Exploring Aiming Techniques for Blind People in Virtual Reality

João Mendes, Manuel Piçarra, Inês Gonçalves, André Rodrigues, and João Guerreiro

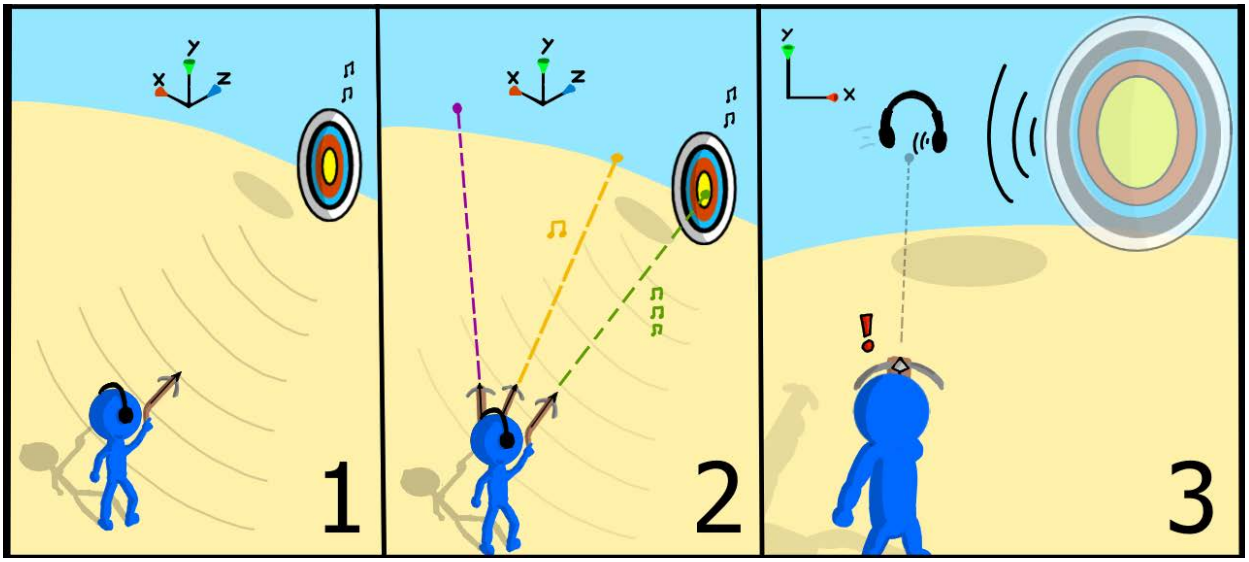

Fig. 1: We implemented three techniques to support blind people in aiming tasks in VR: 1) Spatialized Audio (baseline), where the target emits a specific sound to convey its location; 2) Target Confirmation, which adds secondary beep sounds to indicate proximity to the target – closer to the target means higher frequency of beep sounds; and 3) Reticle-Target Perspective, where the auditory feedback conveys the spatial relationship between the user's reticle/aim location (not the head) and the target.

Abstract— Aiming tasks are common in VR, but are challenging to perform without vision. They require identifying a target's location and then precisely aiming and selecting it. In this paper, we explore how to support blind people in aiming tasks using a VR Archery scenario. We implemented three techniques: 1) Spatialized Audio, a baseline where the target emits a specific 3D sound to convey its location; 2) Target Confirmation, where the previous condition is augmented with secondary Beep sounds to indicate proximity to the target; and 3) Reticle-Target perspective, where the auditory feedback conveys the relation between the target and the user's aiming reticle. A study with 15 blind participants compared the three techniques under two scenarios: stationary and moving targets. Target Confirmation and Reticle-Target Perspective clearly outperformed Spatialized Audio, but user preferences were evenly split between these two techniques. We discuss how our findings may support the development of VR experiences that are more accessible and enjoyable to a broader range of users.

Index Terms—Virtual Reality, Auditory Feedback, Blind, Archery.

1 Introduction

Virtual Reality (VR) has evolved rapidly in recent years, offering immersive experiences that rely on physical movement (e.g., through head and hand tracking) and high-quality graphics to enhance user engagement and interaction. However, the major focus on visual feedback poses significant challenges to blind people, raising critical questions about the accessibility of VR [14, 41, 45].

Complex interactions such as aiming are particularly challenging to perform without vision [20, 42]. Aiming requires spatial awareness to identify a target's location in the 3D space, depth perception, and coordination between the head (which determines the feedback received) and the hand (usually with the controllers) to point to a target precisely. Still, aiming is extremely common in various contexts within VR, such as shooting or target practice games, navigation (e.g., in Point & Teleport [10, 36, 48]), or interacting with elements (e.g., menus) or objects in the environment. Thus, supporting aiming tasks nonvisually can play a key role in making VR experiences more accessible to blind people.

