Speed-of-Light VR for Blind People: Conveying the Location of Arm-Reach Targets

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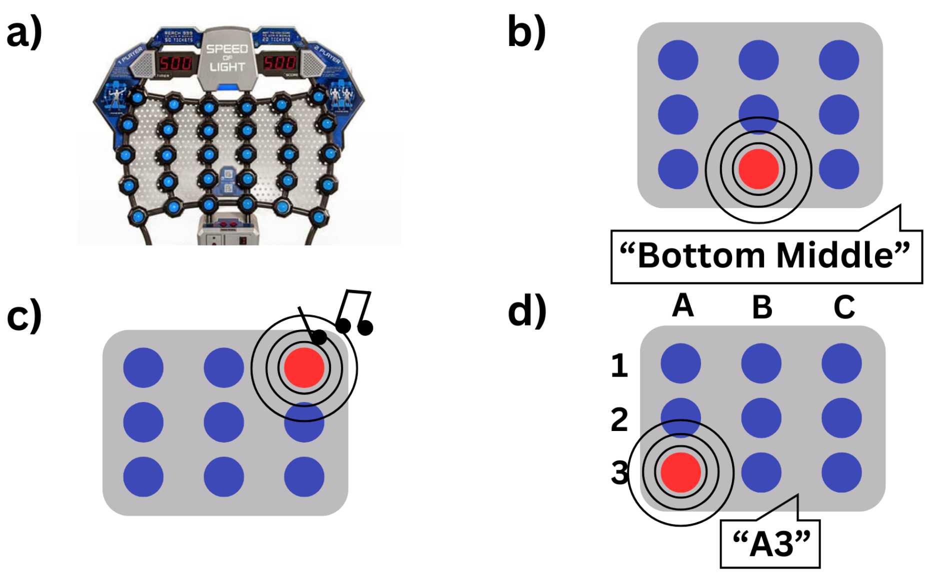

Figure 1: We developed a VR application based on the arcade game Speed-of-Light, incorporating three different techniques to communicate the positions of various buttons on a grid. The figure illustrates: a) a traditional physical Speed-of-Light machine (from Betson); b) The Speech Feedback technique announcing the active button localized in the bottom row and middle column; c) The Sonification technique playing a high pitch sound in the top right side of the grid; d) The 2D Grid Position technique indicating that the active button is positioned in the "A" column and "3" row.

ABSTRACT

Interacting with close-range objects in Virtual Reality (VR) is often prompted by visual cues, making it hard for visually impaired people to perceive their location and interact with them. To study how to enable blind users to locate and interact with close virtual objects, we adapted the arcade Speed-of-Light game as a blind-accessible VR application. We implemented three techniques: 1) Speech Feedback (e.g., "Top Right"), 2) Sonification, and 3) 2D Grid Position (e.g., "A3" for column and row); and conducted a user study with 15 blind participants aiming to provide insights into the design of non-visual techniques that convey information about targets at arm-reach. Speech Feedback was the most intuitive overall but verbose and the least flexible, while 2D Grid Position was found straightforward for regular spreadsheet users. Results also showed greater difficulty with Sonification, although it was valued by few participants who appreciated the challenge.

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CCS CONCEPTS

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

KEYWORDS

Visual Impairments, Virtual Reality, Nonvisual Feedback, Sonification.

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1 INTRODUCTION

Current Virtual Reality (VR) applications rely predominantly on visual feedback to create immersive experiences, by engaging users with high-quality graphics and near-eye Head-Mounted Displays (HMDs). This visual-centric approach poses significant challenges for visually impaired people to engage in these VR applications [6, 14].

Previous research has addressed these challenges by investigating alternative feedback modalities (audio, haptic) to convey information that is often visual, while also leveraging the new affordances of VR – e.g., through head- and hand-tracking – to replicate real-world interactions. This led to contributions in accessible VR in several contexts, such as navigating VR environments [18, 19, 21, 24], taking part in social VR [5, 13], and sports [10, 22, 23]. In these environments, it is often essential to convey information about a direction of interest or the specific location of objects. Interesting approaches may be found in prior work on 2D, flatscreen environments [2, 20**?**], or even 3D, real-world interactions (e.g., in photography, or pointing tasks with smartphones [1, 3, 12, 17], or obstacle avoidance tasks [16]). In VR, prior work has also proposed different ways to convey the location or direction of objects (e.g., [4, 7, 9, 10]), but further exploration is needed to understand their potential. In particular, the ability to understand the location of arm-reach objects non-visually and interact with them in VR is underexplored in the literature.

