Virtual Showdown: An Accessible Virtual Reality Game with Scaffolds for Youth with Visual Impairments

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ABSTRACT

Virtual Reality (VR) is a growing source of entertainment, but people who are visually impaired have not been effectively included. Audio cues are motivated as a complement to visuals, making experiences more immersive, but are not a primary cue. To address this, we implemented a VR game called Virtual Showdown. We based Virtual Showdown on an accessible real-world game called Showdown, where people use their hearing to locate and hit a ball against an opponent. Further, we developed *Verbal* and *Verbal/Vibration Scaffolds* to teach people how to play Virtual Showdown. We assessed the acceptability of Virtual Showdown and compared our scaffolds in an empirical study with 34 youth who are visually impaired. Thirty-three participants wanted to play Virtual Showdown again, and we learned that participants scored higher with the *Verbal Scaffold* or if they had prior Showdown experience. Our empirical findings inform the design of future accessible VR experiences.

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CCS CONCEPTS

• Human-centered computing → Accessibility systems and tools
• Human-centered computing → Empirical studies in accessibility

KEYWORDS

Virtual Reality; Blind; Low Vision; Youth; Spatial Audio; Haptics

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1 INTRODUCTION

Virtual Reality (VR) has grown dramatically over the last several years, with new commercial VR experiences such as Oculus Rift [41], Google Cardboard [42], Samsung Gear VR [43], and HTC VIVE [44]. VR, a computer-generated simulation of a 3D environment [45], is a source of gaming, entertainment, exploration of spaces, physical exertion [13], and medical applications [6,12]. While gaming has an impact on people of all ages, youth are playing video games; according to Pew Research Center in 2015, 72% of teens are playing video games [23].

As prolific as gaming is, and as VR is increasing in popularity, the design of these experiences is excluding certain segments of the population. For youth who are visually impaired (YVI), there remain accessibility barriers to VR experiences. There is prior research designing audio (e.g., [7,13]) and haptics [13] for 3D virtual experiences. However, these experiences are motivated as a complement to visuals, with goals of engagement, persuasion, and immersion [7,13], as opposed to a primary cue of interaction. While there are existing 3D audio games [46–50], they involve keyboard input as opposed to using one's body like immersive VR games.

To address this gap, we implemented a VR game (Virtual Showdown) that is inspired by an accessible game called Showdown, where people use their hearing to locate and hit a ball against an opponent. We chose Showdown intentionally to avoid designing the visuals (beyond debugging purposes) because players wear a blindfold. We could focus solely on audio, verbal, and vibration design in VR. For many YVI this may be their first experience with VR. We implemented the system, made design decisions for gameplay, and designed scaffolds to help YVI learn how to play. We present our findings from an empirical user study with 34 YVI to assess the acceptability of Virtual Showdown and the comparison between two types of scaffolds:

1 *Verbal Scaffolds* that provide verbal previews of the ball trajectory across the table, verbal coaching as the ball crosses the halfway point of the table, and constructive feedback if a user misses the ball.
2 *Verbal/Vibration Scaffolds* that provide the same verbal information and employ a vibration "metal detector," meaning the closer one's hand gets to the right location to hit the ball, the more intensely the vibration they feel.

We compared the participants' final scores and levels achieved between conditions. We assessed demographic factors for both conditions (e.g., age, gender, Showdown experience). We also determined body movement strategies that the participants employed while playing the game. We had participants compare the conditions and found no clear preference. Our work addresses two research questions. When YVI play a 3D audio VR game that involves targeting and hitting a moving virtual object:

1 How do they perform with Verbal Scaffolds versus Verbal/Vibration Scaffolds?
2 What are their body movement strategies during gameplay?

From our work, we present three contributions:

1 A detailed system design of Virtual Showdown, a VR game accessible to YVI with 3D audio that encourages body movement and interaction with moving virtual objects
2 A design of two scaffolds for learning to play Virtual Showdown
3 Results of our empirical study with 34 YVI to assess the acceptability of Virtual Showdown and a comparison between the two scaffolds with respect to scores

We discuss background and related work with the game of Showdown, 3D audio design and localization, accessible computing games and VR for people who are visually impaired. We describe our Virtual Showdown implementation and the design of the scaffolds. Then, we present our empirical user study with 34 participants, along with our findings from the user study. Finally, we discuss our contribution and its implications making accessible VR experiences for YVI.

2 BACKGROUND AND RELATED WORK

We discuss the game of Showdown, 3D audio design and localization, accessible computing games, and VR for people who are visually impaired (PVI). While our project focuses on youth, instead most related work focuses on adults with visual impairments. Therefore, we will mention when the related research is with YVI.

2.1 Showdown

Showdown [51] is a sport that is inclusive to players of all vision levels because all players must wear a blindfold during the game. Two players stand at opposite sides of a Showdown table1 (Figure 1). Like air hockey, the objective is to hit the ball with the bat into the opponent's goal across the table. The opponent attempts to block their goal. A

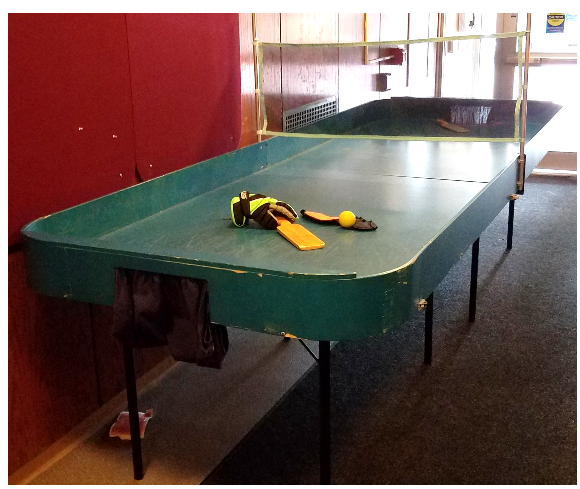

Figure 1. This is a Showdown table with plastic ball, blindfold, and glove grasping a wooden bat at one of our study sites.

player can score 2 points for a goal and 1 point if the ball stops or becomes inaudible for ≥ 2 seconds on the opponent's side, or if the ball flies off the table. The *International Blind Spots Federation* website has further information [51].

