Designing and Evaluating a VR Boxing Experience with Blind People

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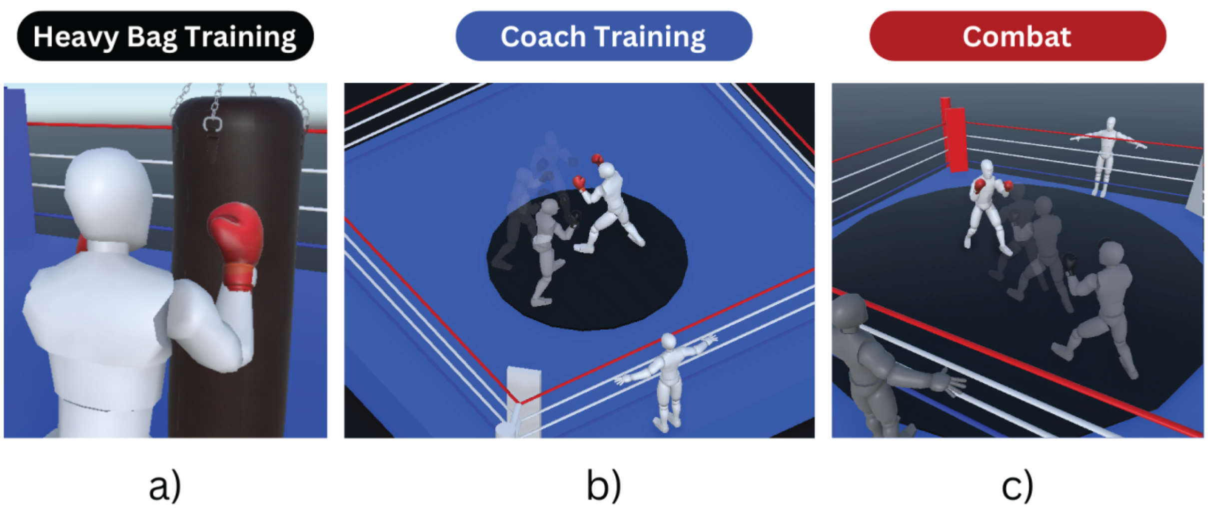

Figure 1: Three modes available in our VR Boxing experience: a) Heavy Bag Training allows the user to train different punches while perceiving the audio and haptic feedback on collisions; b) Coach Training places the user in a more dynamic training experience, with an opponent that attacks and defends while rotating around the user, and a coach that provides both directional instructions of where the opponent is positioned and instructions of what actions to perform; c) Combat is the most complete experience which, besides the features presented on Coach Training, introduces a wider range of movement for the opponent around the virtual ring, an audience sound effect and the opponent's coach.

Abstract

Virtual Reality (VR) offers immersive experiences through advanced interaction mechanisms and rich sensory stimuli but is often inaccessible to blind people due to its over-reliance on visual feedback. While prior work has investigated specific aspects of VR accessibility, there is little knowledge on how to design full, feature-rich VR experiences accessible to blind people. This paper presents the design and evaluation of a VR Boxing experience, developed

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through participatory design with an ex-professional boxer who is now blind. A user study with 15 blind participants explored their perceptions of the three-mode experience developed – Heavy Bag Training, Coach Training, and Combat – to inform the design of accessible VR experiences. Our findings highlight the importance of combining natural movement, rich auditory feedback, and well-timed guidance that also fosters user independence. Furthermore, they demonstrate the value of structured progression in complexity, while also opening opportunities for engaging spatial awareness and coordination training.

CCS Concepts

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

Keywords

Accessible VR, Nonvisual Interaction, Participatory Design, Sports

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1 Introduction

Virtual Reality (VR) shows promise in promoting novel and immersive experiences due to the new affordances provided by recent technology and interaction mechanisms. Features like head and hand tracking establish a direct link between actions in the physical and virtual worlds, such as rotating the head or body to change direction or using hand gestures to interact with virtual objects. By resembling real-world interactions, these features promote more immersive experiences [11, 59] and enhanced spatial awareness [19, 62]. However, VR is often inaccessible to people with disabilities [16, 17, 53, 54, 60], especially to blind people due to an over-reliance on the visual feedback of near-eye displays.

Mainstream VR applications are characterized by presenting a variety of information and stimuli across sensory modalities, including visual, auditory, and haptic feedback. This information richness contrasts with applications and prior research on VR accessibility for blind people, which has typically focused on more controlled settings with limited stimuli [38, 69] or on specific, isolated tasks, such as navigation [22, 65, 70], spatial awareness [28, 61], object manipulation [14, 48], or aiming [4, 20]. These studies provide valuable contributions to the field and inform the design of specific features and common tasks in VR. However, there is little to no knowledge of how to design comprehensive VR experiences that convey more (and varied) information and stimuli, similar to those designed for sighted people.

In this work, we design and evaluate a feature-rich VR experience using a VR Boxing context, aiming to answer the following research questions (RQs):

- **RQ1**. What design features and elements support creating a VR Boxing experience accessible to blind people?
- **RQ2**. How can these features be incorporated into a rich VR Boxing experience?

We selected boxing due to its potential to create rich and dynamic environments that include features present in other VR applications. Boxing leverages VR's affordances through the user's movement (locomotion and rotation) and other physical interactions such as hand gestures to reach targets (e.g., punch and defend); has the potential for multimodality (e.g., collisions motivating audio and haptic feedback); has time-constrained interactions; requires tracking dynamic elements (e.g., the opponent) in the environment; and has the potential to explore multiple stimuli from various sources (e.g., the own user, opponent, coaches, audience, or even a referee). Additionally, boxing is a popular type of experience in VR (e.g., Creed: Rise to Glory[1], or Ultraboxing: VR Boxing[2]).

To develop a VR Boxing application, we followed a participatory design approach with an ex-professional boxer who became blind. We conducted two sessions where we leveraged a design probe (iterated between sessions) to elicit feedback and prompt new designs. These sessions highlighted the importance of the guidance of a virtual coach, of elements to increase immersion (e.g., an audience), and the need to create progressive experiences to cope with different expertise among potential users. We then implemented a three-level VR Boxing experience (Figure 1) comprising of 1) **Heavy Bag Training**, a training setup where the user may throw punches at a boxing bag; 2) **Coach Training**, a training setup with a virtual coach that gives instructions and an opponent that moves around the user, and 3) **Combat**, a setup where the opponent moves through the boxing ring, the virtual coach provides instructions from their corner, and the audience may provide additional feedback.

