Real World VR Proxies to Support Blind People in Mobility Training. Mensch und Computer 2018 - Workshopband. https://doi.org/10.18420/muc2018-demo-0484

[34] Julian Kreimeier and Timo Götzelmann. 2020. Two Decades of Touchable and Walkable Virtual Reality for Blind and Visually Impaired People: A High-Level Taxonomy. *Multimodal Technologies and Interaction* 4, 4 (2020), 21. https://doi.org/10.3390/mti4040079

[35] Julian Kreimeier, Pascal Karg, and Timo Götzelmann. 2020. BlindWalkVR: Formative Insights into Blind and Visually Impaired People's VR Locomotion Using Commercially Available Approaches. In *Proceedings of the 13th ACM International Conference on PErvasive Technologies Related to Assistive Environments* (Corfu, Greece) *(PETRA '20)*. Association for Computing Machinery, New York, NY, USA, Article 29, 8 pages. https://doi.org/10.1145/3389189.3389193

[36] Orly Lahav. 2022. Virtual Reality Systems as an Orientation Aid for People Who Are Blind to Acquire New Spatial Information. *Sensors* 22, 4 (2022), 1307. https://doi.org/10.3390/s22041307

[37] Orly Lahav and David Mioduser. 2003. A blind person's cognitive mapping of new spaces using a haptic virtual environment. *Journal of Research in Special Educational Needs* 3, 3 (2003), 172–177. https://doi.org/10.1111/1471-3802.00012 arXiv:https://nasenjournals.onlinelibrary.wiley.com/doi/pdf/10.1111/1471-3802.00012

[38] Orly Lahav, David W. Schloerb, and Mandayam A. Srinivasan. 2015. Rehabilitation program integrating virtual environment to improve orientation and mobility skills for people who are blind. *Computers & Education* 80 (2015), 1–14. https://doi.org/10.1016/j.compedu.2014.08.003

[39] Eike Langbehn, Tobias Eichler, Sobin Ghose, Kai von Luck, Gerd Bruder, and Frank Steinicke. 2015. Evaluation of an omnidirectional walking-in-place user interface with virtual locomotion speed scaled by forward leaning angle. In *Proceedings of the GI Workshop on Virtual and Augmented Reality (GI VR/AR)*. GI VR/AR, Los Angeles, USA, 149–160. https://api.semanticscholar.org/CorpusID:51964576

[40] Eike Langbehn, Paul Lubos, and Frank Steinicke. 2018. Evaluation of Locomotion Techniques for Room-Scale VR: Joystick, Teleportation, and Redirected Walking. In *Proceedings of the Virtual Reality International Conference - Laval Virtual* (Laval, France) *(VRIC '18)*. Association for Computing Machinery, New York, NY, USA, Article 4, 9 pages. https://doi.org/10.1145/3234253.3234291

[41] A. Lecuyer, P. Mobuchon, C. Megard, J. Perret, C. Andriot, and J.-P. Colinot. 2003. HOMERE: a multimodal system for visually impaired people to explore virtual environments. In *IEEE Virtual Reality, 2003. Proceedings.* IEEE, Los Angeles, CA, USA, 251–258. https://doi.org/10.1109/VR.2003.1191147

[42] Y.-F. Lin, D.-H. Lin, M.-H. Jan, C.-H.J. Lin, and C.-K. Cheng. 2014. 10.20 - Orthopedic Physical Therapy. In *Comprehensive Biomedical Physics*, Anders Brahme (Ed.). Elsevier, Oxford, 379–400. https://doi.org/10.1016/B978-0-444-53632-7.01024-8

[43] Esteban Segarra Martinez, Annie S. Wu, and Ryan P. McMahan. 2022. Research Trends in Virtual Reality Locomotion Techniques. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Christchurch, New Zealand, 270–280. https://doi.org/10.1109/VR51125.2022.00046

[44] Shohei Mori, Satoshi Hashiguchi, Fumihisa Shibata, and Asako Kimura. 2023. Point & Teleport with Orientation Specification, Revisited: Is Natural Turning Always Superior. *Journal of Information Processing* 31 (2023), 392–403. https://doi.org/10.2197/ipsjjip.31.392

[45] Martez Mott, John Tang, Shaun Kane, Edward Cutrell, and Meredith Ringel Morris. 2020. "I Just Went into It Assuming That I Wouldn't Be Able to Have the Full Experience": Understanding the Accessibility of Virtual Reality for People with Limited Mobility. In *Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility* (Virtual Event, Greece) *(ASSETS '20)*. Association for Computing Machinery, New York, NY, USA, Article 43, 13 pages.

https://doi.org/10.1145/3373625.3416998

[46] Mahdi Nabiyouni and Doug A. Bowman. 2016. A Taxonomy for Designing Walking-Based Locomotion Techniques for Virtual Reality. In *Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces* (Niagara Falls, Ontario, Canada) *(ISS '16 Companion)*. Association for Computing Machinery, New York, NY, USA, 115–121. https://doi.org/10.1145/3009939.3010076

