How VR Systems Impact Virtual Navigation for Blind People

Manuel Piçarra, and João Guerreiro

Abstract—Virtual Reality (VR) offers immersive experiences through embodied interactions like head tracking, going beyond traditional controls like joysticks or keyboards. Prior research has studied the impact of VR affordances on people's experience and performance, but exclusively through sighted people's perspectives. While blind people may also leverage the physical nature of VR interactions, there is no knowledge on how VR compares with traditional controls in nonvisual tasks. We conducted a study where 26 blind participants performed navigation tasks with two conditions: VR and Game Controller. Additionally, as virtual environments can offer various degrees of complexity, we observed how participants performed under different cognitive demands. Our findings showed that VR improved navigation performance, whereas adding a simultaneous cognitive task decreased performance in both conditions. In VR, participants benefited from direct rotation, but with game controllers, the added complexity of rotating often led to reliance on translational 2D movements (e.g., moving sideways).

Index Terms—Virtual Reality, Game Controller, Virtual Environment, Blind People, Accessibility

1 Introduction

Virtual Reality (VR) supports the exploration of virtual environments through embodied actions by using a Head-Mounted Display (HMD) and motion controllers. This technology allows body or head rotation as input, moving beyond traditional controls like joysticks, touchscreens, or keyboards, commonly used in flat-screen-based interactions. Prior research has tried to identify the impact of these different interaction mechanisms on various aspects of virtual experiences, comparing VR with traditional controls in different contexts. For instance, it has explored the differences in users' performance in navigation scenarios [25, 72, 77], cognitive map development [18, 61], or target detection [11, 26]. For navigation, a central aspect of virtual environments, findings are somewhat contradictory (e.g., with more efficient navigation in VR in [72], while in Desktop in [77]). Still, most studies report that (sighted) users achieve better navigation performance with traditional controls than with VR [25, 77, 82]. However, these comparisons rely on visual feedback and focus exclusively on the performance and satisfaction of sighted users. As a result, little is known about how VR interactions compare with traditional controls in non-visual virtual tasks for blind people.

Blind people face significant challenges interacting with virtual environments, as current applications rely heavily on visual feedback to convey spatial and contextual information [4, 57, 62, 66]. Prior research has explored the creation of blind-accessible virtual experiences, with an initial focus on the use of traditional controls. Researchers have developed solutions that translate visual stimuli to audio, haptics, or both, making use of keyboards [8, 79], game controllers [58, 63], or custom devices [53, 83] to navigate the environment. Some of these studies revealed challenges for blind people when interacting with virtual worlds using traditional controls [29, 58], particularly in 3D environments. For instance, when performing virtual navigation or aiming tasks, handling the point-of-view or perspective camera is required but difficult.

Complementarily, other studies have demonstrated promising results with the use of immersive VR and its affordances, such as head tracking [64, 71]. Recent advances in VR systems have supported the development of approaches accessible to blind people across different contexts, including virtual navigation [71, 75], aiming [5, 54], or social environments [15, 35]. At the same time, research on the effects of early visual loss has shown that blind people may exhibit poorer head–trunk coordination during head-tracking tasks in VR [22]. This illustrates a broader gap: despite promising findings on VR's potential, we still lack a clear understanding of how VR compares to traditional controls in shaping blind people's virtual experiences.

In this paper, we present a user study with 26 blind participants, aiming to understand how using VR and Game Controllers impacts performance in navigation tasks. Since virtual environments vary in complexity and cognitive load is known to influence performance in VR [11, 13, 36, 78, 80], we also tested participants under tasks with different cognitive demands, introducing or removing a simultaneous memory task (n-back [39]).

Our findings show that navigation performance was significantly higher in VR, contrasting with prior comparisons (against traditional controls) with sighted people [25, 77, 82]. As expected, performance decreased in both VR and Game Controller conditions as cognitive demands increased. Finally, we observed that navigation in VR relied more on body rotation, despite some participants still using the joystick for translational 2D movements. In Game Controller, on the other hand, participants tended to rely more on translational movements (e.g., moving orthogonally), which ended up impacting their performance.

This paper contributes a first step in understanding how VR and traditional controls (in this case, game controllers) affect blind people's performance, opening avenues for exploring alternative locomotion techniques, controls, and interactions in more complex or realistic virtual environments.

2 Related Work

In this section, we discuss research on blind-accessible traditional virtual environments, VR affordances and accessibility approaches, and prior comparisons between traditional controls and VR.