We conducted a user study with 15 blind participants to understand blind people's perceptions of the VR Boxing experience, aiming to inform the design of future VR applications accessible to blind people. In addition, we wanted to understand the impact and importance of the different elements included in the experience. The study included an experimentation phase, where participants went through the three modes, followed by a semi-structured interview to gather their comments and suggestions.

Our findings show that participants highly valued the natural movement of real walking and turning, alongside the physical actions of punching and defending. The dynamics created with movement-based interactions alongside rich feedback created an immersive and engaging VR experience. Participants appreciated the different levels of complexity, which enabled a structured progression throughout the experience. In addition, the virtual coach had a crucial role in guiding participants in a way that was seamlessly integrated with the domain, while balancing guidance with user agency.

This work contributes with lessons learned from the participatory design and experimentation of a VR Boxing experience and discusses how it can inform the design of other feature-rich VR experiences accessible to blind people.

[1]VR videogame, Creed: Rise to Glory: https://creedrisetoglory.com/. (Last visited on December 8th, 2024)
[2]VR videogame, Ultraboxing: VR Boxing: https://ultraboxingvr.com/ (Last visited on December 8th, 2024)

2 Related Work

In this section, we discuss 1) accessible virtual environments for blind people, 2) more immersive VR experiences in different contexts, and 3) accessible virtual sports and exercise applications.

2.1 Accessible Virtual Environments

From digital gaming [67] to virtual workspaces [58], experiencing virtual environments (VEs) is becoming a common activity. For all the constraints that these applications alleviate by being virtual (e.g., space, travel, social) [44, 57], their primary focus on visual feedback poses significant challenges for people with visual impairments [3, 25, 40, 73].

Prior research explored accessible solutions that translate visual information to audio and haptic feedback. For instance, early work on the topic leveraged the use of haptics to convey the form and texture of virtual objects [14, 34], and audio-based environments to enhance the navigation in VEs [47, 68]. Multimodal approaches integrate both types of feedback (i.e., audio and haptic) in a wide range of contexts, such as Orientation & Mobility (O&M) training [21, 39], transference of knowledge from the virtual to the real world [15, 27], or gaming [2, 55, 71].

Among these, research and practice in digital gaming have seen greater advances with a growing set of accessibility features [1, 10] (and player's strategies), enabling some expert blind gamers to play visual-centric mainstream games [25]. Such efforts primarily involve retrofitting applications after their design. While this approach helps to make applications more accessible, it introduces challenges like cost, architectural constraints, and compatibility issues, which often result in sub-par experiences for people with disabilities [53, 76]. Considering people's abilities by design has the potential to create more coherent and seamless experiences, but it comes with its own challenges, such as the need for proactive planning, accessibility expertise and awareness, and stakeholders' perceived tradeoffs related to adding complexity or reducing the application's appeal.

VR, on the other hand, has seen little to no development in making complex, mainstream applications accessible to blind people. The low number of accessibility features in VR applications [54] reflects this gap, exacerbated by the lack of comprehensive accessibility standards and guidelines for VR design [17, 53]. Still, more immersive virtual environments – e.g., using Head-Mounted Displays (HMDs) – afford different interaction mechanisms that approximate the actions of the physical and virtual worlds. Both retrofitting and accessible-by-design approaches remain plausible and have their merits and challenges. However, VR's emergent stage offers a critical opportunity to prioritize accessibility in early design phases. The next section explores the current efforts in designing accessible experiences for blind people.

2.2 Virtual Reality for Blind People

Prior research efforts have taken advantage of VR affordances to better perceive or interact with virtual environments. This includes further investigating how different feedback modalities support understanding the virtual world [37, 61], but also leveraging the more natural movement abilities of VR to support O&M training [21, 41, 66, 69, 72]. These interaction mechanisms have also supported research on navigation, where multiple approaches take advantage of real-world locomotion and navigation skills and apply them in the virtual world (e.g., relying on white canes or real walking) [43, 70, 78], The ability to track people's hands led to research on aiming or object manipulation [4, 20, 48], while the increasing relevance of social VR led to approaches that support social interaction [12, 35].

These works show valuable contributions to accessible VR environments for blind people. However, they generally focus on specific tasks, such as navigating to a specific point [65], identifying elements in the environment [61], or aiming at a specific target [4]. More complex scenarios, such as the social one contribute with novel techniques for specific aspects of interaction – e.g., sighted guidance [12], or enhancing peripheral awareness [35]. On the other hand, popular VR applications present whole experiences with rich multimodal feedback and a variety of interactions and features that contribute to engaging and immersive experiences. In this work, we aim to support researchers and designers in better understanding how to design such experiences in a way that is accessible to blind people.

2.3 Virtual Sports for Blind People

Sports are a good example of mainstream VR experiences with diverse features and rich feedback [49, 56], with many examples of commercial applications (e.g. Cricket - VRicket; Soccer - Final Soccer VR; Table Tennis - Eleven Table Tennis). Boxing, in particular, is a popular sport with many available applications (e.g. Creed: Rise to Glory, or Ultraboxing: VR Boxing), mostly due to its physical nature that demands movement, includes opponents, and other peripheral elements such as audiences or a coach to either work as a storyteller or encourage the user (e.g., "Stay with it! You got this!"). These elements are intended to increase immersion but do not contribute to creating accessible experiences for blind people as essential information to partake in the experience is conveyed visually (e.g., the opponent's position).

The literature shows examples of VR applications specially designed to be accessible to blind people. For instance, GoalBaural [50], focuses on training hearing abilities but does not focus on the physicality of a typical GoalBall experience. The appearance of videogame consoles able to understand the users' movement through motion control devices and tracking cameras (e.g. Nintendo Wii, PlayStation EyeToy, Xbox Kinect), led to more physical experiences that mix physical exercise with nonvisual feedback modalities [32, 36, 52, 63, 75].