Prior research has explored aiming tasks in a variety of contexts, such as in digital gaming on flatscreens [21, 61] or in smartphone-based interactions such as photography or object recognition [1, 56]. These approaches introduce interesting solutions, leveraging speech-based [21] or sonified [47] (or both [1, 26]) audio cues, sometimes with additional tactile feedback [47]. However, the interaction mechanisms present in such contexts differ from the unique affordances of VR technologies. VR can leverage head tracking to mirror the auditory experiences of the physical world. Additionally, it integrates hand tracking, offering opportunities to combine head and hand movements for more precise and intuitive aiming. These affordances present novel possibilities that remain underexplored in the literature.

This paper investigates how to support blind people in aiming tasks in VR. We built a VR Archery application and implemented three aiming techniques (Figure 1): 1) Spatialized Audio, a baseline approach where the target emits unique 3D sounds that convey their location in the virtual environment; 2) Target Confirmation, building upon Spatialized Audio, it incorporates secondary beep sounds to indicate the proximity

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of their aim to the target; 3) Reticle-Target Perspective, where the auditory feedback goes beyond location cues and instead focuses on conveying the spatial relationship between the user's reticle (to where the user is aiming at) and the target. A user study with 15 blind participants compared the three techniques with stationary and moving targets. Spatialized Audio alone was extremely difficult, while both Target Confirmation and Reticle-Target Perspective outperformed the first by far. Preferences between Target Confirmation and Reticle-Target Perspective were highly user-dependent and sometimes related to individual differences (e.g., early blind participants tended to prefer Reticle-Target Perspective). Our findings showcase the potential of aiming techniques that make VR experiences more accessible to blind people and that may inform the design of future solutions.

2 Related Work

In this section, we discuss previous efforts in making VR accessible to blind people and explore strategies to support aiming in physical and virtual environments.

2.1 VR Accessibility for Blind People

Virtual environments are common in many domains, from entertainment to education and social interactions. Prior work has proposed different approaches to make them more accessible to blind people. In digital gaming, for instance, past work has not only investigated the barriers faced and strategies used by blind gamers [4, 20, 37], but also provided users with tools to understand and move in the environment [2, 42, 44, 53]. Other alternatives have explored haptic solutions either to manipulate virtual objects [39] or to both control an avatar and gain awareness of another object's movement [51]. In other contexts, researchers have developed solutions to gain knowledge about a virtual environment, often to transfer it to the real world [13, 18, 25].

More immersive VR supported by Head Mounted Displays (HMDs) and hand-tracking systems brings new interaction mechanisms and a greater ability to replicate physical-world gestures and movements. Past research has tried to leverage visual feedback to assist people with low vision interacting with VR environments [27, 38, 62, 65]. For instance, SeeingVR [65] consists of a set of tools that provide visual augmentations, such as magnification or bifocal lens, and edge enhancements. In addition, it provides some audio augmentations that can benefit people with low vision and blindness, such as a Text-to-Speech tool that reads aloud text or objects that the user points at.

To support blind people in VR environments, most efforts focus on auditory feedback, often complemented with haptics. For instance, in entertainment scenarios, multimodal approaches have been used in accessible versions of both a racing [19], a table tennis [31], and a speed-of-light [33] game. Additionally, to support navigation researchers have either augmented popular VR locomotion techniques [48] or leveraged blind people's Orientation and Mobility skills and navigation aids, proposing techniques that augment a white cane [32, 34, 52, 64] or that enable users to walk freely in the real world [28, 55].

Research in contexts such as social VR [12, 30], or sports [24, 58, 59] rely heavily on audio – either through verbal or sonified cues – to convey information about the environment, for instance to convey the location of a ball [58] or of the opponent's hands in boxing [24]. While these works help to understand different approaches to convey the location of objects, they do not focus on aiming tasks.

2.2 Aiming Tasks for Blind People

Aiming is common in VR but also in physical-world interactions. For instance, smartphone applications that describe or identify objects [1, 22, 40] in front of the user require the camera to be aligned with the intended target. Similarly, applications to read textual content [15, 63] or to receive remote assistance [7, 9], require that a camera is framed correctly. These contexts, alongside research on blind photography, usually make use of verbal instructions or sonification [1, 26, 29, 56]. Raina et al., [47], for instance, use a smartphone to point at targets in the context of an AR mobile shooting game, using a combination of spatial and non-spatial audio. Guarese et al. [23] proposed different sonification methods for mouse-based guidance in a 2D grid. They explored different methods that use pitch modulation to represent distance to the target. One example is Alternated Pitch, where beeping sounds are more frequent as the cursor gets closer to the tatget. Similarly, Luo et al. [35] designed an Archery game where both sighted and visually impaired people could use a physical bow to aim at a screen, with sound feedback to locate the target.