2.1 Traditional Controls in Virtual Environments

A large body of research has focused on creating solutions for blind accessibility in virtual environments (VEs), including facilitating interaction in social environments [34], for orientation and mobility training [23, 44], and digital gaming [58, 76]. Studies on gaming, for instance, have examined both the experiences, challenges, and opportunities faced by blind players [4, 29, 52, 69] and the development of solutions that allow blind users to interact effectively with VEs and their components [8, 30, 47, 53, 58, 63]. Collectively, these efforts have identified key challenges while outlining strategies to enhance accessibility, supporting more inclusive VE design.

Prior work has highlighted that virtual navigation remains a major challenge for blind users in VEs, leading researchers to explore multiple input alternatives. A common approach for non-visual navigation is the use of keyboards, which are typically employed in 2D virtual environments [3, 53] and audiogames [4]. However, keyboard-only input becomes restrictive in 3D environments, where users must

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control both movement and camera orientation. While this is often addressed by pairing the keyboard with a mouse, prior work has shown that mouse-based camera manipulation is considerably more difficult for blind users [19, 20]. Other alternatives include mobile-based interactions that leverage built-in accessibility features for VE exploration and gaming [21, 69], as well as motion controllers that support embodied input through arm and hand movements [44]. Among these options, game controllers stand out as a well-established input method for 3D navigation, due to their dual-stick layout that enables integrated control of both directional movement and camera/orientation. In addition, it is frequently used in accessibility-focused research [12,33,50,55,58–60,63,76] and used by blind players in mainstream games. For instance, prior work investigating how blind players navigate visual-centric games through YouTube videos [29] often refers to controller-based input, while only once to keyboard, explicitly describing strategies to avoid reliance on mouse-based camera control.

2.2 Virtual Reality for Blind People

VR enables embodied interactions within virtual environments, such as walking, reaching, and rotating the body or head. Yet, despite these capabilities, most VR applications remain largely inaccessible to blind users [2, 17, 56, 57, 62].

To account for that, recent work has explored blind accessibility across various contexts, including aiming and object manipulation using body tracking [5, 54], sport-related activities [27, 37], and social interactions [15, 35]. Virtual navigation, a core challenge in VEs with traditional controls, underlies many VR interactions, requiring perception of objects, environmental changes, and avatar movement. VR enables new possibilities for blind users through head- and body-tracking, including familiar interfaces like a virtual white cane that collides with objects [75, 84], and adapted locomotion techniques that convey visual elements via audio or haptic feedback [43, 71].

Furthermore, prior research has explored the effects of vision loss on blind people's VR experiences, particularly how it may result in poorer head-trunk coordination in tasks involving head-tracking [22]. As a consequence, it remains unclear whether VR is more or less effective than traditional controls in enabling blind people to experience virtual environments.

2.3 VR vs. Traditional Controls

Beyond studying the individual effects of different interaction modalities, researchers have compared VR with desktop-based setups that use keyboards or game controllers [11, 25, 49, 72, 73]. For instance, Jiménez et al. [14] found that VR increased users' sense of spatial presence in a horror video game, making the experience more intense, even when users had prior knowledge of the environment. Conversely, Santos et al. [77] reported that in a virtual navigation task, users performed better with a desktop setup, gathering more objects, moving faster, and covering greater distances. Patrick et al. [61], however, found no statistical difference between an HMD, a large projection screen, or a desktop monitor when reproducing a cognitive map after navigation. A consistent distinction is that VR can induce sensorial discomfort, or cybersickness, likely linked to visual feedback, display types, or rendering processes [38, 68, 70].

These comparative studies focus on sighted users, leaving a gap in understanding how these interaction modalities affect blind people's performance in virtual environments. Given the differences in perceptual and cognitive strategies between blind and sighted users, it remains unclear whether VR or traditional controls would yield different outcomes for blind participants.

3 Comparing Virtual Navigation between VR and Game Controllers

We conducted a study with 26 blind participants to compare VR systems and Game Controllers in a virtual navigation task, using controllers as a baseline due to their common use in non-visual 3D navigation (as discussed in Section 2.1). Besides, to account for the varying complexity of virtual environments, participants' performance was assessed under conditions imposing different cognitive demands. In particular, we wanted to answer the following research questions:

1. How does the performance of blind users in virtual navigation tasks differ between VR and Game Controllers?
2. How is virtual navigation performance affected by increasing cognitive demands, in both conditions?

The study was approved by our university's Ethics Committee.