Blind people's desire to experience more complex and immersive experiences [3, 64] alongside the technological advances of VR have enabled exploring more complex sports and applications. Boxing has been previously explored but in a simplified scenario that only conveyed collision sounds and the location of the opponent's hands [26]. Research on Skiing [51] provided an immersive, physical simulation system, but the feedback focused mostly in conveying the location of the gates. In another interesting example, Gluck et al. [24] developed a car racing VR application that uses head and hand tracking for steering while using haptic cues to inform about directions and audio to give lower priority instructions. This game created a rich experience but did not include blind people in the design or evaluation, limiting the ability to understand what worked best and derive broader implications. Overall, these works suggest that applications with careful interaction and feedback design can be both accessible and engaging to blind people. Still, there is little to no knowledge on how to design feature-rich experiences that fully leverage the affordances of VR.

3 Designing a VR Boxing Experience

We built a VR Boxing experience following a participatory design approach, where we collaborated closely with a blind person with extensive experience as a professional boxer before losing his sight (i.e., a prior national champion) and currently (among other functions) a boxing coach – who we refer throughout the paper as Expert. This design process leveraged the unique perspective of a blind ex-boxer to identify relevant features and elements that support designing an accessible boxing experience (RQ1), while seamlessly integrating them into a rich experience that captures the essence of boxing (RQ2). We found this a valuable first step to later present an authentic experience to non-experts.

We conducted two sessions using a design probe to elicit knowledge and inform the design of the experience. Design probes help less tech-savvy people better understand unknown concepts, while facilitating discussion and ideation [31]. The probes and final prototype were developed using Unity3D, running on a Meta Quest 2.

3.1 First Session: Initial Probe

The goal of the first session was to ideate and discuss key elements that could make a VR Boxing experience accessible and engaging for blind people. We used a design probe as the Expert had no prior experience with VR and this served to illustrate its affordances, especially head and hand tracking and how they intertwine with feedback and enable movement-based interactions. We implemented a simple VR application based on our prior work [26], where the main functions were to convey feedback about the punches thrown (on collision) and the location of the opponent's hands. This probe had a simplified design using shapes (e.g., cylinders to represent the body and arms) and allowed the selection of different approaches for conveying the opponent's hand location (e.g., speech or sonification, discrete or continuous). The session took approximately one hour and had a loose structure shifting from demonstration to discussion fluidly. The Expert was able to select different configurations, but ended up quickly selecting a simple one and spent most of the time experimenting and showcasing expected actions (e.g., footwork to follow the opponent), and the associated feedback (e.g. guidance from the coach in the corner).

The core feedback was centered on how the focus should be on the overall experience and not on transmitting fine-grained details such as the hands' location. In particular, the Expert suggested mimicking a boxing coach, such as shouting "*defend*" or instruction to perform a particular punch (e.g., "*uppercut*"), as this would serve both guidance and immersion. The design probe had a stationary target, which the Expert attempted to circle and move around as he would in combat, emphasizing that movement (both his and the opponent's) is a crucial element for an engaging experience. He mentioned: "*Movement makes the game more interesting. This is a static game. It would give much more autonomy, in an ample space, for me to move with the opponent.*" Additionally, since the environment lacked audio embellishments, the Expert suggested features that would both add to the experience (e.g., audience sounds) and potentially assist blind users locate themselves or the opponent.

3.2 Second Session: Exploring Features

The first session led us to implement a more realistic VR application and to focus on factors that contribute to the experience as a whole. We relied on the feedback received, complemented by prior work [26], and an assessment of existing commercial applications (e.g., Creed: Rise to Glory, or Ultraboxing: VR Boxing), which revealed, for instance, frequent use of crowd noises to enhance immersion (sometimes tied to big hits), and frequent use of a boxing coach, although used for narrative or encouragement purposes. We implemented a set of features that could be turned on/off independently, as a way to understand which features and elements support creating a VR Boxing experience (RQ1). In particular, we wanted to understand the relative importance of each feature, how they could be improved, and which new features could be added. In addition, we wanted to understand how these would integrate with each other into a rich experience (RQ2). This was particularly relevant as including further functionalities and feedback cues could negatively impact the experience due to the increasing cognitive load [9, 30, 74].

The implementation included a virtual boxing ring with a virtual opponent. The opponent has the same height as the user – calibrated when first using the application – to give a clear indication of their body parts' location. The user has a virtual body, showcasing the gloves that correspond to the VR controllers (i.e., the user's hands). The user may move in the virtual environment by moving in the physical one, following the Expert's suggestion and avoiding the need for additional locomotion commands.

The session started with the most basic setup, where the opponent is placed in front of the user when the match starts (with the ring of a bell). Then, we introduced a set of features (Table 1) step-by-step, on top of the previous ones. In each step, the participant could experiment with the application freely. Then, we asked for feedback about the features introduced and how they align with the experience. At the end of the experiment, we performed two 3-minute rounds with all features activated, where we gradually increased the frequency of the number of instructions provided by the coach and of the opponent's movement. Finally, we discussed the whole experience to gather the participant's overall feedback. This session took one hour and a half, divided into one hour for experimentation and 30 minutes for a follow-up discussion.

This session highlighted the need for additional tools to cope with the increasing complexity of the experience, especially when the number of instructions provided by the coach increases. In addition, the Expert wanted the opponent to move more often but, at the same time, found greater difficulties in locating him in Step 7. He suggested the coach could provide instructions to help reorient himself when the breathing and steps are not enough: "*I think the coach's instruction for movement is important. Because I don't know if he [the opponent] is in my back or in front of me (...) Two steps forward, step back, on your right, to your left. It would help me adjust*

Table 1: The seven sequential steps experienced by the Expert in the second session, describing the features added at each step.