In this paper, we explore alternatives for conveying information about the location of close-range objects non-visually and interacting with them. For that purpose, we developed a VR application mimicking the arcade game Speed-of-Light, where the player is required to reach the active button. While in the arcade game, the button is activated visually, we implemented three techniques to convey the location of the object non-visually (Figure 1): Speech Feedback (e.g., "Top Right", Sonification (a 3D Earcon), and 2D Grid Position (e.g., "B3"). We conducted a study with 15 blind participants evaluating both performance and preferences. Results suggest the directness of Speech Feedback is easier to interpret but may also be found verbose, while 2D Grid Position is also straightforward (only) for those familiar with the concept. Sonification, on the other hand, is harder to distinguish but found (positively) challenging in a game context.

2 SPEED-OF-LIGHT VR

Our main objective is to explore non-visual methods for conveying the location of hand-reach objects. To achieve this, we implemented an inclusive VR version of Speed-of-Light replacing the visual stimuli with audio feedback. The game goal is to press the active buttons in quick succession, with a new one becoming active after a time limit or in response to a correct selection. We used this particular context due to the potential advantages of exergames and incorporating physical movement in the experience, while also using a familiar but currently inaccessible game. In addition, this allowed us to explore interactions that can be applied to other contexts. In this work, we implemented a fully Virtual Speed-of-Light version and three non-visual techniques to convey the position of the active button.

2.1 VR Environment and Gameplay

We developed a 3D VR experience using Unity and the Meta Quest 2. The development process was iterative, as we tried to balance the difficulty and engagement of the experience (e.g., by adding a vibration when close to the target and enabling participants to ask for directions). The application positions a grid in front of the user, representing the targets of the Speed-of-Light game. Users calibrate the position of the grid by extending their arms, placing it within arm's reach in front of them. We implemented two types of grids: a 3x3 grid (9 buttons) and a 4x4 grid (16). These two grids are smaller than those found in the arcade game but enabled a first exploration of three different feedback techniques in this context. A countdown sound (earcon) indicates when the game is starting.

To press an active button, participants have to reach that button by extending their arms in the right direction (needing only to collide with the button). Active grid buttons produce a specific sound depending on the technique (detailed below). For all techniques, we provide additional guidance. When one of the hands of the participant is close enough to hit an active button, the respective controller vibrates, increasing its intensity as it gets closer to the button. If players have difficulty locating the active button, they can press the trigger on their controllers. This action prompts an auditory notification indicating the button's position relative to the hand that pressed the trigger (e.g., hearing "Left" means the user should move that hand to the left). Pressing the correct active button triggers a positive sound (earcon), while incorrect interactions produce a negative one. When incorrect, the system repeats the sound of the active button. The system announces "*Task Completed*" when the overall time is over.

2.2 Feedback Techniques

We describe below the three techniques implemented to convey the position of active buttons:

2.2.1 Speech Feedback. This technique provides verbal feedback to specify the active button's location. Users receive instructions on its vertical (i.e., top, middle, bottom) and horizontal (i.e., left, middle, right) positions, resulting, for instance, in a "Top Right" speech notification. To simplify, the central button reads "Middle", instead of "Middle Middle". The rationale for this technique is to provide very clear and precise instructions. Still, it is less flexible in providing more fine-grained locations and, therefore, was only implemented in the 3x3 grid.

2.2.2 Sonification. Applicable to 3x3 and 4x4 grids, this technique uses 3D sound to indicate buttons' positions. The pitch varies with vertical location (higher for top, lower for bottom) (e.g., as suggested by [16]), while the sound direction (left or right) indicates horizontal position, enabling users to locate the button using auditory cues. For instance, when the active button is in the first column and first row, participants hear a high-pitched sound predominantly on their left headphone ear side. The different pitch sounds are available in the supplementary material.

