Evaluating Accessible Navigation for Blind People in Virtual Environments

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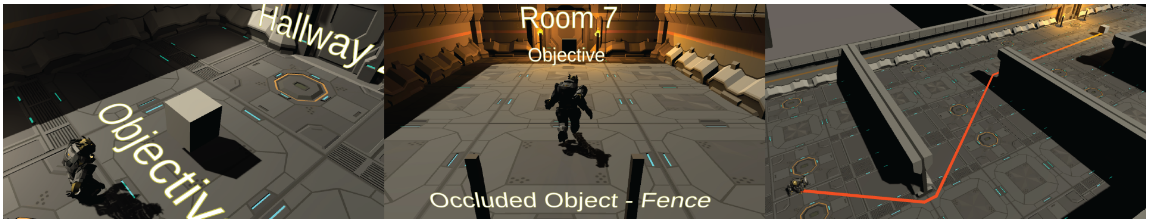

Fig. 1. We implemented a set of accessibility features to support blind people to navigate independently in a virtual environment and evaluated them in a user study with seven blind participants. The figure shows the user's avatar: navigating the environment and reaching a cube by following its sound effect which is the objective for the first task (left); navigating with a silent occluded object (fence) on its way which will indicate via sound when destroyed after the avatar collides with it, with two torches limiting the door's length (middle); following instructions according to the angle of the camera to the automatically generated path (orange line) to guide their Avatar (right) to the desired location.

Blind people that want, and play digital games will often find barriers and a lack of accessibility features available when exploring virtual environments. Prior work has found navigation to be the primary barrier players face, and the one players develop the most coping mechanisms to overcome. In this paper, we explore a set of techniques that augment or are even embedded in the game design to facilitate navigation and spatial awareness of virtual environments. We conducted a user study where seven blind participants faced a number of navigational tasks in a virtual environment with these techniques and shared their perspectives on the experience. We contribute with an exploration of a catalog of techniques used to facilitate the navigation of virtual spaces and a reflection of their impact on players' experience, highlighting avenues for future work in the field.

CCS Concepts: • **Human-centered computing → Accessibility systems and tools**; **Empirical studies in HCI**; • **Software and its engineering → Virtual worlds software**.

Additional Key Words and Phrases: accessible virtual environments, accessibility, design guidelines, people with visual impairments, blind

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1 INTRODUCTION

Digital games are a popular form of recreation that can promote social interactions and individual well-being. Prior literature has shown that gaming can have cognitive and emotional benefits [4, 11] and can promote prosocial behavior [5]. While it can empower people with disabilities in mixed-ability games [6, 9], most virtual environments (VE) found in games are designed with a major focus on players with visual abilities, with limited attention given to accessibility. Despite current efforts (e.g., by governments and companies) to offer accessibility guidelines or features, blind people face barriers that make it difficult (and sometimes impossible) both to explore virtual environments and to play major releases independently [8, 10].

These barriers to playing mainstream games gave rise to games designed specifically for blind people (i.e. audio-only games or text-based). However, these experiences are very different from mainstream high-budget and high-profile games, where the most common and complex VEs can be found on. Features like voice-acting, sound quality, haptic feedback, and quality of available content make these games as attractive to blind people as it does to sighted people. Prior work has either attempted to adapt games to audio-based gameplay (e.g. AudioQuake - [2]), to design accessible versions of features (e.g. acoustic mini-map - [16]), to augment the experience with additional accessibility features such as SeeingVR [19] that provides 14 tools (e.g. text augmentation, depth measurement), or to repurpose the secondary thumbstick to allow players to survey the environment based on line-of-sight [14]. In addition, the careful design of audio [7, 12] and haptic [18] feedback may allow blind people to better perceive and understand their surroundings on VEs, potentially supporting the creation of a cognitive map from their interaction with the VE [3, 13, 18].