Step	Features Added
1	• **Basic Setup**. A virtual boxing ring with a virtual opponent placed in front of the user. The user may attack and is sometimes attacked by the opponent. • **Punch Audio Feedback**. Auditory feedback when the user hits the opponent in the head, body, or gloves/arms or when the user is hit by the opponent (in the same locations). The feedback sound is different depending on the area and on the attacker.
2	• **Punch Haptic Feedback**. The controllers vibrate when the user punches the opponent and when the opponent punches the user's gloves. Intensity and patterns of the vibrations are different depending on the location. • **Audience Sound**. The audience noise as background sound. The sound becomes slightly louder as the user approaches the ropes. The audience cheers after a sequence of successful punches.
3	• **Ask for Coach's Instructions**. The user can ask for the coach to provide an instruction by pressing the controller's trigger button, which was intended to provide control to the user. The coach provides one or more instructions among a set of punch types (jab, hook, cross, uppercut) or to defend. • **Opponent's Coach**. The opponent's coach would sometimes provide instructions, always from his corner, to the opponent in a foreign language. Language conveys that this is not crucial feedback and should not be mistaken with the user's instructions
4	• **Breathing**. The spatialized sound of the opponent's breathing, which may allow the user to estimate the opponent's relative location.
5	• **Opponent Moves Around the User**. The opponent periodically moves to a different position around the user. • **Opponent's Footsteps**. The sound of footsteps (also spatialized) indicates the opponent is moving.
6	• **Automatic Coach's Instructions**. Instead of requesting for instructions, the coach provides them automatically, as a way to make the experience more realistic.
7	• **Opponent Moves Through the Ring**. Instead of only moving around and close to the user, the opponent moves through the whole ring. The opponent sometimes moves to a different position, then approaching the user if not approached.

my perception of the opponent [location]". This balance between difficulty and assistance also raised a discussion about having different experiences that are aligned with the regular boxing contexts of training and combat. The differences in the sounds and vibrations of the punches were perceived as difficult to distinguish: "*Because I know that each sound or each vibration represents a specific thing. I don't know, sometimes it is confusing. I am not sure if I hit him, if I defended. What is happening?*" This resulted in a suggestion to use fewer, but more distinguishable sounds and vibrations. Also, while the breathing and footsteps location was perceived as realistic, the Expert suggested the direction could be more pronounced even if losing the physical world mapping – meaning audio would be transmitted only to his left ear if the opponent is on his left. In addition, automatic coach instructions were preferred over those on request.

3.3 Three VR Boxing Modes

Building on the insights gained from the two sessions with an expert blind user, we developed a VR Boxing experience (Figure 1) accessible to blind people, with three distinct modes. These modes aim to accommodate people with different boxing knowledge and expertise levels. These modes mimic the key components of a typical training and fighting cycle that a boxer goes through: heavy bag training, coach training, and combat. In all modes, users' virtual movement is accomplished by walking (on a 1:1 scale) and physically turning their head/bodies, as well as by moving their hands.

3.3.1 Heavy Bag Training. The first mode simulates a boxing bag training exercise, where users face a virtual punching bag. This mode supports an introductory, simpler experience where the objective may be either to exercise with fewer constraints or to familiarize with the fundamental punches that are taught when first learning - e.g., jab, cross, uppercut, and hook. In this mode, the features implemented are limited to the punches on the bag, which include both auditory and haptic feedback. The audio volume and vibration intensity depend on the velocity/force applied. While the bag has physics applied – meaning it would swing when hit – we slightly reduced its movement by making it heavier. This aimed to decrease the probability of the bag swinging and hitting back the user.

3.3.2 Coach Training. This mode simulates training with a coach and an opponent (i.e., sparring), making the experience more dynamic. It uses the **Basic Setup** from the prototype used in the second participatory session, with a virtual ring and a virtual opponent. We adjust the virtual opponent's position dynamically to ensure they keep the appropriate distance throughout the experience. The **Punch Audio** (and **Haptic**) **Feedback** were simplified due to the reported difficulty in distinguishing them. We added three sounds to indicate punches in the head, torso, and gloves/arms. We made them more distinct, for instance by using a gasp/grunt for a body punch. To reduce the number of sounds, these are exactly the same when attacking or defending, but the sound is lower and muffled when the user is hit. Vibration indicates contact and has the same

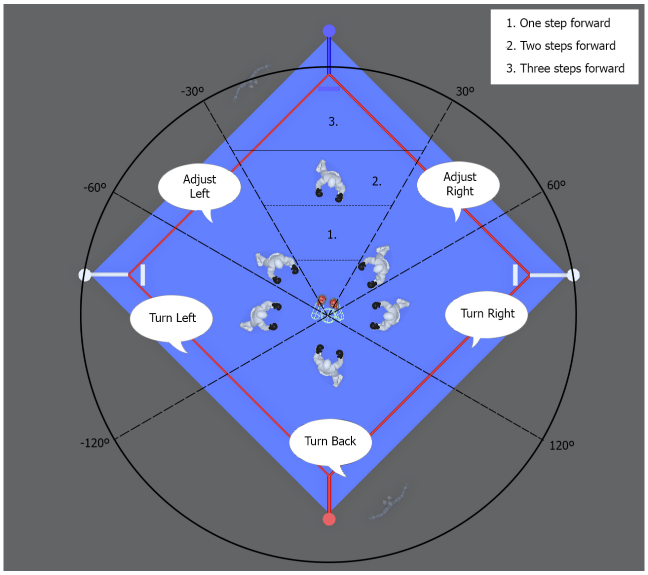

Figure 2: The angles and distance criteria for the coach to convey orientation instructions.

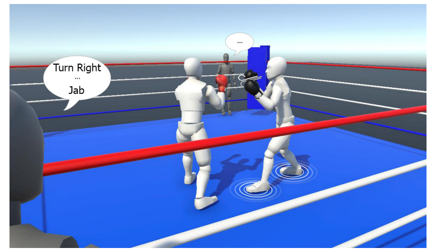

Figure 3: Depiction of the combat mode with verbal feedback, concentric circles representing footstep sounds and visual elements to indicate breathing sounds.

pattern independently of body location. Still, it is more intense when attacking than when defending.

The **Opponent Moves Around the User** as this was perceived to improve the experience, and therefore, we also included the sound of the **Opponent's Breathing and Footsteps** to indicate both movement and location (with dichotic audio – conveying feedback to the right or left ear – rather than 3D Audio). The frequency of movement can be customized, ensuring users (and the researchers in the upcoming study) can control the experience to have more or less movement. We also included **Automatic Coach's Instructions** (rather than on-request), such as a punch type or to defend (as the opponent also attacks periodically), since this was perceived as more realistic. The complexity and frequency of these instructions can also be customized to reflect how frequent and how complex the instructions are (e.g., one or a combinations of punches).