3.1 Participants

We recruited 26 blind participants (12 Female, and 14 Male), aged between 21 and 64 (M=45.77, SD=12.29) years old. Participants had light perception at most and were not able to perceive visual elements in the virtual environment. Twenty participants had minor VR experience (in previous studies), and six had never tried VR before. Most participants reported some experience with video games (M = 3.46 on a 7-point scale). Eight participants reported little to no experience, while three reported being highly experienced, with the remaining participants falling between these extremes.

3.2 Methodology

The study had a 2x3 within-subjects design with Modality and Cognitive condition as independent variables, resulting in a total of six trials. The order of the Modality was counterbalanced, as were the Cognitive conditions within each Modality. In all trials, participants were asked to perform a **virtual navigation task**, where they had to locate an audible virtual target that emits a spatialized sound. As soon as their avatar came into direct contact with the target, another would appear, removing the previous one (an audio cue is given to indicate success). Participants were instructed to reach the **maximum number of virtual objects** within a fixed time limit of 240 seconds.

3.2.1 Modality

The two modalities used in this study considered common implementations of both Game Controller- and VR-based interactions:

Game Controller. We used the Xbox One wireless controller as it is one of the most widely used controllers. It has two analog sticks, where the left one controls translational movement, while the right one controls the rotation of the camera (meaning, avatar orientation). The right trigger serves as input for the cognitive task described in the next subsection.

VR. We used the Meta Quest 2 VR system with an HMD and motion controllers. We used the thumbstick-based steering technique, Linear Movement, as it is one of the most common VR locomotion techniques [51] and has been used previously with blind people [71]. In Linear Movement, users control movement with the left-hand controller (e.g., pushing the thumbstick forward to walk forward or sideways to move laterally) while using head movement to rotate and change the avatar's orientation. The right trigger served as input for the cognitive task.

3.2.2 Cognitive Task

To assess the effect of additional cognitive demands on navigation task performance, we included an additional task to be performed simultaneously with the navigation task. In addition to examining the overall impact of cognitive load, our goal was to determine whether increasing cognitive demands affected VR and Game Controller interaction differently. We used the N-Back task as it is used in several studies that aim to assess the impact of different cognitive demands [6, 40, 65]. We relied on three cognitive conditions, **Navigation-Only** (no simultaneous task), **N-Back1**, and **N-Back2**, as prior studies showed the largest performance differences between N-Back1 and N-Back2 [9, 65]. In the N-Back Task, consonants are announced sequentially, and participants respond when the current stimulus matches the one presented 'N' steps earlier. For instance, in N-Back1, a match occurred when the current consonant matched the immediately preceding one (e.g., "B", "B"). In N-Back2, a match occurred when the current consonant matched the one presented two steps earlier (e.g., "B", "J", "B"). Consonants are

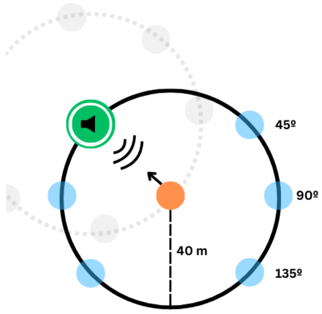

Figure 1: Our Virtual Environment contains the user's avatar (orange circle), and a single active audible virtual object (green circle). The virtual object can be heard through spatialized sound. When the avatar collides with the active virtual object, this one is deleted and a new one is created. Every new virtual object is created at a 40-meter distance from the avatar, at a randomized angle relative to the avatar's forward direction (blue circles) (+-45º, +-90º, or +-135º).

presented consecutively in a randomized sequence, every five seconds (in a total of 47 letters in a 240-second trial).

3.3 Virtual Environment

We created a simple virtual environment in Unity3D, consisting of an open area measuring 650×650 meters containing only the user's avatar and a single active virtual object (Figure 1). Virtual objects were placed 40 meters from the avatar at randomized angles relative to the avatar's forward direction (+-45º, +-90º, or +-135º). When the avatar reached the active object, it was replaced by a new one (at the same distance and with the same angle restrictions), accompanied by an audio alert. At any time, only one audible object, the active target, was present in the environment. We did not include other virtual objects (e.g., obstacles) in the VE so that performance differences could be attributed solely to the navigation modalities and cognitive tasks. Introducing obstacles could add confounding factors, such as collisions that alter performance or the need for pre-emptive cues to help users avoid obstacles. These additional stimuli and feedback mechanisms would influence non-visual navigation independently of the modality, making it more difficult to isolate the effects we aimed to study.

The avatar, when in movement, had a constant walking speed of 2.5 m/s, which is in between the range of locomotion speeds used in related literature (1.4 to 3.0 m/s) [10, 46, 71].