Aiming is also common in virtual environments. For instance, mainstream digital games often include complex environments and interactions, where even expert blind players struggle with aiming at specific targets [6, 20, 42]. The solution is often to simplify the experience – e.g., aim assistance, sharing control with friends, relying on audiences, or auto-aim – which affect the user's agency or engagement [20]. Alternatives include the works of Nair et al. [42, 43] who explored different ways to convey spatial information to visually impaired users, including the ability to scan by pointing to a specific direction and obtain feedback about existing elements.

The aforementioned works, either in digital gaming or in smartphone-based tasks, employ different interaction mechanisms and challenges. VR enables natural interactions and perspectives that are not possible with smartphones, keyboards, or joysticks, where head movements do not affect spatial audio. Additionally, targeting specific objects at a distance in VR introduces greater complexity compared to framing objects, as even minimal user movements can result in missing a target. Yet, there is limited work in VR aiming for blind people. Chung et al. [11], explored omnidirectional guidance feedback, enabling users to locate the target's vertical position, followed by a horizontal search, or vice-versa. Apavou et al., [5] explored different sonification techniques, ranging from variations in pitch to variations in different properties of sound. Despite showcasing interesting approaches, they were only evaluated with sighted participants. Another solution relied on the person's head movements to control the trajectory of an arrow [17], using also the relation between head and trunk to rotate the arrow.

Overall, prior work showcases the challenges of aiming tasks for blind people in VR but also calls for alternative solutions that support blind people in contexts where aiming is required.

3 VR Aiming for Blind People

We built a VR Archery application to explore three VR aiming techniques for blind people: Spatialized Audio, Target Confirmation, and Reticle-Target Perspective. In this scenario, blind users have to identify the target's location, aim at it, and shoot.

3.1 VR Archery Prototype

Our VR prototype was developed using Unity3D, running on the Meta Quest 2 VR system, with the XR Interaction Toolkit. Meta Quest 2 includes a HMD and two controllers. The HMD is essential for head-tracking, influencing the audio feedback received, while the controllers are used to detect the user's hands and where they are aiming at. We used the standard audio plug-in provided by Unity for sound spatialization – using generalized Head Related Transfer Functions (HRTFs) – and MicMonster for Text-to-Speech.

The virtual environment (Figure 2, a) resembles an empty common room (25 x 11 x 7 meters) and places the user 20 meters from a target (diameter = 1m) positioned on the wall in front of them. The user aims and shoots using a crossbow to simplify the shooting experience, compared with a bow and arrow approach, while providing a longer arrival time (when compared to a shooting gun, for instance). There is no effect of physics to avoid external effects and to focus on aiming alone. After the shot, the arrow produces a sound hitting the target, wall, ceiling, or floor. In addition, a verbal message is conveyed – a score of 5 (the highest, at the center) to 1 point when the target is hit, or an indication of what the arrow hit (wall, floor or ceiling).

3.2 VR Aiming Techniques

To support blind people aiming at targets in VR, we developed three techniques (Figure 1) that rely on audio feedback to convey the location of a target. All techniques require participants to aim with one controller and shoot by pressing the trigger button.

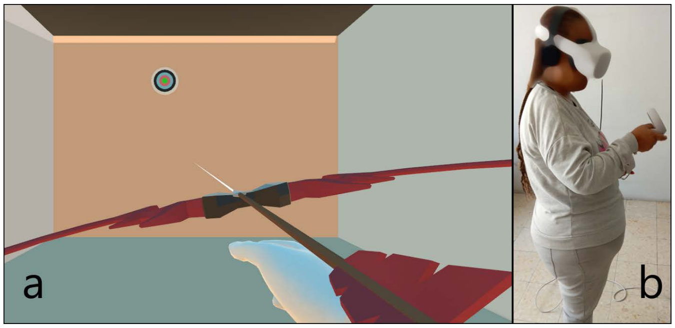

Fig. 2: a) The virtual environment developed for the aiming and shooting experience, with a target far away, inserted in a big room. b) Participant aiming at the target.