To account for difficulties locating the opponent, as suggested in the second session, we introduced a new feature where the **Coach Provides Directional Instructions** to help users adjust their orientation. This only occurs if the user is not facing the opponent for at least three seconds, to give them time to locate the opponent by themselves. These correspond to an "adjust right/left" instruction when the user is misaligned between 30º and 60º, "turn right/left) when between 60º and 120º, and "turn back" when between 120º and -120º as portrayed in Figure 2.

3.3.3 Combat. This mode represents the main stage of a boxing experience (Figure 3), combat. It shares many features with the Coach Training mode, such as the **Basic Setup**, **Punch Audio** (and **Haptic**) **Feedback**, **Automatic Coach's Instructions** including **Directional Instructions**, and **Opponent's Breathing and Footsteps** as the **Opponent Moves Around the User**.

Combat introduces more movement with the **Opponent Moving Through the Ring** (e.g., retreating). In this case, the opponent moves to a pre-determined location (among a set of locations) and waits for the user to approach them. If that does not happen, the opponent re-approaches the user after ten seconds. The frequency of such movement can also be customized before starting a round. The coach provides directional instructions, but may also instruct the user to give a number of steps forward depending on the distance (Figure 2). This positional feedback was partly informed by the Expert who referred to, for instance, "two steps forward" or "turn/adjust right". The main requirement was to be simple and immediate to interpret, excluding more precise instructions about location (e.g., using degrees or clockwise references).

To increase immersion we included other peripheral features that are common and that were found to improve the experience, such as the **Audience Sound** and the **Opponent's Coach**. These two features can also provide additional cues about the user's location (e.g., by the relative location of the opponent's coach and the proximity to the ropes/audience). To account for more movement in this experience, we also added **Haptic Feedback when Touching the Ropes** to indicate the ring boundaries.

4 User Study

We conducted a user study to understand: 1) blind people's perceptions of the three modes – Heavy Bag Training, Coach Training, and Combat – and their pros and cons, and 2) the most valued features and their impact on the overall experience. By examining these aspects, we wanted to evaluate how the features and elements identified during the participatory design process were perceived by blind users and how they contribute to creating an engaging VR Boxing experience. Beyond assessing this specific application, we aimed to uncover insights to guide the design of accessible, feature-rich, and immersive VR experiences for blind people.

4.1 Participants

We recruited 15 blind participants (Table 2) through our list of contacts and through a local institution for people with visual impairments. Participants were aged between 20 and 64 years old (M=43.1; SD=14.7). Twelve participants were blind and three had light perception or very low residual vision – none was able to detect any element in the virtual environment. One participant (P10) had a hearing impairment in his right ear. Most participants

Table 2: Participant demographics and the rating to 7-point Likert Items about their experience (from 1, Not Experienced to 7, Very Experienced) with Boxing, Technology, and Virtual Environments (VEs). We also asked how many times they have interacted with immersive VR.

ID	Age	Gender	Boxing	Tech.	VEs	VR
P1	39	F	1	6	3	2 - 5 times
P2	23	F	1	5	1	None
P3	24	M	2	4	1	None
P4	64	M	1	4	4	5 times
P5	49	F	1	2	2	None
P6	59	M	3	2	1	None
P7	61	M	1	4	4	1 - 2 times
P8	36	F	1	7	1	None
P9	38	F	1	7	3	None
P10	60	M	2	7	4	2 - 5 times
P11	20	F	1	7	1	None
P12	37	M	5	5	1	None
P13	36	M	2	6	4	2 - 5 times
P14	57	M	3	6	5	1 - 2 times
P15	44	M	4	6	3	1 - 2 times

rated themselves as not knowledgeable about boxing (i.e., rules, types of punches, among others), and experienced with technology but less experienced with virtual environments. Eight participants had never tried VR, while the remaining tried VR between two and five times.

4.2 Apparatus

We used the VR Boxing prototype previously described running on a Meta Quest 2, with a wired connection to a laptop with compatible system graphics (NVIDIA GeForce RTX 3060). The wire connection enabled the researcher to set up the study sessions and have visual feedback of the virtual experience.

Participants were instructed to wear headphones in addition (and connected) to the Meta Quest 2 headset to enhance spatialised audio. The data from the study was logged locally. The study was conducted at a local institution for most participants, at our university (P4), or at a location at the participants' convenience (P13 - P15). We ensured all locations had enough space to move and low noise levels.

4.3 Methodology

The study tasks were structured around the three modes, organized in order of complexity – starting from Heavy Bag Training and finishing with Combat. We performed brief questions after each mode and at the end, and a semi-structured interview after completing all tasks to gather further insights about their experience.

4.3.1 VR Boxing Tasks. Participants performed a set of rounds in each of the modes. The number of rounds and their timings were defined based on our prior experience in the two participatory sessions and on pilot studies within the research team, to mitigate potential concerns about fatigue.

Heavy Bag Training. This part has two one-minute rounds. This mode is an entry point to the whole experience and may be considered an introductory step due to its lower complexity – for that reason, it is shorter than the previous parts. In the first round, participants could punch the bag freely without the intervention of a researcher, while in the second, one researcher would provide punch instructions as a way to practice the different punch types.

Coach Training. This part has three two-minute rounds. Our goal was to give enough time for participants to experience all features, while also slightly increasing the complexity of the experience in the upcoming rounds. The features available are the same throughout the three rounds, but the complexity of the punch instructions and how often the opponent moves increase (Table 3). The coach gives punch instructions every 7 seconds in all rounds. The first round starts with 1-punch instructions (e.g., "right hook") and the opponent moves twice around the user (every 45 seconds); the second round keeps the 1-punch instructions, but the opponent moves more often (three times, every 30 seconds); and the third round includes 1- and 2-punch (e.g., "jab, left uppercut") instructions, while also moving three times. These intervals accounted for users with no expertise in boxing, who would take their time to identify and perform the appropriate punches.

Combat. This part also has three rounds, two minutes each, with increasing complexity over time. The punch instructions are the same as in Coach Training. The opponent maintains the same frequency for rotating around the user (two, three, and three times, respectively), but also moves away from the user (two, two, and three times). This is the most complex experience, where movement becomes twice as frequent as in Coach Training.