In order to understand how to better support accessible experiences in mainstream games, in our prior work, we investigated the barriers blind players face when playing mainstream visual-centric games, as well as the strategies they employ to navigate the environment [8]. Such strategies often rely on game design features that were not designed with accessibility in mind, but that can support blind players and their understanding of the space (e.g., specific audio cues as landmarks). In this paper, we developed a set of techniques inspired by the coping mechanisms that blind players used to navigate (mostly) inaccessible environments. These techniques involved a combination of accessibility features and environmental design. To understand the effectiveness of these techniques, we conducted a user study with seven blind participants who explored a virtual environment and tested each of the techniques on a corresponding challenge, such as jumping over a pit. The participants completed eight tasks, each utilizing a different technique.

We observed that most of our participants could complete these tasks with relative success. Our findings most importantly demonstrate that blind people without much experience with mainstream games were quickly able to complete simple navigational tasks. These results highlight several environmental design choices and accessibility features that, if included by design, can vastly improve the experience of blind people when navigating virtual environments.

2 NAVIGATION TECHNIQUES FOR VIRTUAL ENVIRONMENTS

In this section we detail each of the techniques implemented, providing examples of mainstream games that served as inspiration. The techniques were selected based on the coping mechanisms used by blind players in such games, as described in our prior work [8], and were also inspired by prior solutions presented in the literature [2, 3, 7, 14, 16]. In particular, we focused on techniques specifically relevant to support the navigation within a 3D environment and the perception of the surrounding space.

Identifiable Environmental Audio. Audio effects that are familiar or can be instantaneously identified by the player (e.g. fire or water running). These can be leveraged as waypoints in their navigation or as guiding sources to try to move towards/away or keep to one side. For instance, *Animal Crossing: New Horizons* uses a range of audio effects that are easily identifiable. Therein, even similar objects, such as trees, have their own sound effects enabling players to distinguish them.

Audio Cue On Environment/ State Change. The existence of a sound effect, earcon or audio that informs of a change in the environment, such as the appearance of an object or changes in the disposition of a room. *The Elder Scrolls V: Skyrim* allows the player to identify characteristics of their location, by changing the sound effect associated with the footsteps, demonstrating audibly if the avatar is walking over grass, stone or even water.

Navigation Instructions. Providing an indication of where to go and what actions to take as a way to support the player in aligning the avatar toward a specific direction. In *Forza Horizon 5* the player receives directions to where and when to turn the wheel while driving through a chosen route.

Quick Save/ Load. The ability to save and load the virtual environment within a game allows players to revisit familiar points and navigate freely within it.

Navigation Failsafe. Game elements that prevent the avatar from doing something suddenly without confirmation from the player, such as walking out of a ledge, throwing an item, or selecting an option from the User Interface. *Ratchet & Clank: Rift Apart* allows the player's avatar to hold onto the ledge should the player simply try to walk over it.

Camera Axis Limits. One effective technique for controlling the camera in video games is to set limitations on its movement, preventing it from going beyond a certain distance to each side. Alternatively, players can be given the ability to recenter the camera to match the avatar's point-of-view. An example is the camera range limitation on the Y axis (Up and Down) that occurs when a player changes their avatar's stance on *Call of Duty: Black Ops 4* (2018). These are more natural in games like *Diablo III* (2012) that maintain the camera in a top-down view.

Footsteps Only When Moving. Ability to know if characters/vehicles (e.g. avatar/NPCS) are in motion by providing sound sources in relation to the listener. *The Legend of Zelda: Majora's Mask* allows the player to identify its avatar movement via audio of the steps, which will be silent should the player stop or collide against an object. NPCs can also be located and followed through the sound of their own footsteps.

Identifiable Haptic Event. The use of vibration to inform the player of something or to reinforce information already given by a sound effect. *Dead Space 2* (2011) illustrates some relevant moments with haptic feedback, allowing players to associate it with the avatar having a flashback.

Assisted Action/ Automatic Progression. Assistance in part or automatically by solving a puzzle or moving the avatar to the desired position on the VE. *Final Fantasy VII Remastered* (2020) has several parts of the game automated, such as combat scenes or transitional sequences to other environments.