3.2.1 Spatialized Audio

Spatialized Audio is the baseline technique of this study, as it represents behaviors already seen in VR applications, digital games, or adapted shooting sports [5]. It intends to represent the status quo of VR sound localization, where the only cue of an object's location is the sound it emits. For instance, in shooting games enemies often produce sound, which helps – to some extent – to identify their position. In our Archery experience, the user could press a button (A or X depending on the dominant hand) of their aiming controller, and the target emits a spatialized sound effect. This technique replicates how we process sound in the physical world, as the sound is relative to the user's head position and orientation. Therefore, users may rotate their heads to try to understand the target position.

Dealing with Verticality. Prior work has reported difficulties in perceiving vertical differences in sound location when compared to horizontal ones [54,60]. Our preliminary assessments confirmed such difficulty, as aiming nonvisually was extremely difficult. For that reason, we manipulate the pitch of the abovementioned sound effect as a way to assist in vertical aiming. As found appropriate in prior research [5,33,46], a lower pitch would mean the user is aiming too low, while a higher pitch would be too high. The farther from the target height, the greater the difference. For comparison, users could press a button on the secondary controller to hear the pitch associated with the correct height.

3.2.2 Target Confirmation

This technique is built on top of Spatialized Audio and intends to provide a secondary audio cue in addition to the sound emitted by the target. A first audio source is exactly the same as Spatialized Audio (including pitch differences to assist in verticality), being therefore dependent on head location and orientation. A secondary sound source is triggered to play when the user aims close enough to the target. This sound effect is based on beep sounds that occur more frequently the closer the user aims toward the center of the target – i.e., more frequent beep sounds at the target's center. While the first sound source is related to the head location and orientation, the secondary sound depends on the controller's orientation. This technique intends to replicate the visual cue provided by the aiming reticle, which confirms that the user is aiming at the target. Through audio, this confirmation is given by the more frequent beep sounds instead of a visual overlap of the reticle and target. In addition, it has similar attempts in prior work [11,23,40,47] that use the frequency of beeps to convey proximity to a target.

3.2.3 Reticle-Target Perspective

This technique shifts the audio listener's position from the user's head to the aiming reticle (Figure 3). As a result, it does not rely on head tracking. Instead, the audio feedback is determined by the position of the aiming reticle. Like the secondary (beep) sounds in Target Confirmation, this feedback is based on where the user is pointing rather than their head location. However, it does so by preserving the target's sound rather than using a secondary sound for that purpose. Our goal with this technique was to guide the user's aim without introducing additional stimuli that could potentially overload them. By conveying the spatial relationship between the aiming reticle and the target, this approach enhances horizontal feedback (i.e., is the target on the left or right?), as the user's audio perspective is now on the same depth (Z-)plane as the targets. This aimed at addressing the major challenges of aiming at distant targets [8], where small differences in location are not easily perceived through spatial audio alone. After shooting, the user can also listen to the sound of the arrow hitting the wall, which produces directional feedback – if heard on the right, the user may adjust their aim to the right.

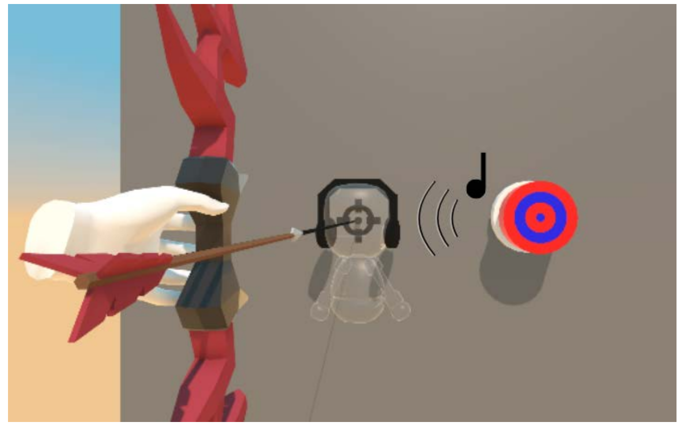

Fig. 3: The Reticle-Target Perspective technique, where the audio listener is at the aiming reticle location instead of the user's head.

4 User Study

Our main goal is to investigate how the three implemented techniques support blind people in aiming tasks in VR. In particular, we wanted to answer the following research questions: 1) What are the differences among Spatialized Audio, Target Confirmation, and Reticle-Target Perspective regarding performance and user preference? 2) How do the different techniques support aiming at stationary and moving targets?

The study followed a within-subjects design, where participants engaged in aiming tasks with the three techniques in a counterbalanced order to avoid carryover effects. The tasks consisted of aiming and shooting either at stationary or moving targets, and were followed by a semi-structured interview to obtain a comprehensive insight into participants' strategies and preferences. The study received approval from the Ethics Committee of Faculdade de Ciências, Universidade de Lisboa.