We chose Showdown as the game to implement in VR because of the fast-paced fun nature of the game. In fact, at one of our study sites (sports camp for YVI); YVI took advantage of their access to Showdown by creating tournament brackets. Further, Showdown allows people to move their bodies during gameplay, which allows a player to be physically active. The non-visual aspect of Showdown allows us to focus solely on the audio, verbal, and vibration design to make VR accessible. Finally, we can make Showdown accessible to YVI who do not own a table.

2.2 3D Audio Design and Localization

3D audio is used in VR to create realistic virtual environments [28]. In fact, Oculus and Microsoft have thorough documentation on spatialized 3D audio [52,53]. Developers can use 3D audio to help people localize sounds, which is the ability to determine where sound is coming from in a virtual environment.

Lateralization, the most important cue for localizing a sound source's angular position, involves the difference in the sound waves coming between one's left and right ears [7]. When listening to 3D audio, it is important to wear headphones (ideally on-ear or over-ear) to discern between the left and the right ears. Head-Related Transfer Functions (HRTFs) are also important because they filter sounds based on the user's physical characteristics. Because we want Virtual Showdown to work with a wide audience, we use a generic HRTF with the Microsoft Audio Spatializer, bundled with Unity3D and Windows 10 [27].

3D audio does not just move horizontally or vertically, it must also convey distance. Research shows that computers can simulate the attenuation of a sound source using the Inverse Square Law by decreasing volume and intensity as an object moves further away [7]. Sound reflections can also help convey distance in a virtual environment. Companies such as Oculus and Microsoft provide the ability to reflect sound in 3D environments [52,54]. Virtual Showdown conveys subtle reflections based on the ball's location to convey distance without sounding artificial or distracting.

A barrier in 3D sound localization is the cone of confusion where a person cannot distinguish sound between the ears[2]. To alleviate this issue, VR headsets have head tracking [2,7,53] so that users can tilt or turn their head to hear the sound from different perspectives. Virtual Showdown uses the Microsoft Kinect Face Tracking SDK [37] to track a user's head.

Implementing 3D audio in a game can be computationally expensive. Both research [10,22] and industry [52,53] have optimized acoustics in VR to work in real time. For instance, Unity3D excludes audio occlusions [35].

The related work on 3D audio and localization provides us best practices for Virtual Showdown. However, the goal of the related works – that the sounds are "complementary to visuals" or make it "feel immersive" in a virtual environment [7] – is different than ours, which is to use audio as a primary cue. There is an opportunity to explore how to implement 3D audio as a primary cue of gameplay along with verbal and vibration scaffolds to make VR accessible to YVI.

2.3 Accessible Computer Games for PVI

Several audio-based games exist for people who are blind where they replace visual cues with binaural sound or 3D audio. Audiogames.net has over 638 audio games [55], including Shades of Doom, AudioQuake, Terraformers, and PB-Games' Showdown [46–49]. PB-Games' Showdown uses recorded stereo audio effects, including left and right audio cues to locate the ball. Based on the sound of the ball, players use the left or right arrow keys to move the bat and the enter key to hit the ball. Giannakopoulos et al. also developed an 3D audio-based tennis game that employs the keyboard [11]. However, these games are not immersive: they do not have head tracking to account for the cone of confusion and the keyboard, not the body, solely controls the game.

VI-Bowling [21] and VI-Tennis [19] (tested with youth and adults who are visually impaired) are accessible games that involve body movement and moving objects. Both games use a Wii-Mote along with audio and haptic feedback to communicate where to aim the ball or when to swing the racket. In Virtual Showdown, we leave the decisions of aiming and swinging up to the player. We explore scaffolding to help players learn how to play the game.

2 The cone of confusion [7] results from identical Interaural Intensity Differences (IID) and Interaural Time Difference (ITD).

Lastly, Smith and Nayar developed a Racing Auditory Display (RAD), an accessible implementation of a racing game that uses 3D audio [3]. In their paper, they classified accessible games for PVI. They found that most games either felt *intention-preserving* and authentic but had slow gameplay or were *efficiency-preserving* but felt contrived to play. The goal is to develop games that are both *intention-preserving* and *efficiency-preserving*. The authors presented a racing game that used RAD as an example: the user decides when and how sharp to turn during a fast-paced race. We designed Virtual Showdown to be *intention-preserving* in that players can locate the ball and *efficiency-preserving* by having the ball move constantly during gameplay.

2.4 Virtual Reality for PVI

Recently, people have developed accessible VR games. A puzzle game called "Blind" [56] includes audio cues and was released September 18, 2018. Blind Swordsman (2015) [50] uses 3D audio cues to locate enemies, and a player is to "swing" the sword by pressing a button. Virtual Showdown presents a more immersive VR experience by having the player move their body to hit the ball.

There are research efforts exploring VR for PVI, but to our knowledge, no research in accessible VR *games*. Zhao et al. [36] created a VR experience to simulate white cane interactions in a virtual environment. A person uses a white cane modified with haptics, and a VR headset with 3D audio feedback. Torres-Gil et al. [15] created a VR experience where users walk through the environment with specialized equipment using 3D audio. There is an opportunity to explore how to convey information about moving objects that are separate from the person (e.g. ball), and how to scaffold interactions with these objects.

3 VIRTUAL SHOWDOWN DESIGN AND IMPLEMENTATION

Our goal was to develop an accessible VR game that encourages body movement and interaction with moving virtual objects. We explain the design and implementation of Virtual Showdown, addressing the challenges of: 1) dimensions and physics emulation, 2) body interaction, 3) audio, 4) vibration, and 5) scoring.

3.1 Dimensions and Physics Emulation Design

To develop Virtual Showdown, we used Unity3D [38] to create a 3D virtual environment, using a physical Showdown table as a base for our virtual table design. Considering the challenges of adapting the physical game to a VR setting, we made several design decisions to create a balance between the ability to recognize the game and playability.

First, we made the virtual table smaller in length and width (100cm wide and 260cm long) than the physical table. Players can reach both edges of the virtual table without experiencing fatigue, and we kept the aspect ratio the same as the physical table.

Second, we made the bat and ball size larger than their physical counterparts did (by 26% and 66%, respectively). This choice increases the likelihood that the players can locate and hit the ball with the bat. In a full-featured game, the size of the ball and bat could be made smaller to increase the game difficulty as players increase their skills to fulfill the goals of GameFlow [26].