Identifiable Audio Collision. The identification of virtual objects that do not passively produce sound effects, although present on the VE, by triggering a recognizable audio effect as the avatar collides with these. *Call of Duty: Black Ops 4* (2018) allows players to use a melee action, triggering a different sound effect should they hit a wall or the floor.

3 EVALUATING BLIND ACCESSIBLE NAVIGATION FEATURES FOR COMMON BARRIERS

We designed a virtual environment composed of eight areas (Figure 2 (a)) where in each we introduced one new navigation technique and a challenge for blind participants to experience. After introducing each technique, it remains

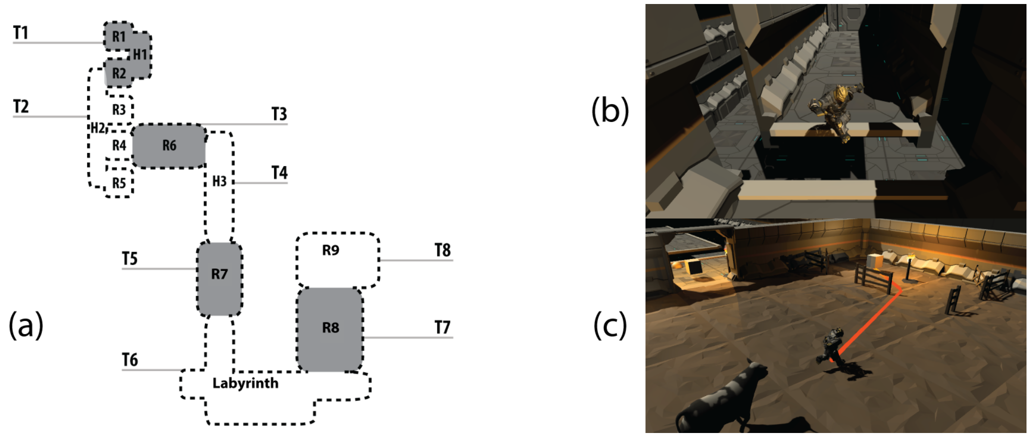

Fig. 2. The challenges implemented are separated into eight tasks. Image (a) shows the rooms that correspond to each task, some having more than one or a different shape. The rooms are connected in succession, with closed doors limiting the area available. The participant will only be able to progress to a new area as soon as the current task ends, either by completing the previous one or after the recurring four minutes limit per task. Image (b) demonstrates the avatar jumping, during Task 5 in Room 7. As for image (c), the avatar leads a non-playable character to the final objective for Task 8, in Room 9.

accessible for all future tasks, enabling users to familiarize themselves with the tools and utilize them in ways that suit their needs.

3.1 Virtual Environment

Our virtual environment is a collection of rooms and hallways, connected between them by closed doors to properly separate the different tasks, as observed in Figure 2 (a). The tasks and corresponding rooms were designed to be specific to the challenge being explored at the moment and to the use of the appropriate technique. Audio sources were placed in the center of objects, with no adjustable volume besides the application's general output. Audio sources were placed using the built-in Unity Engine spatial audio feature, which allows for the indication of a maximum range for where the audio can be heard. Voiced sound effects are altered recordings of short sentences from the Google Translator Text-to-Speech. For visual representations of both the VE and avatar, we used low polygon 3D assets created by Synty Studios, with the character's animations from Adobe Mixamo.

Our character controller implementation allows users to control an avatar in a third-person view, similar to **Dark Souls**. The camera follows the back of the avatar from a distance, although the sound receiver was purposefully placed on the avatar. This allowed the sound receiver positioning to correspond to the left and right sides of the camera position, in regards to the interpretation of the spatial audio [2, 3]. The user controls the avatar with a controller (XBOX Wireless Controller) which also provided haptic feedback. The left analog stick moves the character freely in every direction. The right analog stick controls the camera rotation.