4.3.2 Questionnaire and Semi-Structured Interview. To gather participants' feedback, we asked brief questions after completing the interaction with each mode. We asked participants to rate how much they enjoyed their experience with that mode using 7-point Likert Items (from 1- I didn't enjoy it at all to 7- I enjoyed it very much) and to pinpoint what they liked and disliked the most.

After interacting with all modes, we performed the miniPXI questionnaire [29], a validated eleven-item measure to assess player experience across eleven constructs, each represented by one item, classified from -3 (Very Difficult) to 3 (Very Easy). In addition, we asked participants to rate from 1 to 7 (1- Not Important, 7- Very Important) how important each feature was for the experience as a way to identify trends in their preferences. We then conducted a semi-structured interview to gain a deeper understanding about participants' interactions, challenges and preferences, and suggestions. For example, we asked participants to rank the three modes according to their preference and to list the advantages and disadvantages of each mode; and to describe which (and why) elements and features were easier to identify in the environment, and which caused greater difficulties.

Table 3: Opponent movement patterns and participant punch instructions and combinations across rounds in Coach Training and Combat modes. It details the intervals for movements around the user, away from the user, and punch commands

<table>
<tr><th>Mode</th><th>Round</th><th>Circles Around</th><th>Moves Away</th><th>Punch Instructions</th><th>Punch Combinations</th></tr>
<tr><td rowspan="3">Coach Training</td><td>1</td><td>Every 45s</td><td>-</td><td rowspan="6">Every 7s</td><td rowspan="2">1</td></tr>
<tr><td>2</td><td rowspan="2">Every 30s</td><td>-</td></tr>
<tr><td>3</td><td>-</td><td>1 or 2</td></tr>
<tr><td rowspan="3">Combat</td><td>1</td><td>Every 45s</td><td rowspan="2">Every 45s</td><td rowspan="2">1</td></tr>
<tr><td>2</td><td rowspan="2">Every 30s</td></tr>
<tr><td>3</td><td>Every 30s</td><td>1 or 2</td></tr>
</table>

4.4 Procedure

All sessions were conducted by at least two researchers, and took between one hour and a half and two hours, including time for breaks. The first author led the study, while the second author took notes and provided support throughout the experience and interview. The last author participated in two sessions, mostly as an observer and assisting with the interview. The study protocol was approved by the Ethics Committee of Faculdade de Ciências, Universidade de Lisboa.

Each session started with a brief introduction to the goal and setup of the study. We then briefed participants about their rights and presented them with a consent form. We performed a questionnaire focused on demographics and experience with technology, VR, and boxing. The audio of the entire session was recorded after consent.

Before starting to interact with the VR application, the researcher gave a brief explanation about the VR hardware to participants unfamiliar with it, letting them explore the components with their hands. Next, the researcher explained the four basic types of punches, how to defend, and the fighting position, similar to a boxing mitt/pad work format. Participants were then assisted in wearing the Meta Quest 2 and position themselves at the center of the room to ensure they had enough space.

We then provided a brief explanation of the first mode (Heavy Bag Training) and of the duration of each round, ensuring that the participants understood its features. After each round and mode, we informed what would change in the upcoming trial. After each mode, we asked the questions about how much they liked the experience and if they wanted to take a break. We then repeated the same procedure for the next two modes.

After completing the three modes, we assisted participants in removing the hardware and performed the final questions and semi-structured interview, which took approximately 45 minutes. Finally, we thanked participants for their time and insights. All participants received a 10€ gift voucher for their participation.

4.5 Data Analysis

We performed a descriptive analysis of participants' interactions with the VR Boxing experience and of their questionnaire ratings. Rather than supporting comparisons, this intended to provide a general description of how participants interacted with the experience and what features they valued the most.

We transcribed all semi-structured interviews and conducted a mixed deductive-inductive codebook thematic analysis [7]. The initial codebook was created based on our concepts of interest (for instance, the three modes, the different features, participants' suggestions, and accessibility) and our familiarity with the data, complemented by notes taken during the study. Then, two researchers independently coded the same two interviews, adding new codes as necessary (e.g., progression, familiarity). They met to discuss and refine the resulting codebooks, ensuring that the relevant topics were covered, and further reviewed the codebook with a third researcher. The remaining interviews were then split between the two researchers. The research team iterated over multiple in-person and online discussions, resulting in themes presented in the Findings section.

5 Findings

We present our findings through a descriptive quantitative analysis that characterizes the participants' experience in terms of enjoyment, and feature preferences. Following this, we outline the six key themes that were derived from our qualitative analysis.

5.1 Descriptive Quantitative Analysis

The miniPXI questionnaire evaluated participants' experiences across the three modes, revealing an overall highly positive user experience (M=2.3, SD=0.7). The constructs with the highest mean values were Immersion (M=2.7, SD=0.5), Audiovisual Appeal (M=2.7, SD=0.6) and Clarity of Goals (M=2.7, SD=0.6), while the lowest one was Mastery (M=1.6, SD=1.8).

When classifying how much they enjoyed each mode, participants also rated them positively overall: Heavy Bag Training (M=6.4, SD=0.8), Coach Training (M=6.5, SD=0.9), Combat (M=6.6, SD=0.7). Despite the similar scores, Combat was preferred by ten participants, while four and one preferred Heavy Bag Training and Coach Training, respectively. For ten participants Coach Training was second, while Heavy Bag Training was the least preferred for eleven participants.

Participants were generally positive about most features, when asked to assess the importance of each feature experienced during the study (Figure 4). Still, the ones found most important across participants are related to the audio feedback of punches (thrown and received), the coach's instructions (punches and positional), the audience sound, and those related to the opponent's movement.