Third, we set the Unity 3D physics settings [31] to allow the ball to bounce easily and experience friction while on the table. We set the ball's dynamic friction so that it comes to rest quickly so the ball would not roll infinitely, confusing players with endless spatial audio. We set the bounciness with almost no loss in energy so that beginner players could hit the ball at different speeds and still experience gameplay.

Fourth, we controlled the speed range of the ball, which is difficult to do during natural gameplay. Our computer opponent (described in "3.5 Game Design") hits the ball at a speed range of 40 - 250 Unity3D units, which correlates to 1.87 – 8.2ft/s. We made this choice to allow for various levels of challenge for gameplay. We capped the speed at 250 (8.2 ft/s) so that the Unity3D physics engine could calculate collisions quickly enough to prevent the ball from phasing through the walls and bat.

3.2 Body Interaction Design

Players can stand either in open space or in front of a table. A table is preferred because it increases the realism of the game and decreases fatigue because players can rest their body on the table.

3.2.1 Body Tracking. To track the player's body, we used the Microsoft Kinect for Windows SDK version 2.0 [37], C#, and a Unity3D plugin [57]. We used Kinect's Body Tracking [18] to track the player moving in the game space as a form of "outside-in" VR positional tracking, where the Kinect tracks the position of the body in a space instead of with user-worn equipment [39]. Xbox One Kinect recommendations suggest that a player stands 1.4m away from the Kinect [16], but the game will work as long as the Kinect is properly tracking the player.

Because the table is optional for gameplay, the Kinect does not track the table directly. Therefore, we calibrate the location of the table via "the center of the table edge on the player's side," which we call the player's virtual table position (PVTP, Figure 2). The player stands at "the center of the table edge" on their side during calibration. We calculate PVTP using Kinect's Body Tracking. The Z-axis of PVTP is the minimum distance of the spine, hips, waist, and mid-section. The X-axis of PVTP is the center point of the chest. After calibration, the player can move around the game space. Without the table, the virtual table follows the center of the player's body in case a player drifts over time.

3.2.2 Bat Positioning. To determine the bat position, we calculate the difference between the PVTP and the user's tracked hand position in the Z and X dimensions. We omit the Y-axis because we cannot assume the table height or that the player has a table. The user can place their hand as high or low as preferred.

To calculate the rotation of the bat in the virtual world, we first detect the Z and X position of the wrist and the Z and X position of the fingertips (Figure 3). We create a right triangle, where the line segment between the wrist and fingertips is the hypotenuse, and the adjacent segment runs parallel to the player's chest (Figure 3). Arctangent provides the angle between these segments. Because the real-time position of the wrist and hands introduce jitter, we used built-in Unity smoothing functions [32]. Further, we locked the rotation of the bat to the closest angle of -45, 0, 45, 135, and 180° to keep the bat steady (Figure 3). These angles allow the player to hit the ball back to the other side of the table using straight and angled forehand and backhand shots. A player can use their right or left hand.

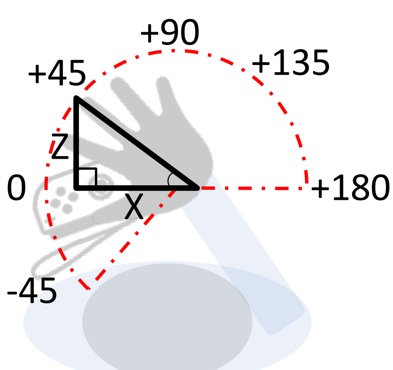

Figure 3. This is a top down view of the available bat rotations for the right hand. Photo attributions: Detachable Switch Controller Armband Right by Chad Remsing from the Noun Project CCBY 3.0, Hand by Alexander Wiefel from the Noun Project CCBY 3.0

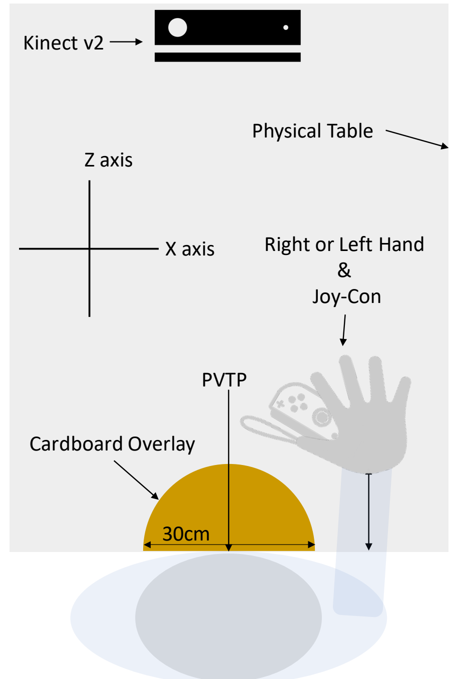

Figure 2. This is a symbolic diagram with Kinect, Joy-con, PVTP, and cardboard overlay. Photo attributions: Game console by Vangos Pterneas from the Noun Project CCBY 3.0, Detachable Switch Controller Armband Right by Chad Remsing from the Noun Project CCBY 3.0, Hand by Alexander Wiefel from the Noun Project CCBY 3.0

3.3 Audio Design

3.3.1 Location of the Audio Listener via Head Tracking. To ease body movement, we do not use a VR headset to perform the head tracking. Instead, we track the pitch, roll, and yaw of the person's head with Kinect's Face Tracking [17]. We have the player's head control Unity 3D's main camera with attached audio listener. In turn, the game conveys the sound of the ball with spatial audio with respect to the player's head in the virtual world (Figure 4). For example, if the player turns their head to the right, the

Figure 4. Screen shot of a visual debugging interface showing a person controlling the camera and audio listener. Left: camera view, Right: top-down view with camera and audio listener at the bottom

camera view and audio listener will turn and face the right side of the table.

However, we fixed the Y position of the camera at 25cm above the virtual table – the same height as the audio sources. While this position is lower than a person's ears in the real world, we chose this height to exaggerate the left and right audio cues. Lastly, we used Unity's built in smoothing functions [33] to smooth the Face Tracking data so that the camera and audio listener movements are fluid.