[47] Vishnu Nair, Jay L Karp, Samuel Silverman, Mohar Kalra, Hollis Lehv, Faizan Jamil, and Brian A. Smith. 2021. NavStick: Making Video Games Blind-Accessible via the Ability to Look Around. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 538–551. https://doi.org/10.1145/3472749.3474768

[48] Vishnu Nair, Shao-en Ma, Ricardo E Gonzalez Penuela, Yicheng He, Karen Lin, Mason Hayes, Hannah Huddleston, Matthew Donnelly, and Brian A Smith. 2022. Uncovering Visually Impaired Gamers' Preferences for Spatial Awareness Tools Within Video Games. In *Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility*. Association for Computing Machinery, New York, NY, USA, 1–16. https://doi.org/10.1145/3517428.3544802

[49] Moloud Nasiri, John Porter, Kristopher Kohm, and Andrew Robb. 2023. Changes in Navigation over Time: A Comparison of Teleportation and Joystick-Based Locomotion. *ACM Trans. Appl. Percept.* 20, 4, Article 16 (oct 2023), 16 pages. https://doi.org/10.1145/3613902

[50] Sabrina A Paneels, Dylan Varenne, Jeffrey R Blum, and Jeremy R Cooperstock. 2013. The walking straight mobile application: Helping the visually impaired avoid veering. *Georgia Institute of Technology* 2 (2013), 25–32. http://www.eletel.p.lodz.pl/icad2013/paper/03_S1-2_Paneels.pdf

[51] Manuel Piçarra, André Rodrigues, and João Guerreiro. 2023. Evaluating Accessible Navigation for Blind People in Virtual Environments. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI EA '23)*. Association for Computing Machinery, New York, NY, USA, Article 105, 7 pages. https://doi.org/10.1145/3544549.3585813

[52] Zsolt Radák. 2018. Chapter 4 - Fundamentals of Strength Training. In *The Physiology of Physical Training*, Zsolt Radák (Ed.). Academic Press, Cambridge, Massachusetts, USA, 55–80. https://doi.org/10.1016/B978-0-12-815137-2.00004-8

[53] Kirill Ragozin, Kai Kunze, Karola Marky, and Yun Suen Pai. 2020. MazeRunVR: An Open Benchmark for VR Locomotion Performance, Preference and Sickness in the Wild. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–8. https://doi.org/10.1145/3334480.3383035

[54] Jeff Sauro and Joseph S. Dumas. 2009. Comparison of Three One-Question, Post-Task Usability Questionnaires. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Boston, MA, USA) *(CHI '09)*. Association for Computing Machinery, New York, NY, USA, 1599–1608. https://doi.org/10.1145/1518701.1518946

[55] Yoshikazu Seki and Tetsuji Sato. 2011. A Training System of Orientation and Mobility for Blind People Using Acoustic Virtual Reality. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 19, 1 (2011), 95–104. https://doi.org/10.1109/TNSRE.2010.2064791

[56] Alexa F. Siu, Mike Sinclair, Robert Kovacs, Eyal Ofek, Christian Holz, and Edward Cutrell. 2020. Virtual Reality Without Vision: A Haptic and Auditory White Cane to Navigate Complex Virtual Worlds. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376353

[57] Brian A Smith and Shree K Nayar. 2018. The RAD: Making racing games equivalently accessible to people who are blind. In *Proceedings of the 2018 CHI conference on human factors in computing systems*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3174090

[58] Jaime Sánchez. 2012. Development of Navigation Skills Through Audio Haptic Videogaming in Learners Who are Blind. *Procedia Computer Science* 14 (2012), 102–110. https://doi.org/10.1016/j.procs.2012.10.012 Proceedings of the 4th International Conference on Software Development for Enhancing Accessibility and Fighting Info-exclusion (DSAI 2012).

[59] Lauren Thevin, Carine Briant, and Anke M. Brock. 2020. X-Road: Virtual Reality Glasses for Orientation and Mobility Training of People with Visual Impairments. *ACM Trans. Access. Comput.* 13, 2, Article 7 (apr 2020), 47 pages. https://doi.org/10.1145/3377879

[60] Felix J. Thiel and Anthony Steed. 2022. Developing an Accessibility Metric for VR Games Based on Motion Data Captured Under Game Conditions. *Frontiers in Virtual Reality* 3 (2022), 10. https://doi.org/10.3389/frvir.2022.909357

[61] Oculus VR. 2021. Now Available: VR Locomotion Design Guide. https://developer.oculus.com/blog/now-available-vr-locomotion-design-guide/

[62] Yuhang Zhao, Cynthia L. Bennett, Hrvoje Benko, Edward Cutrell, Christian Holz, Meredith Ringel Morris, and Mike Sinclair. 2018. Enabling People with Visual Impairments to Navigate Virtual Reality with a Haptic and Auditory Cane Simulation. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3173574.3173690