Some of the accessibility features to be used during the user study are activated using the controller, while others are already present on the VE by design. Following the nomenclature of the controller used, the *directional pad*'s left and right buttons trigger the save/load feature, correspondingly. The *Menu button* requests an indication of the current room. And finally, the *B button* triggers the Navigation Instructions feature, the jump mechanic uses the *X button*, and the *A button* is for interaction (this last one is to be used specifically on Task 7 to authorize the automation feature).

The environment and tasks were iterated after a pilot test with a blind participant, which led us to a final version of the VE and the accessibility features.

3.2 Tasks and corresponding Accessibility Feature

Participants initiate their experience with the VE in a testing room, Room 0 (R0). This is a single room that allows participants to **collide with the walls** and react to **footsteps** while providing a continuous sound source positioned on one side of the room. This audio allowed them to perceive the **rotating camera** feature via spatial audio. Once participants were comfortable with the controllers and understood all features, we started the experiment in Room 1. The design of the VE, the rooms associated with the tasks, and how these are connected can be seen in Figure 2.

Following your Instincts. The first task **(T1)** gives access to the **Footsteps Only When Moving** and **Identifiable Audio Collision** features. Participants start this task in a squared room (R1), which is connected to a hallway (H1) leading to a second room (R2). The objective is to reach the target (one block) at the center of R2 (Figure 1 (left)). Without audio identification of the walls and areas, this task presents the challenge to create a cognitive map of the rooms in order to navigate to a silent objective. Footsteps and identifiable audio collisions represent the bare minimum that environments need to have for blind participants to be aware of their movement.

With the Sound of my Voice. **T2** unlocks an input for **Audio Cue On Environment/ State Change**, which triggers a voiced indication of the room where the participant's avatar either automatically (when entering a new room) or by request (pressing a button). The participants would enter H2, hearing the indication "hallway 2". H2 comprises four interconnected rooms, including the starting room of this task, R2. The objective is located in "room 4" (R4). This challenge highlights the importance of voicing the location of specific areas when entering them, as this enhances spatial awareness and aids navigation.

Attention to your Surroundings. **T3** makes use of **Identifiable Environmental Audio**. R6 has a sound source in its center (water fountain) and the objective is near a door with two torches (and the sound of fire crackling) indicating its position. From T3, all tasks include a single division, with the objective located at the door of the following room, also identifiable with two torches. This also creates a focal point in the room that allows users to identify entries and exits for the current division.

Invisible Wall. **T4** exposes participants to **Identifiable Audio Collision**, with an occluded object that acts as a barrier in the middle of their path (Figure 1 (middle)). Traversing this hallway (H3), participants have to interact with a fence through collision. A sound effect will alert the participants when the obstacle is touched and destroyed after enough collisions.

Minding the gap. In **T5**, participants can perceive the ledge and the gap they need to jump over with the help of an **Identifiable Haptic Event**. Additionally, a **Quick Save/Load** feature is available. The room (R7) has a similar layout to previous hallways, but with a gap in the middle that poses a risk of falling off, demonstrated in Figure 2 (b). If this happens, the participant's avatar is automatically transported to the previously saved position, located at the entrance of the current room.

Following Directions. In **T6**, participants can request **Navigation Instructions** to guide them to the current objective, specifically on how to turn their character to reach it. The room is designed as a labyrinth, making the feature particularly useful, although participants may still attempt to navigate on their own (Figure 1 (right)). The feature mimics waypoints found in various video games, such as the visible beams of light in *The Legend of Zelda: Breath of the Wild* or the accessible Fabricator Ping system in *Gears 5*.

Automatic Function. In **T7**, participants need to use **Assisted Action/Automatic Progression** to jump over gaps automatically by responding to the correct audio cue with the interact button, to activate the feature. The room (R8) features gaps on the floor with an isolated platform in the middle. Since it is not possible to jump manually, participants must locate the designated positions where they can trigger the automatic jump.

Leading the Way. In the eighth and final task, **(T8)**, no additional tools are provided, allowing participants to apply the skills and tools acquired in previous tasks. In R9, participants must approach a character (a cow) that will begin to follow them once they get close enough, triggering a spatial sound effect. Their objective is to lead the cow to the final objective area, as Figure 2 (c) shows, either by listening for the typical sound effect (fire crackling) that accompanies objectives or by requesting and following navigation directions to the objective.