3.3.2 Conveying the Location of the Ball. Like real-world Showdown, Virtual Showdown employs audio as the primary cue in determining the location of the ball. The ball has a digital sound [30] that oscillates between low and high frequencies (648.00Hz – 735.00Hz). We chose this type of sound effect based on the Oculus Audio documentation [53]; a sound that oscillates in pitch is easier to locate than a constant tone. We used Unity3D to generate the 3D sound based of the ball with respect to the audio listener. For lateralization, we used Microsoft Audio Spatializer with a generic HRTF [27].

To help the player infer depth, we created a custom volume rolloff curve based on Microsoft's recommendations [29]. We added a Doppler Effect level of 0.25 to help convey the direction of the ball's movement. We also employed a dynamic Audio Mixer in Unity3D to convey when the ball is on the far side of the table. To convey when the ball is on the far side, we added slight early reflections using the Unity3D audio filter SFX Reverb effect [34]. We also applied a low pass filter (cutoff of 2975.00 Hz) to exaggerate the sound. When the ball is on the player's side of the table, we programmatically remove the reflections and low pass filter to generate a clear sound.

Our approach to audio effects is computationally cheap because the game is not dynamically calculating occlusions, reverb, and reflections for every location and 3D object in the virtual environment for every frame. Instead, we add simplified audio effects based on which side of the table the ball is on.

3.3.3 Other Sound Effects. The player constantly hears the ball sound, but we include other intermittent sound effects when the ball collides with a wall, the bat hits the ball, and the player's hand goes out of bounds. When the ball hits a wall, the ball makes a "bloop" sound effect [30] and then bounces off the wall. The "bloop" has spatialized audio like the ball. When the bat hits the ball, the system plays a "hitting" sound effect (self-recorded). If the player's hand moves out of the game boundaries, Virtual Showdown plays a warning sound effect [30] to notify the user so they move their hand in bounds.

Finally, we dynamically changed the pitch of the ball based on its velocity. The pitch would modulate on a scale of 80% to 125% of the original pitch on a linear scale. At the ball's lowest velocity, the pitch was 80% of the original sound effect. At the maximum velocity, the pitch is higher than the original at 125%.

3.4 Vibration Design

To provide multimodal feedback (which is helpful during gameplay [20,22]), we used a Nintendo Switch Joy-Con [58] because the controller is small enough for youth (10.21cm high, 3.58cm long, and 2.84cm deep), light (1.7oz), and includes a wrist strap. In this way, players can make body gestures without experiencing fatigue or losing the game controller. Further, the Joy-Con supports HD-rumble, which are different intensities of vibration [59]. We connected the Joy-Con to Virtual Showdown with a Unity3D plugin that interfaced C# and the Bluetooth connection [40].

The Joy-Con vibrates with HD-rumble in complement to the sound effects. Vibrations convey when the player hits the ball with their bat and when the player's bat moves out of bounds. Because Joy-con's HD-rumble has different intensities [40], Virtual Showdown uses different vibration intensities based on how hard the player hits the ball. The vibration was set to a low frequency of 160Hz and a high frequency of 320Hz. The amplitude changes on a linear scale based on the squared magnitude of the collision impulse. The harder the player hits the ball; the Joy-con vibrates more intensely. When the player's hand moves out of bounds, the vibrations were set from 90Hz-270Hz. As the player's hand moved further out of bounds, the frequency increased linearly to indicate that they needed to move their hand back to the table.

3.5 Game Design

To conduct a controlled lab study, we preselected the directions in which the virtual opponent hits the balls toward the player. Therefore, our game is a Showdown drill session. The player does not serve the ball. The computer opponent sends 30 balls one at a time along 15 trajectories in a random order. The balls start in three locations on the opponent's side: left, center, and right. Dividing the width of the table (100cm) by the width of the ball (20cm) gives us five destinations on the player's side: far right, center right, center, center left and far left (Figure 5).

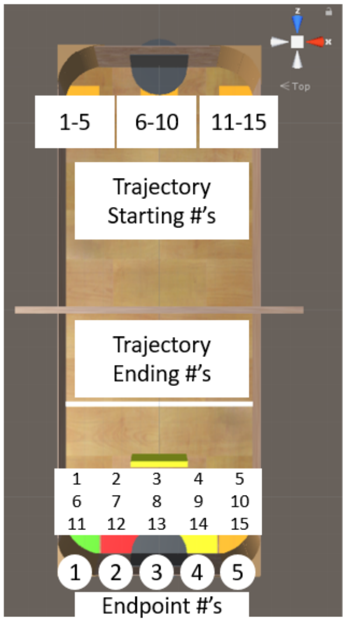

Figure 5. Illustration of the trajectories and endpoints. Two examples: 1) Trajectory 1 starts in the upper left corner and finishes in the lower left corner; 2) Endpoint 5 is located in the lower right corner.

The objective of Virtual Showdown is to earn as many points as possible, with the highest score being 90. Following GameFlow's [26] and Brewer et al.'s recommendation [1], we added points to keep YVI engaged and give them a task to accomplish. If the player hit the ball into the opponent's goal, they receive 3 points. If the player hits the ball and it made it at least halfway across the table within 8 seconds, they receive 2 points. If the player tapped the ball, they receive 1 point. Lastly, if the player hit the ball into their own goal or they did not strike the ball within 8 seconds, they do not receive points.

4 VIRTUAL SHOWDOWN SCAFFOLD DESIGN

To explore our research questions of how scaffolds with verbal or verbal/vibration hints affect performance and movement, we included seven levels in Virtual Showdown with increasing difficulty. Over the play session of 30 balls, a player can reach level seven based on their personal progress. To advance to the next level, a player must hit four out of the last six balls in a sliding window. In Levels 1-3, we employ our scaffolds, while keeping the ball at a constant speed of 40 Unity units (1.87 ft/s). In Levels 4-7, we remove our scaffolds, and the ball increases at a speed of 10 Unity units per level. We present the verbal and verbal/vibration scaffolds explored in our user study.

4.1 Verbal Scaffold

Levels 1-3 provide verbal scaffold support to help the player learn how to interact with Virtual Showdown (Figure 6). In Level 1, Virtual Showdown presents a verbal preview of the ball's trajectory. It reveals where the ball will depart from on the opponent's side (with respect to the player's right and left side) and where it will arrive on the player's side in a complete grammatically correct sentence. Further, the verbal preview uses spatial audio. In Level 2, we present the same information in Level 1 also using spatial audio, but with shorter incomplete sentences. The volume rolloff curve used in the verbal statements is the same as they are on the ball. This technique allows users to be acquainted with the distance before Virtual Showdown releases the ball. In Level 3, we present the same phrase as Level 2, but without spatial audio. Virtual Showdown presents Level 3 prompts with a medium volume in the center of the virtual table.