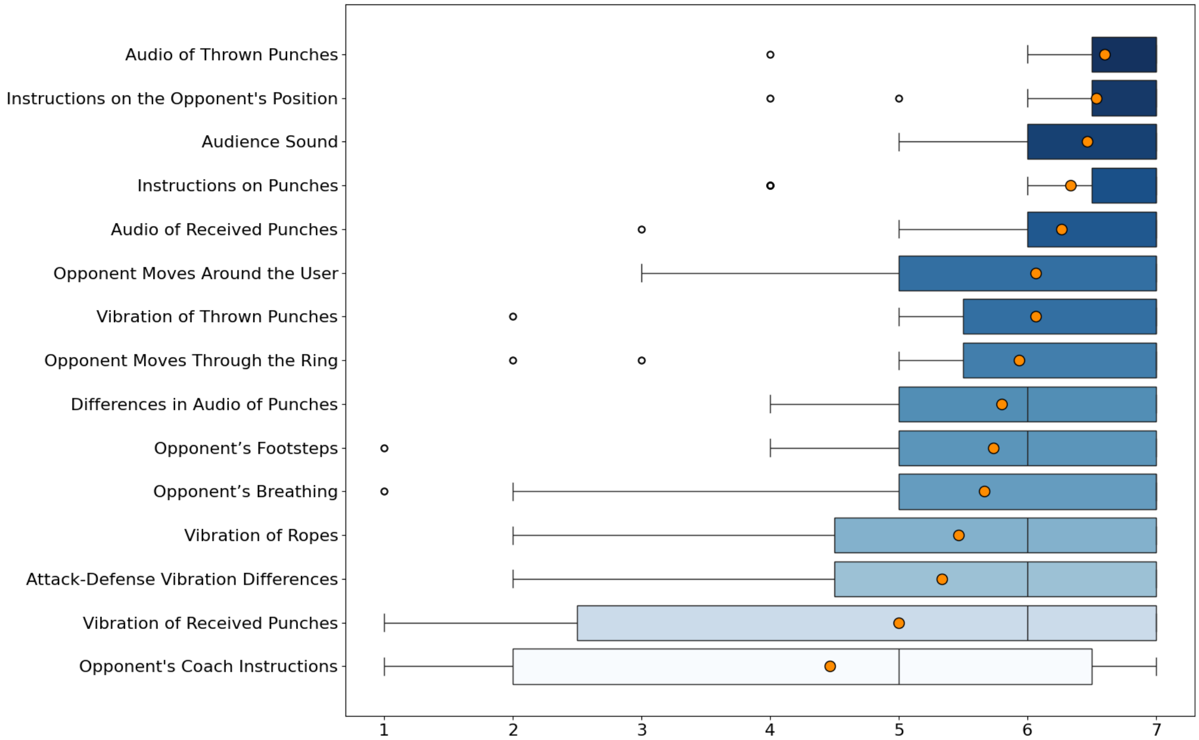

Figure 4: The Box Plot Graph demonstrates the variation of the answers to the Likert Items, from 1 (Not Important at All) to 7 (Very Important), about the importance of each implemented feature.

Vibration and the opponent's coach instructions were generally considered less, but still important. The opponent's footsteps and breathing were often considered very important but sometimes overshadowed by the coach's positional instructions. The complete ratings for the feedback importance, miniPXI, and enjoyment of each mode can be found in the supplementary material.

5.2 User Experience and Preferences

All participants enjoyed the full VR Boxing experience, with some affirming how VR replicated real boxing, enabling them to learn about the sport:

> "*Today I will leave here with the feeling that it was worth it because I had no knowledge of this at all, and now I will know boxing techniques (...) You can have a helmet and an earpiece, and it can be done almost like in real boxing, just in a virtual way.*" - (P3)

Combat was preferred for its greater interactivity, rich feedback and physical challenge, which further helped participants enjoy the VR Boxing experience. In particular, it added to their sense of immersion and motivation to participate in the ultimate goal of the experience, as P13 said:

> "*The combat is always more stimulating, I think it's the … when we think of a game related to boxing, we think of the combat, just like when we think of a flight game, we think of the flight itself; or in a soccer game, we think of the game itself, the competition. That's it, it's what stimulates us the most, right, it's what will also require more movement from us, more reaction capacity, more concentration, etc...*"

This ability and the freedom to move in the environment and interact with the opponent was guided by the coach's instructions, which was also a key factor to enjoy the experience: "*I liked Combat because I enjoyed the coach's instructions. I felt freer to turn, move forward, adjust left and right. That's why I liked it more*" (P8).

Coach's Training was considered the second preferred mode by most participants and considered a middle ground while sharing many advantages with Combat. P3 preferred this mode since it was easier to understand the opponent's position in comparison to Combat: "*Regarding the second mode, I liked it a lot because... the opponent was more or less in place, and I had a better sense of where the opponent was and where I needed to punch*".

Combat and Coach's Training also prompted a higher sense of realism as the interaction felt more tangible (mostly due to reciprocity):

> "*I was punching, pretending to punch, it felt real. I heard the sound, I felt the vibration as if someone was hitting me. That's why I liked it a lot. With the bag, I felt like I was punching, but didn't feel like anyone was hitting me back, that's the difference.*" - (P12)

On the other hand, four participants preferred the simplicity of Heavy Bag Training. This mode, being less dynamic and demanding, allowed them to feel more relaxed and in control: "*I liked the first mode because it didn't have instructions and it was a bit more free*" (P2). In addition, this mode gave some participants a greater sense of accomplishment due to the lower complexity, often complemented with a factor of stress relief: "*You noticed I went more to the boxing bag. To release stress (...) And I really liked it (...) It's something I did better in, and when I was throwing punches, I felt a sense of relief*" (P5).

5.3 Progression and Experience

Participants appreciated the progression of the VR Boxing experience, noting how the gradual increase in complexity helped them learn the basic mechanics before advancing to more complex modes. This structured approach was seen as an effective way to build their skills over time: "*I don't think there's anything to add because, in the end, it ends up being a progression in our learning of the game.*" (P1). Similarly, P13 highlighted the training's utility in improving movement and understanding the coach's instructions: "*The training is useful for us to better grasp the movements, the coach's directions, and to get used to the different sounds.*"

Participants also valued how the progression allowed them to position themselves better, control distances, and enhance the fun by gradually mastering the experience mechanics:

> "*The first step is important because it gives us… a sense of our body positioning, when to get closer. It's because sometimes I punch and don't feel any vibration because I am too far from the bag. So starting from there is good, because we gain control of the distance.*" - (P12)

As participants progressed, many began to develop their own strategies, gradually claiming greater agency over the attacking strategy:

> "*At first, I was very attached to the coach's instructions and I waited for what he said. So, wait... the coach doesn't say anything, but let's throw some punches to see what happens! (...) I mean, the time interval he gave us … [allowed us to] interact a bit more with the game. To be more spontaneous.*" (P1)

Other participants further commented that, if playing again, they would start from the more advanced modes, and continue increasing its complexity, as the simpler experiences were already too easy for them. This evolution helped participants not only to improve but also envision more advanced levels where they could eventually play without the coach's guidance: "*I would remove the coach. I would practice with the coach's voice (...) to orient myself better, until I totally master the game without the coach's guidance*" (P12). This is in line with other suggestions to gain further control over the coach's instructions (e.g., turning them on or off).