4.1 Apparatus

We used the previously described VR Archery prototype. We used a wired connection to give 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, we connected headphones to the HMD to enhance spatialized audio. This means that, in the study, participants received audio feedback from the headphones and not from the HMD speakers. The data from the study (e.g, success rate, time) was saved locally. 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.

4.2 Participants

We recruited 15 blind participants (10 male, 5 female) through a local training institution for people with visual impairments. Seven participants were totally blind and eight had light perception at most (and could not distinguish different elements in the environment). Their ages were between 27 and 64 (M=43.6, SD=11.98). Twelve participants rated themselves as experienced with technology (at least 5 on a scale

Table 1: Demographics of the participants, with their self assessment of experience with both Technology (Exp. with Tech) and Virtual Environments (Exp. with VEs), rated from 1 (Not Experienced) to 7 (Very Experienced)

ID	Gender	Age	Blindness Onset	Exp. with Tech	Exp. with VEs
P1	Female	39	Late	6	4
P2	Male	50	Late	4	2
P3	Female	38	Early	4	2
P4	Female	49	Late	4	2
P5	Male	40	Late	7	7
P6	Male	35	Late	5	4
P7	Male	55	Late	3	2
P8	Male	55	Late	4	5
P9	Male	64	Early	4	4
P10	Male	35	Early	6	4
P11	Female	54	Late	6	1
P12	Male	28	Late	5	2
P13	Male	28	Late	5	6
P14	Female	27	Late	7	6
P15	Male	57	Late	6	5

of 1 to 7), but most (9) were not experienced (3 or lower in a 1-7 scale) with virtual environments. Only two participants (one of them prior to becoming blind) have experienced VR in contexts outside of research studies (with most participating in one or two previous studies).

4.3 Procedure

Each session took around 90 minutes and 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 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, the weight of the headset, and the overall button position in the controllers. Then, participants were assisted in wearing the Meta Quest 2 hardware and headphones.

Participants were then asked to experiment with the three aiming techniques (Figure 2, b) in sequence (order counterbalanced). They were always positioned facing the VR wall where the targets would appear. When starting with each technique, participants entered a learning environment akin to the study environment (described in VR Archery Prototype), but where the appearance of targets was controlled by the researcher in order to introduce all features sequentially (e.g., the target's sound effects, and the pitch differences). This learning phase took approximately five minutes.

After ensuring participants understood the technique, they were presented with two tasks: Stationary Targets and Moving Targets. In **Stationary Targets**, the target remains still, only changing its position on the wall if participants successfully hit it or if they miss it five times. In **Moving Targets**, the targets move horizontally at a constant speed of 1m/s; participants were informed that targets move (not their pattern). Targets are also re-positioned after being hit or after five missed attempts. In both cases, a voice message indicates that the target is changing its position.

Each task started with a distinct beeping sound and had a maximum of five minutes or fifteen shots, to avoid fatigue. Participants always started with the Stationary Targets and only transitioned to Moving Targets if they hit at least two targets to avoid frustration.

After completing each task, we asked the Single Ease Question [50] where participants had to rate task ease/difficulty from 1 to 7 (1- Very Difficult, 7- Very easy).

The study trials were repeated for the remaining two techniques, including the learning and task phases. We then conducted a semi-structured interview to understand the rationale behind participants' preferences and each technique's relative pros and cons. We audio-recorded the interview for later transcription and analysis.

4.4 Data Analysis

To assess participants' performance with each technique and task type (Stationary and Moving), we focused mainly on the **number of points**. In addition, we considered the **distance to the target's center** (and the **vertical** and **horizontal offsets**), and the **average time per shot**. We ran the Shapiro Wilk test to assess the normality of the performance metrics. As the distribution was not normal, we ran the (non-parametric) Friedman test to compare the three techniques for each type of task. When a significant difference was found, we ran pairwise comparisons with the Wilcoxon Signed-Rank test, with Bonferroni correction for multiple comparisons.

5 Results

We performed a quantitative analysis of participants' performance, complemented by their subjective feedback.

5.1 Performance Analysis

5.1.1 Stationary Targets

Two participants did not complete the trials with Spatialized Audio – P1 due to a technical problem, P4 due to frustration in the learning period. The comparison of **number of points** (Figure 4) has shown significant differences between the three techniques ($p<0.001$). Pairwise comparisons have shown participants scored significantly (both with $p<0.005$) fewer points with Spatialized Audio (M=0.54; SD=1.45) than with Target Confirmation (M=7.93; SD=6.54) and Reticle-Target Perspective (M=10.67; SD=10.76) – still, results showed no significant differences between the two (p=0.23).