To generate spatialized audio (3D), we used the Steam Audio Unity Plugin [1]. This plugin applies a head-related transfer function (HRTF), based on subject 124 from the CIPIC data set [1]. To enhance spatial localization, we enabled the Doppler effect on the virtual object audio, raising its pitch when the avatar is moving closer to the active target, and lowering it when the opposite occurs (as in the "Fabricator Ping" accessibility feature, implemented in Gears 5 [2].

3.4 Procedure

The study sessions were conducted at a local institution (except P25, as we conducted the study at his home). We ensured the locations had enough space for the VR experience and low noise levels.

Introduction. Participants were first briefed on the study purpose, provided consent, and completed a demographic questionnaire. Depending on the assigned modality and cognitive condition, they received instructions for either the navigation task alone or both the navigation and cognitive tasks. We described the equipment (game controller or headset with hand controllers) and let participants try them, followed by a practice phase in the virtual environment. During these trials, participants performed navigation with or without the cognitive task to familiarize themselves with the required actions, including movement, rotation, and the operation of the N-Back task.

Study Trials. We began the study trials as soon as the participants were familiarized with the controls and task(s). The order was counterbalanced and, after each trial, participants were asked the NASA-TLX questionnaire [32] to assess participants' self-reported mental workload. We also performed a control question to understand the priority given to each task (in N-Back1 and N-Back2 conditions) [0 – 100%], and the Single Ease Question [74] regarding the difficulty of each task [1 (Very Difficult) - 7 (Very Easy)].

Semi-structured Interview. We concluded each session with a semi-structured interview to gain further insights about participants' experience and perspective. Each study session lasted approximately 90 minutes. At the end, we delivered to the participants a 10€ gift voucher for their participation.

3.5 Apparatus

During the study sessions, the application ran on a laptop (NVIDIA GeForce RTX 3060) connected by wire to the VR headset (Oculus Meta Quest 2) and via Bluetooth to the Xbox One wireless controller. The wired connection enabled the researcher to set up each session and monitor the virtual environment on the laptop screen.

Participants wore Pulse3D wireless headphones in all trials to ensure consistent audio quality. They were seated when using the Game Controller, as is typical for this modality, and stood during VR trials to facilitate movement such as full-body rotation.

3.6 Data Collection & Analysis

We recorded each participant's performance, including the number of virtual objects reached and, for the cognitive task, the number of correct, incorrect, and missed responses. Frame-by-frame navigation inputs were logged, and the NASA-TLX captured self-reported workload.

For the quantitative analysis, Shapiro–Wilk tests showed that most variables were non-normally distributed. We therefore used Generalized Linear Mixed Models (GLMMs) to analyse each dependent variable with Modality and Cognitive Condition as explanatory factors.

We first fitted a full model including the Modality × Cognitive conditions interaction to assess whether the effect of cognitive load differed between modalities. As the interaction was not significant, we refitted the model to focus on the main effects, as common in mixed-effects modeling [85].

Our analyses focused on overall effects across the full sample rather than subgroup-specific differences (e.g., age, onset of blindness, or prior experience). Although participants varied across these characteristics, the study was not designed to evaluate their individual effects, as they may be interrelated. For example, participants who were early blind were, on average, younger than those who were late blind (Early Blind: M = 38.5 years; Late Blind: M = 52.0 years), making it difficult to attribute any observed differences to blindness onset rather than age. Investigating subgroup-specific effects is therefore left for future work.

3.6.1 Navigation Performance

To understand the effects of modality and cognitive condition on the number of virtual objects reached, we ran a GLMM with a Poisson distribution and log link, appropriate for count data.

3.6.2 Cognitive Task Performance

This variable captures the consonant sequences that participants correctly identified or correctly ignored during the N-Back1 and N-Back2 tasks:

$$\text{Cognitive Task Performance} = \frac{\text{Letters Heard} - \text{Letters Wrongly Pressed} - \text{Letters Missed}}{\text{Letters Heard}}$$

To understand the effects of modality and cognitive condition on cognitive task performance, we used a GLMM with a Gamma distribution and log link, appropriate for the positive and skewed data.