2.2.3 2D Grid Position. Also for both grids, this technique adopts a coordinate system similar to a chessboard or spreadsheet table. Audio feedback provides the button's position using letters (A, B, C, and D for the 4x4 grid) for vertical, and numbers (1, 2, 3, and 4 for the 4x4 grid) for horizontal positioning. As an example, when the active button is located in the first column and second row, the audio notification played is "A2". This technique was explored due to its flexibility in extending to larger grids.

2.3 User Study

We conducted a user study to gain further insights into the usage of the three techniques implemented, aiming to inform the design of non-visual techniques that convey information about targets at user's arm-reach. We recruited 15 blind participants (M=10; F=5), aged 28-64 (M=44.6; SD=10.2) from a local institution.

2.3.1 Procedure. We introduced the project to participants, who were asked to sign an IRB-approved consent form (including permission to record audio) and to answer a demographics questionnaire. Twelve participants rated themselves experienced with technology, while the others had some experience. Four had never tried VR before, while the others had experienced it at least once (mostly in research studies).

Participants were introduced to the Quest 2 headset and controllers, as well as the headphones used to convey better spatialized audio. Then, we provided a brief explanation of the game and of the 3x3 grid configuration.

Afterwards, participants performed tasks with all techniques in a randomized order, but always starting with the 3x3 grid and finalizing with the 4x4 grid due to the increased complexity. Each session took approximately one hour and participants were encouraged to take breaks between trials to minimize fatigue effects. When starting with each technique, participants spent approximately five minutes in a training mode where the game had no time limit, in order to get comfortable with the technique. Subsequently, participants were asked to play two 1-minute games, with the goal of hitting as many active buttons as possible. Buttons remained active for 7 seconds, adding a time-sensitive element to the task.

After completing the tasks, participants took part in a semi-structured interview to better understand their preferences, behaviours, and the perceived pros and cons of each technique. Participants were also invited to share their overall thoughts and suggestions. They were all compensated with a 10€ gift voucher.

2.3.2 Design and Analysis. Each study session involved at least two researchers responsible for conducting the sessions, note-taking, and intervening when necessary. The whole session was audio-recorded for further analysis.

The study has a within-subjects design, where the techniques' order was counterbalanced. All data regarding participants' interactions were logged in a database. Two participants were excluded from the quantitative analysis due to a technical problem regarding data collection.

For the quantitative data, we conducted the Shapiro-Wilk Test of Normality to assess data distribution for user scores, help requests (by using the trigger button), wrong interactions across the three techniques and the two grid sizes. As distributions were not normal, we used the non-parametric Friedman Test to make comparisons among the techniques. When significant differences were observed, we used post-hoc Wilcoxon Signed-Rank Test, with Bonferroni correction for multiple comparisons.

3 RESULTS

In this section, we present both quantitative results related to the efficiency of the three implemented techniques, as well as qualitative results based on participants' feedback and their preferences for the techniques.

3.1 Quantitative Analysis

Regarding the 3x3 grid (Mean and st. dev. values in Table 1), there were no statistically significant differences for score ($p=0.101$) and for wrong interactions ($p=0.156$). However, results showed a significant difference in the number of help requests ($p<0.001$). In particular, pairwise comparisons have shown that participants performed more help requests with Sonification than with Speech Feedback and 2D Grid Position (both with $p < 0.005$).

For the 4x4 grid, we found significant differences in score ($p=0.035$) and in the number of help requests ($p=0.023$), but not for the number of wrong interactions ($p=0.162$). This indicates Sonification was significantly harder than 2D Grid Position, portrayed by its lower score and higher number of requests. (Table 1). These results are somewhat expected due to the more objective and direct feedback of the two verbal techniques. Still, differences may be even greater with larger grids, as an average listener can only distinguish a limited number of pitches reliably [15]. Alternative approaches to represent height – e.g., using natural sounds [11] – may be explored in that case.

3.2 Subjective Feedback

The overall feedback about the game and the whole experience was very positive, with participants classifying it as fun and wanting to play it more often. P8 mentioned: *"I found it quite interesting and fun (...) It was a game that made me want to try again and keep trying (...) It is challenging in the sense that I feel like 'I want to improve this!'"*. The game's physical demands were also referred to positively, as referred by P1: *"After a while of playing, you have already completed your workout."*.