In line with these results, participants shot further from the target with Spatialized Audio (M=4.42m) than with Reticle-Target Perspective (M=2.40m) and Target Confirmation (M=2.00m). A closer look finds that in Spatialized Audio the horizontal offset (M=3.57m) was higher than the vertical (M=1.45m). The horizontal offset was significantly lower ($P<0.01$) in Reticle-Target Perspective (h=0.61m; v=0.92m) than Target Confirmation (h=0.77m; v=0.71m), and there were no significant differences regarding the vertical offset. Participants ended up taking a similar amount of time aiming between shots with the Target Confirmation (M=21.75s; SD=23.07) and Reticle-Target Perspective (M=20.46s; SD=16.68), and less with Spatialized Audio (M=14.62s; SD=11.84).

5.1.2 Moving Targets

Thirteen participants performed this task with Target Confirmation and Reticle-Target Perspective, meaning two hit one or less targets with these conditions in the Stationary task. Only one participant performed the Moving Targets task with Spatialized Audio. Therefore, we compared Target Confirmation and Reticle-Target alone.

Regarding the **number of points** ((Figure 4), there were no significant differences between Target Confirmation (M=2.69; SD=3.17) and Reticle-Target Perspective (M=1.46; SD=2.47). The distance of the shots fired to the target was similar between them (Reticle-Target Perspective, M=2.53m; Target Confirmation, M=2.45m). In addition, the vertical offset was significantly lower ($p<0.001$) in Target Confirmation (h=1.44m; v=0.78m) than Reticle-Target Perspective (h=1.51m; v=1.26m), but there were no significant differences regarding the horizontal offset. Finally, participants also ended up taking a similar amount of time aiming between shots with Target Confirmation (M=22.61s; SD=23.75) and with Reticle-Target Perspective (M=20.29s; SD=20.60).

5.2 Subjective Feedback

In this section, we present the subjective feedback from participants and our observations during the user studies.

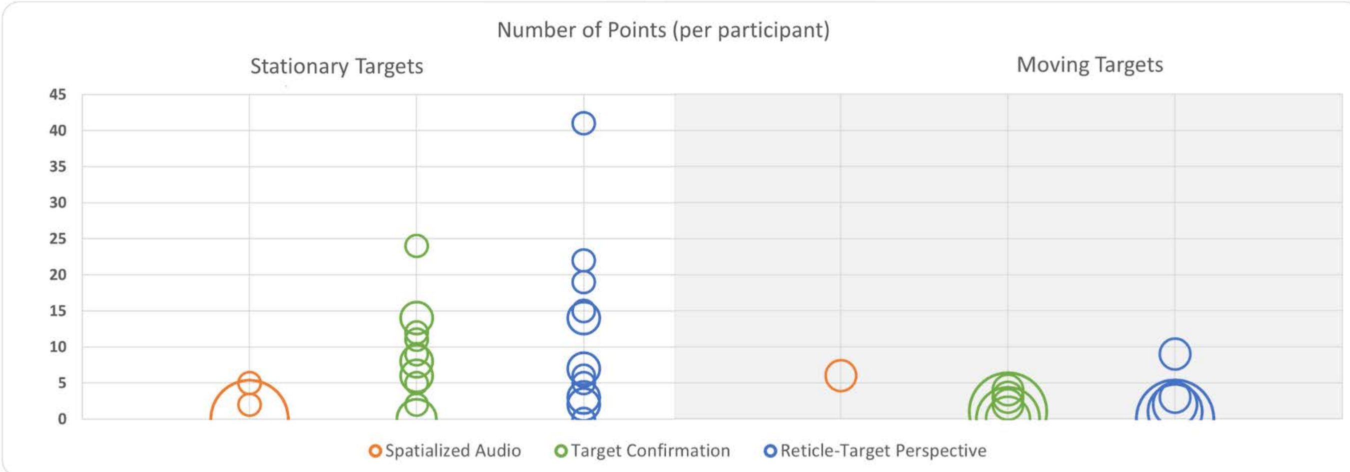

Fig. 4: Two dispersion graphs showing visualizations of the total number of points scored per participant with stationary (left) and moving (right) targets with each aiming technique. Bubble's size represents the number of participants with such score.