Fisch's work on making educational games recommends using hints along with scaffolding when players are incorrect [8]. Hints help lead players in the right direction to help them understand the underlying context of game play. Therefore, we created midway audio prompts in Levels 1-3. As the ball moves from the opponent's side and across the halfway point on the table, Virtual Showdown assesses whether the player's hand is in the correct position to hit the ball back. If the player's hand were not in the

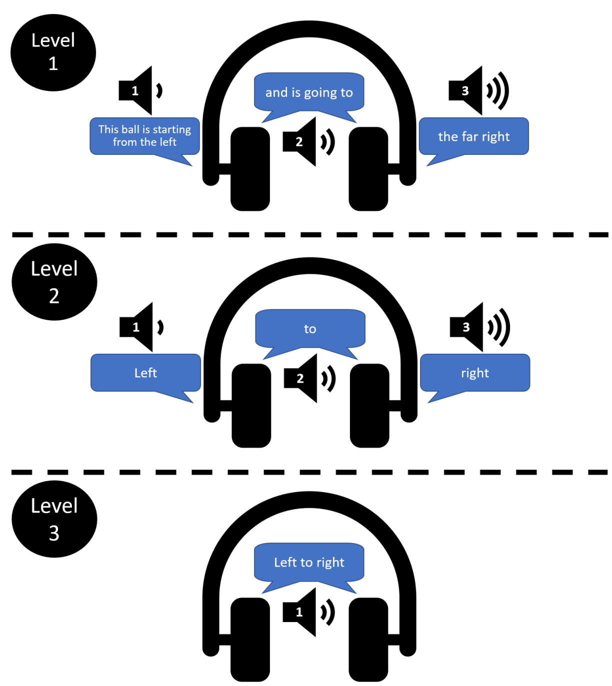

Figure 6. Presented is an example scenario of Levels 1-3 with Verbal Scaffolds.

correct position, then the game would say, "Move to the right" or "Move to the left." These quick audio prompts last 1.012 seconds.

Finally, we present constructive feedback after each ball hit attempt. Previous research demonstrates that a game needs to not only have feedback on performance, but explanatory feedback to scaffold users toward doing the correct action next time [8,26]. Following the recommendation of Giannakopoulos et al.'s tennis game, we provide guidance for all seven levels [11]. If a player misses the ball, the game provides feedback on how far and in which direction the player had to move their hand. We divided the constructive feedback evenly between quantifiable distances and metaphors that represent distance. The metaphors included are "off by a foot", "by the length of a pen", "by the length of an arm", "by a pinch", while; the quantifiable distances were all presented in inches.

4.2 Verbal/Vibration Scaffold

This condition is identical to the Verbal Scaffold, except that we add vibrations. We chose not to implement a Vibration Scaffold alone because we expected too much delay in players interpreting previews and constructive feedback encoded solely as vibrations. Virtual Showdown would no longer be 'efficiency preserving' [3], where the game is at a fast pace. We explore a tradeoff between two possible effects: 1) providing multimodal feedback helps the player understand the information faster or more clearly, which has been shown to help users perform better in video games [20]; and 2) providing vibration information will compete with the player's ability to listen to the moving ball due to extra cognitive load [24].

In Levels 1-3, we employed tactile dousing (similar to the proximity-sensitive sound coming from a metal detector), as utilized by the work done in Morelli et al.'s VI Bowling [21]. For our tactile dousing, we used the Joy-con HD Rumble. In real time, as the player's hand moved closer to the ball's incoming destination, the Joy-con's vibration increased. First, if the hand was ≥ 30cm away from the destination, the Joy-con did not vibrate. From 21-30cm, the controller vibrated at 10% its maximum capability. At 11-20cm, the controller vibrated at 30% its maximum capability. When the hand was closest (≤ 10cm), the controller vibrated at 50%. We chose to limit the vibration amplitude to 50% to avoid fatigue from the vibrations [5].

While in the Verbal Scaffold, we decreased the detail as the players advanced from Levels 1-3, with tactile dousing, we could not decrease the intensities of the vibrations between levels. Otherwise, players would have to relearn the relationship between vibration intensity and proximity of hand to the destination.

5 USER STUDY

5.1 Participants and Study Locations

We had 34 participants in our study who are visually impaired (ages 8-20, 13 females, 21 males). Ten participants reported no vision, totally blind, or light perception only. Nineteen reported having low vision, two have peripheral vision, one has light sensitivity and color blindness, one has vision in only one eye, and one participant did not know (but used a cane). Twenty-eight had experience with video games, but only seven had experience with VR. Fifteen had experience with Showdown. We conducted the user studies in separate rooms or areas during two different sports camps for YVI. We received permission from the directors of both camps to conduct user studies.

5.2 Device Setup

Participants stood at the head of the table to participate in the study. They held the Joy-con with wrist strap and wore on-ear style, Skullcandy Grind Wireless Headphones [25]. At the center of the head of the table, we taped a semi-circle cardboard piece that matched the size of the virtual goal (Figure 2). The cardboard semicircle has a 30-inch diameter. We told participants to stand in front of the semicircle for calibration to determine the PVTP. On the other head of the table were the Microsoft Kinect, laptop, and experimenter. There was a video camera on a tripod next to the experimenter to video record the participant's motions and reactions during gameplay.

5.3 Study Procedure

Our study was within-subjects, so participants experienced both the Verbal and Verbal/Vibration Scaffolds. We counterbalanced the participants, where 17 experienced Verbal first and 17 experienced Verbal/Vibration first to ensure learning effects or fatigue did not bias the conditions. Our independent variable was Verbal Scaffold versus Verbal/Vibration Scaffold. Our dependent variables included gameplay measures: final score and final level; attitudinal measures of participant's preference and ease of hitting the balls; and body movement strategies.