[1]Steam Audio. 2025 (Open Source).
https://valvesoftware.github.io/steam-audio/

[2]The Coalition. 2019. Gears 5).
https://www.gearsofwar.com/games/gears-5/accessibility/

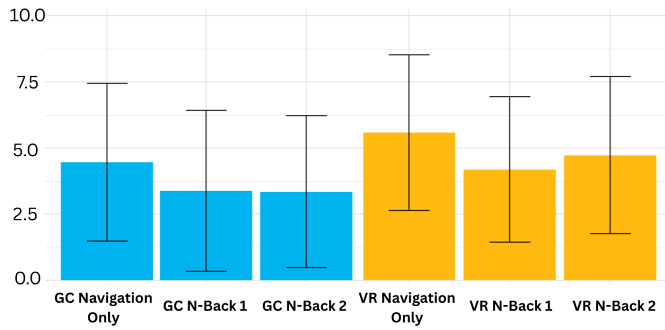

Figure 2: Average Number of Virtual Objects Reached during each Cognitive Condition (Navigation-Only, N-Back1, and N-Back2), for each Modality (Game Controller (Blue) and VR (Yellow)).

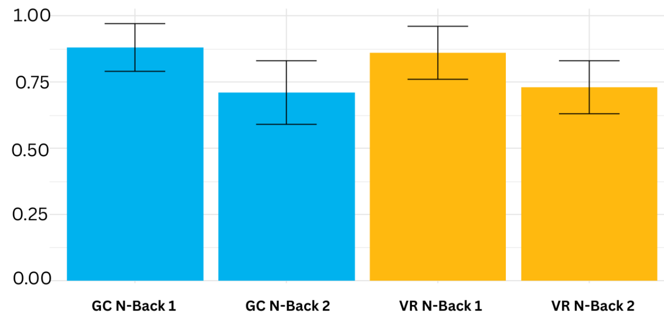

Figure 3: Average of Cognitive Task Value for N-Back1 and N-Back2 cognitive conditions, for each Modality (Game Controller (Blue) and VR (Yellow)).

3.6.3 Navigation Direction Control

We analyzed **Forward Input Usage** as an indirect measure of how participants balanced rotation and translational movement. This metric reflects the percentage of time they pressed forward (movement within 45 degrees of the avatar's orientation) relative to total movement time. Higher values indicate reliance on rotation to orient before moving straight, whereas lower values suggest greater use of sideways or diagonal movement.

We used a GLMM with a Gamma distribution and log link to assess the effects of Modality and Cognitive Condition on Forward Input Usage.

To examine relationships between navigation performance, cognitive performance, and forward input, we used Pearson correlations for parametric data and Spearman correlations for non-parametric data.

3.6.4 NASA-TLX Scales

Following prior work [31], we analyzed the individual scores (0–20) of the six NASA-TLX scales. For each scale, we used a GLMM with a multinomial distribution and cumulative logit link, appropriate for ordinal multi-category responses.

4 Results

We conducted a quantitative analysis of performance, complemented by NASA-TLX workload ratings and insights from interviews and observations.

4.1 Navigation Task Performance

The GLMM analysis first tested whether the effect of cognitive condition differed across modalities. No significant Modality × Cognitive Condition interaction was found (F(2,150)=0.24, p=0.78). When focusing on the main effects, both modality (VR and Game Controller) and cognitive condition (Navigation-Only, N-Back1, N-Back2) significantly affected the number of virtual objects blind users reached per trial. Regarding modality, participants had a better navigation task performance when using VR (B=.24, SE=.07, p=.001), reaching, on average, more virtual objects (Navigation-Only (M=5.58, SD=2.94), N-Back1 (M=4.19, SD=2.76), N-Back2 (M=4.73, SD=2.97)) than with Game Controller (Navigation-Only (M=4.46, SD=2.98), N-Back1 (M=3.38, SD=3.05), N-Back2 (M=3.35, SD=2.88)) across all three cognitive conditions (Figure 2).

Regarding the Cognitive conditions, participants reached significantly fewer objects during N-Back1 (B=-.28, SE=.08, p<.001) and N-Back2 (B=-.22, SE=.09, p=.022) when compared with the Navigation-Only condition. There was no significant difference between N-Back2 and N-Back1. This may be explained by participants giving a lower priority to the cognitive task under the N-Back2 condition (suggested in Table 1, but showing no significant differences), which is portrayed by the decrease in performance of the cognitive task in N-Back2.

4.2 Cognitive Task Performance

The GLMM analysis showed no significant Modality × Cognitive condition interaction (F(1,100)=0.96, p=0.32) on the performance of the simultaneous task. When focusing on the main effects, only the cognitive condition, not the modality, significantly affected participants' performance. Participants performed better in the N-Back1 condition (B=.18, SE=.01, p<.001) than in N-Back2, with no significant differences between VR and Game Controller. On average, performance in N-Back1 was higher (Game Controller: M=.88, SD=.09; VR: M=.86, SD=.10) than in N-Back2 (Game Controller: M=.71, SD=.12; VR: M=.73, SD=.10) across both modalities (Figure 3).