3.3 Procedure

We informed our participants about the study and explained that they would need to complete a set of tasks in the interactive VE. Each task had a four-minute time limit, after which the researcher would proceed to the next task. Two minutes into each task, the audio aid cue, a spatial audio sound source placed on all objectives, would be triggered to help participants locate the objective. During the tasks, one researcher observed the participants' behavior and noted relevant aspects and feedback. Upon completing T8, we ended the session with a semi-structured interview requesting the participant's opinions regarding the tasks and tools, as well as their suggestions for additional accessibility tools to help them navigate independently in a VE. As the participants mainly relied on the auditory channel to perceive and react to audio feedback from the VE, we remained as observers during the tasks, speaking to participants only when necessary. We captured video recordings of the VE and audio from both the participants and the researcher during the testing and interview, along with annotations of relevant visual details observed by the researcher. We analyzed each participant's performance task by task, transcribing and translating their dialogue and interjections, and providing detailed accounts of their performance. Annotations and the automatic reports provided contextualized time stamps of the necessary interventions.

3.4 Participants

We recruited seven blind participants over 18 years old, with light perception at most. Most participants were indicated and contacted by a local institution, Fundação Raquel e Martin Sain. Among the participants, one was between 18-30 years old, five were between 30-50 years old, and one was over 50 years old.

3.5 Findings

We conducted a preliminary qualitative analysis based on the observations and interviews, alongside the user task performance. One researcher, who was present in all study sessions, revisited notes and recordings and created a reflection of the lessons learned for each task. The research team met, discussed, and iterated the findings into the ones presented below. Overall, participants were able to complete their tasks in most cases, with 32 out of 56 tasks completed successfully. As expected, we found that the most challenging tasks for participants were T1 and T2, with a total of ten unsuccessful attempts out of 14. In what follows, we present the main findings organized by task.

T1 - Simplified Navigation. The success rate of T1 was 2 out of 7. Without environmental sound sources, blind players would often roam with no proper mental map of the rooms and hallway, relying solely on audio feedback from collisions, footsteps, or the lack thereof. Only one participant (P6) was able to complete the task without requiring the audio aid cue, while P3 reached the objective with the help of the audio cue.

Regarding the first two tasks (T1 and T2), one participant (P1) suggested that having information about the direction the avatar was headed could improve their orientation while moving: *"I think it must have indications, North, South, East, West, so the person can try to perceive where they are. [...] I would lose myself a lot, I didn't know if I was on the left side, if I was on the right side."*. P6 suggested *"The character should talk. It should tell if I'm close or far from the hallway"*. Participants were not necessarily required to control the camera unless to navigate towards the spatial audio signal of the audio aid cue, which raised a few questions about the function of the camera input. For instance, P5 questioned: *"This one does not move the character. (...) So rotating does not give a signal?"*.

T2 - Close Surroundings Identified. The success rate of T2 was 2 out of 7. Although it did not provide detailed descriptions of the rooms, T2 still enabled the participants to understand their location, particularly when they reached another division. As anticipated, T1 and T2 were challenging, with only one participant (P3) able to complete both tasks.

Despite the difficulty of the task, participants were able to perceive their location through the numerical room designations. However, locomotion and orientation remained challenging as they had to rely solely on footsteps, resulting in participants moving slowly and changing directions when colliding with walls. The camera was majorly ignored, often misleading those who used it without the audio aid cue enabled. By being unable to reach the objective, P6 replied *"If I was playing something, I would have lost."*, suggesting some frustration. P7 shared some insights regarding their mental map creation while exploring the VE. Saying *"The hallway is long."* when walking and colliding for some time highlights the difficulties blind participants faced when compared to a sighted person that might easily visually assess the length of the room. Another question raised the issue that participants may have preconceived notions (or questions) about how the virtual environment may be designed.: *"How do I enter the room? I simply walk?"* suggests that the participant expected a door or the requirement of an input.