We gave a tutorial to participants to explain, "If the ball is louder in your right ear, it is on the right side, and if it is louder in your left ear, then it is on your left side." We also explained, "Sometimes the ball is in the center, so it may sound equal in both ears." We explained to participants that as the ball gets louder, the ball is also getting closer to them. We explained that the objective of the game is to locate and hit the ball and that you can earn points based on the hit. We also mentioned that when a participant hit the ball, they would hear a click sound and feel a vibration.

Once we explained the game, we instructed participants to stand in front of the semi-circle cardboard piece, wear the Joy-Con wrist strap, and hold the Joy-Con in their dominant hand, and to wear the over-ear headphones. We started the game software, finally having participants reach far to the right and the left so they could hear the repeating out of bounds sounds and feel the vibrations that represent going out of bounds. Participants would then play the game for six minutes.

After each condition, we conducted a brief interview about whether hitting the balls was easy or hard. After both conditions, we asked participants to choose their favorite scaffold, reflect on playing the game again, and playing the game again with friends. Each study took 30 minutes, and we did not compensate participants. We audio recorded and transcribed the interviews.

5.4 Data Measures

We conducted a mixed-methods study. Using our software, we measured whether the participant hit or missed each ball along with the number of points earned for each ball. For each participant, our software calculated:

- *Final Score*: How many points did the participant earn during the 6-minute gameplay?
- *Final Level:* What level did the participant reach during the 6-minute gameplay?
- *Ball Outcome:* For each ball, how did the participant score (from 0 to 3)?

From participant interviews, we collected:

- Preferred Condition: Participant's preference between Verbal Scaffold and Verbal/Vibration Scaffold
- Play again (and with Friends): Whether the participant would want to play again and play again with friends

5.5 Data Analysis

We conducted the Shapiro Wilk test for normality on all measures and found that Final Score for both conditions was normal. While Final Level in Verbal Scaffold was normal, Final Level was not normal in Verbal/Vibration Scaffold (W=0.99, p=.002). As a result, we use a paired t-test to compare the conditions with respect to Final Score and the Wilcoxon Signed Rank test to compare the conditions with respect to Final Level. We assessed the "binary" demographic factors on Final Score (gender, experience with showdown, video games, or VR) with a t-test, and assessed age with the Kruskal Wallis rank sum test.

We also assessed the impact of the ball trajectory and ball arrival location on the Ball Outcome (e.g., if a ball moves diagonally, if a ball arrives in the center). We "flipped" the outcomes for left-handed participants, so the trajectories and arrival locations were with respect to the dominant hand. We compare those trajectories using the Friedman test and completed pairwise comparisons using the Wilcoxon signed rank test. For the 15 trajectories and for the 5 endpoints, we applied Bonferroni correction to make alpha 0.05/105 = 0.00047 and 0.05/10 = 0.005, respectively to mitigate Type I error.

We conducted coding on the video footage to determine Body Movement Strategy. We omit P22 from this analysis due to video recording error. Four researchers independently skimmed video footage of participants to determine an initial codebook. Using the codebook, three researchers independently coded two random participants (P4 and P34) using BORIS [9], and then met to discuss all disagreements and in turn reach agreement. We updated the codebook after discussing each disagreement. Then, two researchers independently coded 20% of the remaining videos (P1, P10, P16, P18, P21, P25, and P32). Cohen's Kappa was calculated for each code category, and we removed any coding categories with an agreement labeled as "poor" or "fair" [14]. Then the two researchers independently coded the rest of the videos with our final codebook. We present our codebook and Cohen's Kappa scores in Table 1.

Finally, two researchers conducted open coding for each interview question [4]. The researchers discussed and reached agreement on the codes.

6 RESULTS

6.1 Quantitative Results

Below we discuss the results that span across *Verbal* and *Verbal/Vibration Scaffolds* followed by the results where we compare the two conditions.

6.1.1 Effect of Demographic Factors on Final Scores. Age, gender, video game, and VR experience had no effect on the Final Score for both conditions. We hypothesize that prior video game and VR experience involves different types of input (e.g., controller, keyboard), but not necessarily body movement as an input. However, prior showdown experience affected the Final Score in both conditions (Verbal: t=-3.03, df=30.02, p=0.005; Verbal/Vibration: t=-

2.17, df=31.66, p<0.05). Participants with prior Showdown experience got a higher Final Score than those without experience (Verbal: mean w/experience = 41.87 versus w/o 30.95; Verbal/Vibration: mean w/experience = 36.13 versus w/o 29.68). Looking at the two groups of participants separately (Showdown experience (n=15) and without Showdown experience (n=19)), no demographic factors had an effect on Final Scores.

6.1.2 Effect of Ball Trajectories & Arrival Location on Ball Outcome. We wanted to assess whether the ball trajectory (e.g., diagonal path versus straight path) or the ball arrival location (e.g., near dominant hand versus center of table) effected the Ball Outcome, or what score they earned from the ball hit attempt.

While we found that across all ball trajectories that there was a statistically significant effect on Ball Outcome (χ2=45.89, df=14, p=2.92e-5), that only one pairwise comparison had a difference in Ball Outcome that was statistically significant after applying Bonferroni (V=45.5, p=0.0003). Specifically, trajectories 10 and 15 had the difference, where 10 started from opponent's center toward dominant hand, and 15 moved straight down the table, always on the side of the person's dominant hand. Participants scored better when the ball remained on their dominant hand side (mean=2.35) versus when the ball moved diagonally from opponent's center to their dominant hand side (mean=1.63).

We also found that the ball arrival location effected Ball Outcome (χ2=10.73, df=4, p=<0.05). However, there was only one pairwise difference between endpoints 1 (opposing dominant hand) and 3 (center). Participants scored better when the ball arrived at the center of the table (mean Ball Outcome = 2.32) than when it arrived at the opposite of dominant hand (mean Ball Outcome = 1.72). We hypothesize that it was easier to block the goal than to reach one's hand across the table.

Looking within participants with and without Showdown experience, we found that for both groups the trajectory had an effect on Ball Outcome that was statistically significant (with: χ2=23.69, df=14, p<.05; without: χ2=29.33, df=14, p=.009); however, we found no pairwise differences. Further, we did not find that endpoint had a statistically significant effect on Ball Outcome.