Further analysis revealed a positive correlation between cognitive and navigation performance. In VR, this correlation was significant for both cognitive conditions with the N-Back task (N-Back1: rs(26)=.503, p=.009; N-Back2: r=.523, n=26, p=.006). With the Game Controller, it was significant only for N-Back2 (N-Back1: rs(26)=.271, p=.181; N-Back2: rs(26)=.474, p=.014). These results suggest that participants who performed better on the cognitive task were also more successful in reaching navigation objectives.

4.3 Strategies Used for Virtual Navigation

The GLMM analysis showed no significant Modality × Cognitive Condition interaction (F(2,147)=1.93, p=0.14) for forward movement (Forward Input Usage). When focusing on the main effects, only modality significantly affected forward input usage, with no effect of cognitive condition. Participants relied more on forward movement in VR (B=.50, SE=.06, p<.001), with consistently higher averages across all cognitive conditions (Navigation-Only: M=.46, SD=.31; N-Back1: M=.49, SD=.30; N-Back2: M=.49, SD=.33) than with the Game Controller (Navigation-Only: M=.30, SD=.23; N-Back1: M=.26, SD=.22; N-Back2: M=.28, SD=.23) (Figure 4). Still, even in VR, participants sometimes used lateral, diagonal, or backward movement.

Observations confirmed this trend. Although translational movement was possible in VR, more participants favored forward navigation, suggesting use of natural locomotion strategies. With the Game Controller, some relied almost entirely on translational movement.

Participants' localization strategies also shaped behavior. Objects directly in front of the avatar were sometimes misperceived as being behind, but in VR these errors were quickly corrected through head movements. Some participants also moved laterally while remaining parallel to the target—more common with the Game Controller—which limited spatial discrimination.

We found a positive correlation between Navigation Task Performance and Forward Input Usage. With the Game Controller, this held across all cognitive conditions (Navigation-Only: rs(26)=.425, p=.031; N-Back1: rs(26)=.437, p=.026; N-Back2: rs(26)=.510, p=.008). In VR, the correlation was significant in Navigation-Only (rs(26)=.567, p=.003) and N-Back2 (rs(26)=.537, p=.005), though not in N-Back1 (rs(26)=.317, p=.115). These results indicate that participants who relied primarily on forward movement coupled with rotation tended to

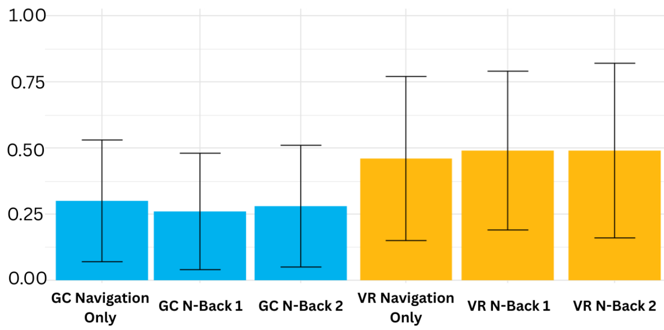

Figure 4: Average Forward Input Usage Value during each cognitive Condition (Navigation-Only, N-Back1, and N-Back2), for each Modality (Game Controller (Blue) and VR (Yellow)).

reach more objectives in both modalities.

4.4 NASA-TLX

GLMM analyses showed significant effects across several NASA-TLX scales. For mental demand, cognitive condition had a significant impact: N-Back2 was rated as more demanding than Navigation-Only (B=1.62, SE=.36, p<.001) and N-Back1 (B=.89, SE=.35, p=.013), and N-Back1 was more demanding than Navigation-Only (B=.73, SE=.35, p=.040). For physical demand, VR was rated as more demanding than the Game Controller (B=1.60, SE=.31, p<.001). Participants rated their performance higher in VR (B=.81, SE=.28, p=.006) than in Game Controller, and higher in Navigation-Only (B=1.03, SE=.35, p=.004) and N-Back1 (B=.72, SE=.34, p=.040) than in N-Back2. Cognitive condition also influenced effort, with higher effort in N-Back2 (B=1.52, SE=.35, p<.001) and N-Back1 (B=.89, SE=.34, p=.011) than in Navigation-Only. No significant effects were found for temporal demand or frustration.

Overall, these results show the expected impact of cognitive load: mental demand and effort increased with task difficulty, while performance and physical demand were rated higher in VR.