T3 - Auditory Landmarks. The success rate of T3 was 6 out of 7, which overall was completed easily. Since these tasks were required to be completed during a time schedule, we avoided creating a simple linear course. Participants were seen exploring the sounds of their surroundings by rotating the camera, moving back and forth, and reacting to collisions according to their mental map of the VE.

While the task implemented spatial sound sources near the objective, it did not necessarily help reduce the number of times the audio aid cue was activated. Still, it ended up being necessary to support participants to detect the precise location of the objectives. Regarding orientation, P7 shared some alternatives to the use of the torch or the audio aid cue sound effects: *"How do blind people walk on the street? It has to do with the absence of air. If I'm walking in a hallway and there's an open door, there is air coming from that door. (...) If it makes an echo, or if there is a sound coming, I can understand that the door is right there. And it is easier than the beep because the beep will overlap the rest."*.

T4 - Occluded Objects. The success rate of T4 was 2 out of 7. The walls limit the environment and end up being occluded objects for blind people. The only way to detect their presence is through the absence of the footsteps' sound effect and the sound of collision upon contact. Changeable obstacles pose an additional challenge, as the moment of change may be difficult to identify without visual cues, such as the remains (or complete disappearance) of the previous obstacle.

Although most participants were able to break the fence, they had difficulty perceiving the location of the fence before it broke and the change in the sound effect afterward. To P6, the different sound effects of the fence were noticeable *"I broke something"*. And yet, most demonstrated doubts about the situation, as shared by P1: *"I don't know if it broke or not"*.

T5 - Virtual Obstacles and Environmental Changes. The success rate of T5 was 5 out of 7. Most participants ignored the quick save and load feature, which is a skill that expert players may have more experience with [8]. The participants had varying degrees of sensitivity and reaction times to the problem of the ledge, with some struggling initially. P1 quickly replied *"It can not be done. This is hard."*, before quickly pressing the inputs and managing to reach the other side. Others were able to jump slowly, moving step by step until they received the warning to jump. P7, on the other hand, only responded to the vibration to know when to jump, stating *"I did not hear the sound, only felt the vibration."*.

T6 - Following Directions. The success rate of T6 was 5 out of 7. The audio aid cue was enabled for five participants, with two of these being unable to reach the objective. The other three had trouble reaching the precise location of the objective. Although being able to follow the directions, some ended up not using the assistive feature after some time.

The Navigation Instructions feature proved to be very helpful for the final three tasks. However, even with a brief explanation of the requirement of camera rotation for the feature, participants had difficulty familiarizing themselves with it, and some even forgot or avoided using it after a while. This suggests difficulties interacting with the camera as rotating it may prevent users from maintaining a mental model of the VE.

T7 - Automated Actions. The success rate of T7 was 5 out of 7. Both participants who were unable to complete this task faced technical errors preventing them to reach the destination. In addition, one participant required the audio aid cue to successfully reach the objective. The linearity of the room might have been too simplistic, as also observed in T5 or T3. The objective was to capture the participants' attention to the warnings and their reactions. Still, this led participants to simply react passively instead of allowing a proactive stance toward the challenge. P6 even suggested *"This was very quick"* when reaching the objective easily.

T8 - Interaction and Perception of Others. The success rate of T8 was 5 out of 7. The two participants who needed the most assistance from the researcher throughout all tasks (P2 and P5) were unable to complete this task on their own. Additionally, P6 also required the audio aid cue to successfully complete the task.

By mixing the use of the navigation instructions feature (T6) and the audio aid cue, most participants found it easy to complete the task. P1 indicated *"Ok, this must be like as the person gets closer, it bellows louder, I think."*, demonstrating an understanding of the spatial audio feature.

4 DISCUSSION

The study offered insights regarding the requirements for blind people to independently explore and use VEs. The **first two tasks** were designed to provide the basic features needed for blind players to navigate a VE. As also noted in the literature [10], it reveals how **frustrating** and **difficult** it can be for blind players to experience a VE **without** dedicated **accessibility** features. In contrast, T6 indicated that similar orientation and objective-focused challenges can be accomplished when using accessibility tools or adaptive techniques such as previously done in AudioQuake [2], for instance.