Overall, there were changes in Ball Outcome based on time. When comparing average Ball Outcomes per minute of gameplay, minutes had an effect that was statistically significant (χ2=27.53, df=5, p=4.45e-5). Pairwise comparisons (with Bonferroni = 0.05/15) show that minute 2 had higher Ball Outcomes than minutes 4 (V= 1453, p= 0.0008), 5 (V=1707, p-value = 0.0001), and 6 (V= 1715, p-value = 2.703e-05). We hypothesize that participants learned how to play in the first couple of minutes, but because subsequent levels increase in difficulty, their performance degraded.

6.1.3 Effect of Scaffold Conditions on Data Measures. Overall, participants had a higher Final Score in Verbal than Verbal/Vibration (t=2.28, df=33, p<0.05), where the mean Final Score in Verbal was 35.76 and Verbal/Vibration was

Table 1. Table of code category titles, labels, corresponding agreement (percentage), and Cohen's Kappa. We omitted categories with a Cohen's Kappa score that corresponds to "fair" or "poor." See Appendix for the full codebook and omitted categories.

Category	Labels	% agreement	Cohen's Kappa
Holding Controller	Grasp Controller, Rest Controller on Hand, Pinch Controller, Hold with Two Hands	98%	0.95
Respond to Midpoint Feedback	Yes, No, N/A	95%	0.88
Amount of Attempts	Deliberate Attempt, Multiple Attempts, Free for All	92%	0.82
Type of Swing	Forehand, Backhand, Joust, Sweeping, Overhand, No Swing	93%	0.77
Other Hand	Idle, Feeling Boundaries and Goal, Resting on the Table	88%	0.73
Dominant Hand Height	Table, Torso, By Head	86%	0.72
Body Movement	Stationary, Movement within the Table, Movement outside of the Table	86%	0.68
More Attempts after Hitting the Ball	Yes, No	85%	0.66

32.53. Further, we did not find learning effects; there were no statistically significant differences in Final Score between the participants' first condition versus their second condition. Interestingly, the participants who experienced the Verbal Scaffolds first did not have different Max Scores between conditions that were statistically significant, but those who experienced Verbal/Vibration first did ($t=3.70$, $df=16$, $p=0.002$). The participants who had Verbal/Vibration first were able to improve their Final Score once the vibration hints were removed (mean Verbal/Vibration Final Score = 31.88, mean Verbal Final Score = 37.59).

The Final Level reached did not differ between conditions. However, participants who experienced Verbal/Vibration Scaffolds first did ($V=66$, $p<0.05$). Participants improved on the Final Level in the Verbal Scaffold (mean Final Level for Verbal/Vibration: 2.82, mean Final Level for Verbal: 3.53).

When investigating subgroups of participants with Showdown experience (n=15) and without (n=19), we find several interesting differences. First, while participants with Showdown experience had higher Final Scores in Verbal than Verbal/Vibration ($t = 3.40$, $df = 14$, p-value = 0.004), this was not the case for those without Showdown experience. Mean Verbal Final Score for participants with Showdown experience was 41.87, but only 36.13 with Verbal/Vibration. Therefore, the Verbal/Vibration Scaffold had a negative effect only on those participants who had played Showdown in the real world.

Participants without Showdown experience had no learning effects between the first and second conditions. However, those participants with Showdown experience who experienced Verbal/Vibration first did ($t = 4.15$, $df = 6$, p-value = 0.006). They were able to improve their score when they played Verbal second (mean Verbal/Vibration Final Score = 39.86, mean Verbal Final Score = 47.86).

6.2 Qualitative Results

Below we discuss the body movements of participants across the conditions along with the participant responses to the game and each scaffold.

6.2.1 Body Movement Strategies of Participants. Participants employed different strategies during gameplay. We list the strategies used for each category:

- Holding Controller: 32/33 participants held the controller with a grasp (as explained in our tutorial). Six participants also allowed the controller to rest atop their hand. Five participants also held the controller with two hands. P6 exclusively pinched the controller between two fingers. For most people, we can assume a natural grasp, but also encourage use of a wrist strap when pinching or resting the controller.
- Respond to Midpoint Feedback: During levels 1-3, participants may have heard feedback for where to move their hand to hit the ball. All 33 participants correctly responded to feedback, while 18 participants did not respond at least once. On average, the participants correctly responded to the midpoint feedback 85% of the time.
- Amount of Attempts: 25/33 participants made single attempts at a ball, while all 33 participants had also made multiple attempts at a ball. Eight participants had employed a "free for all" approach by constantly swinging their arm.
- Type of Swing: Participants employed several types of swings (or lack thereof) while attempting to hit the ball. Most participants used backhand (n=28) or forehand (n=15) swings. However, 16 participants also used a "joust" approach by poking the Joy-con forward to tap the ball. Eight participants had used a back and forth sweeping motion, and two had used overhand throws. A final type of swing was called "no swing movement," where participants placed their hand in the general location and let the ball bounce off their controller (n=20).
- Other Hand: Most participants either rested their hand on the table (n=25) or by their side (n=28). Only five participants used their hand to feel the game boundaries.
- Dominant Hand Height: Most participants kept the height of their dominant playing hand at the table surface (n=27) or by their torso (n=24). Six participants moved their playing hand to the height of their head. P6 did this 100% of the time. While most participants placed their hand at an expected height, not requiring the hand to be at a specific height increases accessibility of gameplay.
- Body Movement: While most participants remained stationary in front of the table (n=32) or moved side to side within the bounds of the table (n=26), 10 participants moved outside of the bounds of the table at least once.
- More Attempts after Hitting the Ball: All 33 participants had attempted to hit the ball after they had already hit the ball. This happened on average for 18 balls/participant.

6.2.2 Participant Responses to Conditions and the Game. Overall, there was no clear choice of preferred condition. Of the 34 participants, we found that 16 preferred the Verbal Scaffold, 15 preferred the Verbal/Vibration Scaffold, and three said that they like both conditions. Participants did not prefer either condition significantly higher than chance. However, the participant's rationale for choosing each condition corresponds with our quantitative results.

Overall, participants scored higher with the Verbal Scaffolds; our hypothesis is that Verbal/Vibration Scaffolds could cause higher cognitive load. Participants 10, 13, 19, 30, and 34 reported that the vibrations were more confusing than the Verbal Scaffold. P10 mentioned that "I think that vibrations actually kind of like threw me off a bit." P19 mentions more specifically, "The vibrations were confusing between the out of bounds and hitting the ball." P5 and P14 preferred the fact that they could solely focus on their ears: "it was easier to focus on the ear, like where the ball is coming from on the headphones than on the controller" (P14).