After completing each task, participants rated the perceived ease of use (from 1 to 7) of the technique. We found significant differences between the three techniques (p<0.001) with Stationary Targets. Pairwise comparisons demonstrated that Spatialized Audio (M=1.64) was much harder than Target Confirmation (M=4.33) and Reticle-Target Perspective (M=3.80). With Moving Targets we found no significant differences between the Target Confirmation (M=3.23) and Reticle-Target Perspective (M=2.85) techniques. Overall, the tasks were rated as hard (or medium) to complete.

When asked about their preferred technique, eight participants preferred Reticle-Target Perspective, while seven preferred Target Confirmation. Nine participants preferred the technique in which they scored the highest.

Participants preferring Reticle-Target Perspective referred either to enjoying the increased challenge of this technique or to "*making the target search more intuitive.*" (P10). P9 stated: "*This bidirectionality of the sound, for me at least, made it a little easier to understand the position of the target.*" Reticle-Target Perspective was preferred by all three participants with early blindness onset. P2 provided a possible justification related to the influence of head orientation in the other techniques: "*There are a lot of people, especially those who haven't seen since they were little, [that] do not align themselves with where the sound is coming from. (...) And this [Reticle-Target Perspective] is an advantage for those people.*"

On the other hand, some participants enjoyed the additional feedback of Target Confirmation: "*It is not monotonous, because there were also beeps, and the more elements appear the better, (...) the game becomes more interesting*" (P15). Some participants ended up referring to a possible combination of Reticle-Target Perspective and Target Confirmation where the first is augmented with the beep confirmation of the latter when aiming at the target.

Spatialized Audio was often referred as "*too difficult*" (P10). Similarly, Moving Targets were considered much harder to hit. Still, some participants reported no major differences in comparison to Stationary Targets, despite the decrease in performance: "*It is also more difficult for those who can see, I think. It got just a little more difficult*" (P13).

We also noticed that minor movements ended up affecting users' performance, particularly those done during a shooting action. Some participants performed a slight movement of the wrist when shooting, which caused them to miss the target. In addition, some participants leveraged the head-tracking capabilities in Spatialized Audio and Target confirmation (and their hands in Reticle-Target Perspective) to help disambiguate the location of targets by trying to position the targets aligned with their right or left ear first.

Participants suggested to add haptic feedback, for instance to substitute the beeps. Conversely, P13 suggested that the beeps should always be active: "*The sound of the whistle [beeps] should be active when it is closer, but also when it is further away, slowing down, but never stopping. It got to a point where no beep was playing and I did not know if the target was to the left or right.*" This happened because the beeping sound is triggered only when aiming closer to the target and P13 focused his attention on that sound alone, neglecting the spatialized sound of the target.

6 Discussion

In this section, we revisit our research questions and discuss the lessons learned from our analysis, aiming to inform the design of accessible VR experiences and aiming techniques.

6.1 Target Confirmation and Reticle-Target Perspective outperform Spatialized Audio

Careful audio design and the use of spatialized audio can improve the accessibility of virtual environments [3, 20]. Still, aiming tasks require precision, which is even harder when considering distant targets [8]. In our study, Spatialized Audio alone resulted in very poor performances, which can be explained by the difficulty in distinguishing small differences in vertical and horizontal location. This resonates with prior work on digital gaming reporting difficulties in aiming tasks and a preference for tools requiring less precision and having a large effect area – e.g., using a shotgun or grenade in combat scenarios [20]. However, this also suggests our task was particularly difficult when compared with similar works (e.g., [5, 11, 47] – likely due to the distance to and size of the target.

Target Confirmation and Reticle-Target Perspective clearly outperformed Spatialized Audio, indicating they can potentially increase the accessibility of aiming in VR for blind people. However, their success rates were still relatively low, reinforcing the difficulty of the task. Future work may try to find a balance between the challenge and assistance provided to users as a way to improve engagement and avoid frustration. As an example, some participants missed the targets due to a minor wrist movement when shooting. By being aware of this challenge, future solutions may attenuate the effect of wrist-movements that occur right before (or when) shooting. In addition, explaining the reason for missing a target – e.g., due to these movements – may help users understand and correct these behaviours as we noticed these were not easily perceived by participants. In addition, despite the difficulty of the study tasks, the scenarios were relatively simple and had reduced time constraints. Future work may explore how these two techniques can be applied or augmented to deal with more complex scenarios, such as those in mainstream VR applications (e.g., with multiple targets or more dynamic targets).

As expected, aiming at moving targets was more difficult than at stationary ones. In addition, we found no significant differences in score between Target Confirmation and Reticle-Target Perspective in Stationary or in Moving Targets. Future work may investigate how the increasing complexity of the aiming tasks affects the effectiveness of each technique, while finding ways to improve them.