Our findings suggest that dealing with **occluded objects** in VEs may require more **detailed feedback** on the object's shape or condition. T4 ended up being more challenging than expected, highlighting the need for additional tools. Nair et al., [15] explored promising ways to augment environments with additional audio feedback. They did this by exploring techniques to make either map-like features accessible, or creating techniques that provide audio feedback about the surroundings upon user request. While this is an important step in making virtual environments more accessible, it is more akin to adding assistive technology to existing games, rather than baking in audio features that enable navigation. Our work explored how to achieve both immersion and accessibility by implementing audio features by design. We believe a mixture of the two is necessary for guaranteed immersion without sacrificing accessibility.

Auditory landmarks and identification of areas provide a foundation for **confident navigation** and mental map creation for blind people in VEs. T3 only scratched the surface of how VEs can be made accessible for blind people. By incorporating dynamic, complex, and recognizable audio and sound effects, blind individuals can use them as part of their orientation strategies, as exemplified by Oumard et al., [17] or observed by Gonçalves et al., [8]. The high success rate in this task may be attributed to the simple design or clear orientation cues via sound. Further research and exploration of different approaches are needed to fully understand and learn from the results of this specific task and its elements.

Virtual obstacles and **environmental changes** – e.g., when entering a different area or moving objects in a division – can be easily conveyed with **haptic** and **audio feedback**. The audio aid cue feature proved to be an essential tool for participants in locating objectives with precision in several instances. Besides the first two tasks, approximately half of the participants needed it for T4, T6, and T8. Still, only three participants managed to reach the objective for more than half of the tasks. The effective use of spatial stereo audio and precise movement within a confined area needs further investigation, leading to potential additions or modifications to enable blind players to reach a specific location in a VE. Moreover, the audio cues should blend seamlessly into the game's natural environment, without being unrealistic and detracting from the immersive experience (e.g., a beep). **Automated actions** can **help** with problematic scenarios, offering a solution if requested, **avoiding forcing** them onto the users.

Following directions is **intuitive**, even though the **camera** perspective and handling needs to be **carefully considered** when designing these systems. The final four tasks suggest that the tools presented were useful and relatively simple to learn and adapt to. While two of the participants had no difficulties completing the tasks, three required audio aid cues for some or could not complete one of these tasks. It is worth noting that these tasks demanded more of the participants' ability to react appropriately rather than to contemplate and execute their own orientation, despite still requiring movement from the player.

Specific game features may require users to spend time **familiarizing** themselves with them and may also require an explanation due to their unfamiliar or unnatural concepts. When alerted that a specific tool was crucial for a particular task, participants made an effort to use it but often abandoned it once they moved on to another task. This may be due to their perception that each task had a unique scenario, and the tools could not be applied uniformly. Participants' familiarity with level-based games and virtual environments with distinct levels might have influenced their understanding of the rules of this environment. Further explanation of the continuity of the virtual environment and its tasks could have been beneficial since it is more easily understood visually. Researchers and designers should seek to develop these techniques in ways they can be easily integrated into VEs, independently of the level or the game (e.g., as the toolkits developed in SeeingVR [19]). Finally, like Andrade et al. [1], we also obtained suggestions from the participants for the use of these tools, similar substitutes, and other design possibilities.

5 CONCLUSION AND FUTURE WORK

Our findings emphasize the need for the game (and virtual environments) designers to prioritize accessibility from the start, ensuring that game mechanics, tools, and environmental design choices can reach a wider population, particularly those who are visually impaired or blind. We hope that our work and similar studies will inspire designers to create navigational tasks that are just as simple for blind people as they are for sighted people, without oversimplifying the whole experience. This involves supporting complex interactions that are commonly found in mainstream games and virtual environments to provide an inclusive and enjoyable experience for all users.

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