Eleven of the 16 participants who preferred vibrations stated that finding the ball was easier. P9 said, "The vibrations, while I do well, were pretty good for pinpointing the exact location of the ball, whereas the sound was just good for a more relative location." P1, P12, P23, and P27 felt that it was easier to have two modalities: "It made it a lot easier [be]cause you are going off hearing and feeling in your hand" (P23). While these comments do not agree with the quantitative results, they confirm our choice of exploring the Verbal/Vibration Scaffold condition in our study, in that providing extra information may have been helpful.

Thirty-three of the 34 participants wanted to play the game again (P26 was unsure) and 33 wanted an updated version where they could play with friends (P26 did not). 19 of the 33 participants mentioned having fun as a key reason for wanting to play again: "I can see myself playing this game for hours and hours trying to get the high score" (P18). The remaining participants had several unique reasons for wanting to play again, including the challenge (P5, P14, P29), VR experience (P28, P30, P32), allowing for a level playing ground with others who are sighted (P23, P30), and the novelty (P11, P30). Single participants mention other reasons including depending on ears instead of eyes (P28), physical activity (P8), sharing with friends outside of camp (P29), like air hockey (P2) or videogame play (P12), was "cool" (P16), enjoyed hitting the balls (P6), and felt it was easy (P21).

Participants converged more on their rationale for why they would want to play with friends. Ten of the 33 participants mentioned fun as a reason. Seven participants mentioned that they could compete against someone else: "The whole point of Showdown is to play with 2 players" (P19). Seven participants appreciated that they could play on a level playing ground: "I can play a video game that I can play with my friends. That hasn't happened before" (P1). Six participants spoke to the novelty of the game: "A lot of my friends have sight. It would be cool to see what they thought of the game and see what they felt like when playing with just a sound in the game" (P14). P20, P23, P25, and P24 mentioned the ability to have team competitions, and P8 mentioned physical activity.

Participants suggested improvements for the game, including making the hints (scaffolds) optional; making the game online; making the game multiplayer; adding more music; changing sounds to make boundaries, halfway point, and controller location clearer; making the vibrations exclusively mean out of bounds; making the game faster and harder; adding more vibrations; and adding more speaking. We will employ some of the suggestions in future versions of our Virtual Showdown game.

7 DISCUSSION

From our Virtual Showdown game and empirical study, we learned that YVI were able to play Virtual Showdown, and that 33 of our 34 participants wanted to play again. Further, YVI scored better with solely Verbal Scaffolds than Verbal/Vibration Scaffolds. This difference in performance only pertained to those with Showdown experience, likely because they had already learned how to play Showdown using primarily their hearing. However, there was no definitive preference. While we could suggest avoiding vibrations as part of scaffolding, a counter argument is that it is okay to challenge the player. Designers should reason between the conflicting goals of quick learnability to achieve a higher score and challenge to achieve a lower score. Another option is to give players the choice between the two types of scaffolding.

By playing Virtual Showdown, YVI had the opportunity to explore a 3D virtual environment and use their body to interact with a moving object. We expand on accessible VR by introducing interaction with moving objects. We expand on existing accessible 3D audio games by enabling people to use their body as an input. Even with only 12 total minutes of playtime, the use of Verbal Scaffolds (and Verbal/Vibration Scaffolds) gave participants the opportunity to learn how to use their body to locate and hit moving audio targets. With our game, participants used their body as real-time input (efficiency preserving) and used their hearing and touch to locate and determine when to hit the ball themselves (intention preserving) [3].

7.1 Limitations

While we employed best practices in designing the mapping from ball distance to volume level, we labeled in all participant videos that they were still attempting to hit the ball after they had already (unknowingly) hit the ball. Further research should pursue how to design the volume levels so that people know when the ball is "far enough away" from them without removing the challenge from gameplay. To accommodate the participants' experiences with camp, we were limited to 30-minute user studies. However, we were able to capture enough gameplay through video, logs of gameplay performance, and input from interviews to answer our research questions.

7.2 Implications for Design of Accessible VR

While all the participants were able to play Virtual Showdown, several participants had unique body movement strategies to hit the ball including jousting, overhand throw, and holding the hand stationary. Further, we found that participants who had prior Showdown experience scored higher than participants did without – giving those with prior skill an advantage. While we presented information about where the ball is located, there are opportunities to conduct research in teaching effective body movement strategies in a VR game. For instance, a game could give feedback on how to perform a backhand hit.

Virtual Showdown utilized 3D sound to help participants track one ball. There are opportunities to explore scaffold design when the player is targeting several objects. How would the sound change if we wanted to hear the bat and the ball via 3D sound? How would the sound change if we wanted to design a game with multiple moving objects (e.g., dodgeball)? How would the sounds change when playing a multiplayer game? There are design challenges including how to distinguish objects from one another, and how to represent those objects with sounds and verbal cues. We need further empirical studies to explore whether Virtual Showdown provides a level playing ground with sighted people.

At a higher level, VR interaction goes beyond visual interaction to spatial interaction. The literature only motivates audio as making an environment immersive or persuasive, rather than as the primary information. Further, Unity (a key software in creating VR experiences) is not accessible to a screen reader. There are opportunities to make the creation of VR experiences accessible to people who are blind. Beyond making Unity compatible with a screen reader, how can we make the creation of VR experiences accessible to people who are blind using spatial, audio, or tactile input/output?

8 CONCLUSION

We designed and developed a VR game that is accessible to youth who are blind or have low vision that allowed them to move their body in real time for gameplay. Further, we conducted an empirical study with 34 youth who are visually impaired to explore whether Verbal or Verbal/Vibration Scaffolds were supportive in learning how to play in a unique environment. We learned that Verbal Scaffolds and prior Showdown experience resulted in participants earning higher scores in the game. We found diverse types of body movement strategies during gameplay, which can have an impact on the assumptions the game designer makes when processing body input. We presented qualitative feedback on gameplay experience – the game was fun, and there is a motivation to expand to multiplayer. We hope this work will help researchers in VR, researchers in accessibility working with 3D sound, and people who design accessible VR experiences.

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