6.2 Improving VR Aiming Techniques

The relatively low success rates suggest not only that the task was too difficult, but also that these techniques could benefit from improvements. For instance, the sound pitch indicated verticality, but the differences did not enable to easily distinguish between on-target and near-the-target sounds (similarly to the Target Confirmation beeps). Making more distinct sounds for below- or above-targets (e.g., as in [5]) could potentially improve the results.

Reticle-Target Perspective had lower horizontal offsets than Target Confirmation with stationary targets, suggesting the bi-directionality of this approach supported participants in better aligning their shots. Still, this did not happen for the vertical offset, which ended up being higher with moving targets (than Target Confirmation). This suggests that Reticle-Target Perspective could have also used differences in pitch to complement the volume differences, which were the only cue to distinguish verticality.

Some participants also mentioned the potential of combining both techniques, which resembles a very recent accessibility feature in the digital, flatscreen game Sea of Thieves[1].

One interesting strategy was related to participants over-turning their heads to align their ears with the targets. Some past work refers to a greater ability to distinguish lateral sound location when compared to frontal targets [16]. Future work may use this knowledge to inform the design of aiming techniques or strategically position elements in VR environments based on their relevance and task difficulty, optimizing user performance and accessibility.

6.3 Preferences are Highly User-Dependent

Seven and eight participants preferred Target Confirmation and Reticle-Target Perspective, respectively. These preferences were highly linked with performance, likely due to the established link between competence and engagement in games [49].

In addition, personal characteristics and prior experiences may influence both preference and behaviour. For instance, all three early blind participants preferred the Reticle-Target Perspective, which may be linked with differences in spatial reference systems of early and late blind people [57], causing a mismatch between head and input orientation that has also been suggested in locomotion scenarios [48]. Reticle-Target Perspective, however, depends on where the user is pointing, overcoming these challenges and potentially justifying significantly lower horizontal offsets.

6.4 Finding the Right Amount of Feedback

In Target Confirmation we intended to give users both guidance and confidence while avoiding automated alternatives such as aim assist. Still, participants revealed contrasting opinions about the amount of feedback provided. Some were overwhelmed and were unable to distinguish between on-target and close-by, while others would prefer feedback to start even further from the target. Alternatives would be to provide more distinct sounds or allow customizing the range in which feedback is given. The latter might be particularly relevant in scenarios with multiple targets in close proximity where the range will inevitably be limited.

This also raises questions about the appropriateness of each technique for specific contexts. For instance, Reticle-Target Perspective resembles other interaction mechanisms – e.g., with the smartphone [1, 29, 47] – that do not rely on head-tracking, but instead on the user's hands to determine feedback. Still, conveying such feedback is only useful when the target is already identified. Potential solutions could combine techniques, where spatialized audio is first used to convey information about the elements in the environment, and a shooting mode could activate a secondary technique (Target Confirmation or Reticle-Target Perspective) – as one would select a different weapon or ammunition in a shooting game.

In addition, results show participants shot faster with Spatialized Audio, suggesting the more precise feedback of the other techniques resulted in a more careful assessment of the target location. This reinforces that different contexts, such as the target behavior, or number of and distance to targets, may influence what is the appropriate or preferred technique. In games, this could, for example, be integrated into the design of the experience, with weapons with different ranges requiring different shooting techniques.

7 Limitations

We conducted preliminary trials to adjust the sounds used and differences in pitch. Still, design decisions – e.g., the sonification techniques used to convey verticality – may have impacted user performance and preferences. We have also set a fixed distance to the targets to ensure the study can be completed in a reasonable time and avoid fatigue, but future work may explore the impact of distance for each of the techniques. We tried to enhance spatialized audio by using headphones during the study and we used Unity's standard audio plugin. However, using state-of-the-art 3D audio implementations – including personalized HRTFs, which would be less practical to create for each participant – could potentially impact the results. While we have recruited a diverse set of participants and collected demographics and experience details, we did not collect data about participants' sound localization abilities. Such knowledge could help understand how individual differences affect performance. Finally, we focused on understanding the impact of each technique but did not conduct an overall usability evaluation of the system, which could have provided additional insights into user performance and preferences.

8 Conclusion

We implemented and evaluated three VR aiming techniques for blind people and conducted a study with 15 participants. Findings demonstrate the major challenges of the *status quo* of aiming in VR, but also show the potential of nonvisual aiming techniques that assist the user while maintaining control. Target Confirmation and Reticle-Target Perspective outperformed the baseline Spatialized Audio, while the varied user preferences emphasized the importance of personalization. We discuss our findings intending to provide actionable knowledge to designing aiming techniques in VR, improving blind people's experience and performance.

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