When ranking the techniques by preference, 2D Grid Position and Speech Feedback were ranked first more often (7 and 6, respectively) than Sonification (2). In particular, most participants

Table 1: Mean and Standard Deviation of Performance Metrics for Each Technique on the 3x3 and 4x4 Grids.

Technique	Grid	Score	Help Interactions	Wrong Interactions
Sonification	3x3	M=8.8 ; SD=8.7	M=30.5 ; SD=20.1	M=13.1 ; SD=5.0
Speech Feedback		M=13.6 ; SD=8.6	M=12.8 ; SD=15.5	M=8.7 ; SD=3.8
2D Grid Position		M=13.8 ; SD=8.3	M=16.4 ; SD=14.2	M=10.3 ; SD=4.6
Sonification	4x4	M=4.6 ; SD=3.4	M=34.7 ; SD=16.5	M=18.1 ; SD=4.4
2D Grid Position		M=8.1 ; SD=5.9	M=27.2 ; SD=17.3	M=15.8 ; SD=6.3

who had prior experience with spreadsheet tables or chess found it easy to interpret the instructions given in the 2D Grid Position condition. P2 mentioned: *"Mentally easier for me to orient myself in the game (...) it is easier to use because I use it on the computer daily"*. This aligns with previous research on accessible programming [8] showing that a grid structure enables blind people to discretize a 2D space effectively. However, those without prior experience with grids found it more challenging. P8 stated: *"I feel like I am not that good with grids and interpreting and understanding them (...) It has always been a struggle of mine. I have been trying to play Battleship, and it is only after I have played it about 10 times that I have managed to kind of understand the logic of it."*.

As for the Speech Feedback technique, it was considered the most intuitive by many, providing very direct instructions. However, some participants found the auditory cues too lengthy for a time-sensitive game. P1 mentioned: *"It is too much information (...) when we go for the 1-minute test, while we are listening to 'Top Left' or 'Bottom Right,' maybe it is already been 1 second out of 7."* This is supported by data showing that the "Middle" button was often selected when the "Middle Left" (22.9%) or "Middle Right" (29.8%) were active, suggesting participants would not wait for the whole instruction (while also showing a negative consequence of using "Middle" alone for the central button).

Sonification was the least preferred technique but was the favourite for two participants who valued the increased difficulty and challenge. P11 mentioned: *"I had more fun with the second one, the one with the beeps, because of the degree of difficulty."* On the other hand, participants felt that the pitch differences could be greater to better differentiate height. This explains the greater use of help requests, as explained by P6: *"Sometimes I did not understand the sound well, if it was more acute (...) I was a bit confused, I always had to use the help of the controller."*.

4 CONCLUSION

We developed a VR Speed-of-Light game accessible to blind people and explored three non-visual techniques to convey the location of arm-reach targets: Speech Feedback, Sonification and 2D Grid Position. A user study with 15 blind participants has shown high satisfaction with the VR game itself and with the three techniques. Still, it has also shown the pros and cons of each technique that can help inform the future design of similar scenarios involving the location of and interaction with close-range targets. Speech Feedback, as expected, was found to be clearer and easier to interpret, but was found too verbose for some participants. In addition, it was not explored in the 4x4 grid due to its lack of flexibility, which would likely result in an even more verbose solution. The 2D Grid Position brings such flexibility and is also easy to interpret by participants familiar with the (spreadsheet or chess) concept, but harder for those unfamiliar with it. Sonification, also a flexible technique, posed significant challenges to identifying subtle differences in sound frequencies and lateral position (especially as the grid size increases). Other implementations (e.g., using natural sounds [11]) or combinations of pitch with other sound characteristics, such as volume or timbre may help further differentiate the targets. Still, we also note this technique offered a level of complexity that some participants found engaging, which may be important to maintain in the context of a game.

These findings suggest the applicability of these three techniques in time-sensitive interactions with spatial reasoning. In addition to potential improvements, one may also consider particular contexts, such as entertainment or work, where different techniques or adaptations may be more appropriate. As an example, this work explored rectangular grids at arm's reach for target identification and selection, but further research is needed to understand the variety of spatial challenges (e.g., around the user) that can be created to be engaging, challenging, and accessible for blind users.

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