4.5 Subjective Feedback

The semi-structured interview explored participants' preferences and perceptions of task difficulty across modalities. Twelve participants preferred the Game Controller, eight favored VR, five liked both equally, and one expressed no preference. Overall, preferences tended to align with performance. All participants who preferred VR, or who liked both modalities (except one) or indicated no preference, performed better with VR. Among the twelve participants who preferred the Game Controller, six performed better with the controller and six performed better with VR.

Participants who preferred VR often emphasized the advantages of embodied movement and improved spatial awareness. Ten participants explicitly noted that moving their bodies helped them navigate more effectively in VR, describing physical turning as more natural and intuitive. Some participants posed these advantages explicitly against the use of the controller. P7 mentioned: "*With the glasses, you already have that real part (...) With the Game Controller, you are not in the reality; you are not moving; you have to imagine which button to press to go in one direction or another, and turning becomes even more difficult. So the glasses are definitely much better.*" Other participants commented that VR made the experience feel more realistic, enhancing their confidence and sense of presence.

However, some participants expressed concerns about VR's practicality due to the heavy or cumbersome headset, which negatively influenced their preferences. Despite these limitations, most participants (22) reported being very positive about using VR again in the future.

In contrast, participants who preferred the Game Controller often valued the stability and focus offered by a seated posture. On the broader potential of VR for accessibility, eleven participants noted that, for experiences similar to this study, the Game Controller was already sufficiently accessible.

General reflections on task difficulty varied. Nineteen participants agreed that managing two tasks increased cognitive demand by dividing attention. Three found dual-tasking harder with the Game Controller, while three found it harder in VR. Some felt that practice could reduce these difficulties, and several regarded the dual-task challenge as stimulating rather than negative. P22 noted increased difficulty at first but also a learning curve: "*Sometimes, the way we focus on these multiple tasks is not very easy. Sometimes, where to focus made it a little bit difficult. In the beginning. When I caught on and got some experience, it gradually became easier.*"

These observations complement the GLMM findings, which showed that task difficulty ratings were significantly higher in N-Back1 (B=-1.20, SE=.38, p=.002) and N-Back2 (B=-1.61, SE=.39, p<.001) compared to Navigation-Only, with no significant difference between N-Back1 and N-Back2.

5 Discussion

In this section, we address our research questions and discuss how VR, Game Controller interactions, and cognitive demand influence virtual navigation performance for blind people.

5.1 Performance differences between VR and Game Controller

Participants performed virtual navigation tasks significantly better in VR, a finding that aligns with their NASA-TLX (Performance) self-assessments. This contrasts with prior studies with sighted people, who often perform better using desktop setups with traditional controls [25,77,82]. While lower overall exposure to interfaces such as VR or video games among blind people (and in particular, our sample) may partly contribute to this discrepancy, the observed differences are unlikely to be explained solely by familiarity with a particular controller, as both conditions relied on analog-stick-based translation. A potential explanation is the difficulty of judging rotation with the Game Controller's joystick, which may have contributed to participants relying more on translational movement in this modality than in VR. Challenges in handling rotation are also reported in prior work [29,63] and potentially reduced navigation efficiency. In contrast, more participants (seven) relied mostly on body rotation and forward movement with VR, which correlated with better navigation performance. This is consistent with previous findings that audio-motor feedback supports accurate horizontal localization for blind users [7,86]. However, our data are correlational and do not establish that reliance on forward movement caused the observed performance differences. Alternative explanations, such as participants with stronger navigation abilities naturally adopting more efficient movement strategies, cannot be ruled out.

Participants' navigation strategies appeared linked to how they perceived audio cues from the virtual environment. Objects directly in front of the avatar sometimes caused confusion about direction, leading participants to walk past or around them. The Doppler effect helps indicate movement relative to the object, but only over a sufficient distance, making close-range localization difficult. This challenge is reported in the literature, showing that blind people tend to overestimate distances of nearby virtual sound sources compared with sighted users [41,42], and have greater difficulties localizing audio sources right in front of them [24,48,86].

The differences from results reported with sighted users suggest that VR offers interaction qualities that can support non-visual navigation and, therefore, more inclusive experiences. This distinction is particularly relevant given the limited availability of VR applications accessible to blind people, despite growing efforts to make other digital experiences (e.g., in mainstream digital gaming) more inclusive. These findings point to the potential value of VR in contexts that rely on spatial orientation and embodied interaction to create accessible experiences for blind users. It serves as a first step in exploring if and how VR can enhance the experience of blind people in virtual environments. Further research is needed not only to assess how these methods behave in more realistic scenarios but also to explore other interaction

Table 1: The average values of the six NASA-TLX scales (above) and the additional questions on Easiness and Navigation Priority (under) for all three cognitive conditions, for both Game Controller and VR modalities.

	Game Controller			Virtual Reality		
	Navigation-Only	N-Back1	N-Back2	Navigation-Only	N-Back1	N-Back2
Mental Demand	10.21	11.50	13.36	9.29	12.11	13.68
Physical Demand	5.25	5.71	4.93	7.29	8.21	8.57
Temporal Demand	6.79	8.04	8.29	6.36	7.54	8.11
Performance	11.50	11.04	9.96	14.71	13.96	11.68
Effort	10.29	12.43	14.21	10.93	13.18	14.07
Frustration	3.14	4.89	5.64	3.54	4.68	5.50
Easiness	5.23	4.73	4.50	5.62	5.00	4.73
Navigation Priority		0.54	0.60		0.60	0.61

mechanisms. For instance, locomotion techniques that rely more fully on users' physical movement, such as real-world walking or arm swinging, may better leverage the embodied affordances of VR. Other cases include the manipulation and identification of virtual objects through the user's own hand movements. Moreover, in this study, participants could navigate laterally without reorienting themselves. Investigating contexts that place different demands on spatial orientation, such as those requiring aiming or aligning the body with specific elements, may reveal the advantages of VR for non-visual navigation even more clearly.

5.2 Performance Vs Preference

Participants' preferences generally aligned with their performance, as most either favored the modality in which they performed better (N=14) or expressed no strong preference (N=6). Preferences for VR were closely linked to the ability to rotate the body to better perceive and align with the target sound, which aligns with prior research [27], and several participants described VR as more realistic and confidence-enhancing.

Six participants diverged from this pattern by preferring the Game Controller despite performing better with VR. This may reflect the physical burden of the headset and the simplicity of the task, where the lack of obstacles, additional stimuli, and overall low demands made the Game Controller feel equally effective, without the effort of wearing the HMD or standing. This contrasts with more dynamic contexts, such as sports [27, 37, 81], games [28, 45], or social experiences [16], which leverage VR's broader affordances, such as full-body movement and richer environmental feedback and interactions. In these settings, the advantages of VR may become more evident, making its benefits clearer compared with input methods such as game controllers.

5.3 Effect of cognitive demands on performance

Overall, the increasing cognitive demands had the expected impact on performance, but we did not find evidence that the cognitive load affected the two modalities (Game Controller and VR) differently. Participants reached significantly more virtual objects during the Navigation-Only condition compared with N-Back1 and N-Back2. This finding aligns with participants' self-assessments on the NASA-TLX, which indicated higher mental demand and effort for N-Back2, and higher mental demand for N-Back1. Some participants also reported, in the Navigation Priority question, that they eventually ignored the cognitive task in N-Back2 to focus solely on navigation.

The NASA-TLX served as a control to confirm that our cognitive conditions effectively increased cognitive load. Still, other measures may eventually provide a more nuanced understanding of cognitive effort, with recent work suggesting another approach to measure mental workload [67]. In addition, while the N-Back task remains a widely used approach, it ensures a controlled methodology. Still, future work may also explore cognitive demands across VR and traditional controls in more realistic scenarios with diverse stimuli.

5.4 Limitations

We used a simplified virtual environment without objects or obstacles to isolate the effects of the navigation modality and the secondary task. However, this does not reflect mainstream VR experiences, which typically include more complex spatial structures. Further research is needed to assess how these modalities perform in richer, ecologically valid environments and whether the differences observed here persist under real-world conditions.

In addition, we used a generalized rather than individualized HRTF. Since localization performance depends on the match between the HRTF and the listener, participants may have differed in how effectively they interpreted spatial audio cues. Because head rotation is an important mechanism for resolving localization ambiguities in the VR condition, such differences may have influenced navigation performance. Nevertheless, we selected a generalized HRTF because it reflects current practice in most VR applications and does not require the specialized measurements needed to generate individualized HRTFs.

6 Conclusion

In this paper, we investigated how VR and traditional game controllers affect blind people's performance in simple virtual navigation tasks. We conducted a user study with 26 blind participants and observed that navigation performance was higher in VR. We also assessed the effects of cognitive load and found that adding a simultaneous task reduced navigation performance across both modalities. The study findings highlight the potential of VR to support more natural and efficient interaction for blind people and motivate future research on alternative interaction techniques and more complex, realistic virtual environments.

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