The sense of progression made the experience more engaging, challenging participants at various levels, and keeping them motivated: "*The difficulty goes up, and so does the interest (...) Because people who enjoy playing don't like everything handed to them on a silver platter, right?*" (P14). In addition, P1 contrasted the boxing experience with games she played before:

> "*...because [in other games] there comes a point where it's like, 'Oh, is that all?' (...) We've already figured out all the strategies, and then it's just to pass the time. But in this specific case, no! [...] There is movement, and we have to use a range of things that challenge us on various levels without relying on sight.*"

It is also relevant to note that many participants relied heavily on the coach, both for attacking (and defending) and for locating the opponent – noting that the experience would be less enjoyable without the coach:

> "*I think... the coach is very important because.. like this, we can manage to know where the opponent is with his instructions. When he was in front, to the left, to the right, I didn't have to look back. So... it was very relevant. The coach's instruction*" - (P8)

P3 also noted this dependence, but reflected on what could be done differently: "*I feel like I depended too much on the coach to understand where the opponent was. [And] maybe I should have taken more initiative to attack in some way without always hearing the coach.*". This also supports that not all participants progressed equally and some may need more time to move to more advanced levels:

> "*When I heard the names of the punches, I was thinking about the correct position for the punches. [...] That was it, remembering the position and putting it all together to do it quickly. That's why I got distracted*" - (P8)

This suggested that some participants felt overloaded, especially in the final round of the study, which included more instructions and movement. Still, in some cases, this challenge also peaked participants' motivation:

> "*In the third phase, there was more information, much more information (...) Now, it feels like I've gone out of orbit. But I think it's all part of it, you see. (...) it seems like it's meant... It was made on purpose to motivate us (...) I think it's well-designed for us to... Get excited about it*" - (P5)

5.4 Movement and Location Feedback

With the opponent's movement came the challenge of detecting their location. Participants often relied on a combination of three elements: breathing, footsteps, and the coach's instructions:

> "*When we start hearing the footsteps, okay, I'm hearing them from my left and his breathing. Then, the coach says, 'adjust to the left' or 'adjust to the right,' and the brain processes that sound, indicating the opponent is moving. So, I also have to move to avoid getting hit unexpectedly, basically.*" - (P1)

The coach's instructions were even more important when participants lost track of the opponent's location:

> "*There was a moment when I felt lost, but the coach helped me regain my orientation. There were one or two times I was punching into the air, searching for the target, but the coach quickly corrected me*" - (P10)

P3 noticed that even though he could sometimes hear the opponent, it was hard to reach them without the instructions:

> "*When the coach tells you... two steps forward or... turn left or adjust left. Then we're sure the opponent is close*

> *by. Without the coach's orders, it felt a bit empty. Like, you could hear them, but you didn't know exactly what to do to reach them.*"

Participants' comments suggest breathing was generally more important for detecting the opponent's immediate location, while footsteps indicated movement rather than an exact position: "*I understood the steps, even though sometimes I didn't know where the opponent was. But I understood, I could hear him walk*" (P13). Participants often tried to make use of these elements right away to direct themselves toward the opponent, as explained by P10: "*There were times I heard his breathing behind me and could figure it out before the coach told me to turn. By the time the order came, I was already moving*". P14 focused mostly on this feedback, only using the instructions as a backup:

> "*My movement was very focused on the sound of the breathing and footsteps, and I actually heard the coach say twice, 'to the right' or 'adjust,' but I didn't give it much importance. (...) I was so focused on hearing the opponent's movement that I ended up not valuing the coach's instructions as much in that regard.*"

On the other hand, P3, who focused exclusively on the coach's instructions in the first rounds, started paying more attention to the breathing sounds as he became more comfortable with the experience:

> "*I only started paying more attention to the breathing now at the final part. Because, before, I was more attentive to what I should do (...) and the instructions that the coach gave. So I listened the breathing, but it wasn't important as I was very focused on the other things*"

5.5 Priority and Complementary Feedback

The previous theme is a good example of how the different feedback types – in this case breathing, footsteps and instructions – were sometimes prioritized over or complemented by others. Another example regards the punch feedback transmitted via audio and haptics, where audio assumed a primary role: "*At a certain point, the vibration takes a backseat (...) Because we want to keep playing, to attack or defend. So, sometimes I didn't think about the vibration. I felt it, and that was it, I didn't internalize its meaning*" (P1). Still, some participants found that this complementarity enhanced their ability to distinguish what was happening: "*I think they complemented each other, both were important. I believe one was an extension of the other*" (P10). On the other hand, others fully disregarded the vibration and focused solely on the audio feedback: "*Actually, I barely paid attention to the vibrations. But I heard a lot of them. But honestly, I didn't even learn what was what* (P6)." Still, overall punch feedback was found essential, as it informed participants about the success of their actions:

> "*What gave me even more adrenaline was knowing that I was actually hitting him. In other words, it wasn't in vain. It was on point. I think that's what also gives a certain motivation because he gives the instruction, the person executes it, and you hit the target. That's awesome*" - (P3)

The ability to distinguish different punch feedback was split among participants, but the majority focused mainly on their attacks: "*I think the most important were the ones I gave (...) Because as I identified the target with the first punch I always tried to be quick enough to hit as much as possible*" (P10). Still, most participants noticed that the sounds/vibrations were quieter/softer when they were attacked by the opponent. When detecting the location of the hit, perceptions were also split, as some were able to distinguish the punches (e.g., P5 said: "*I could understand when it was in the head and when I was defending*"), but others were not able to (e.g., P3 said: "*When I threw punches to the head and gloves, sometimes it was confusing (...) I know the head was a bit stronger, but sometimes I had doubts about where I hit*"), suggesting the sounds could be even more different from each other.

The opponent's coach was often disregarded as most participants didn't see how they could leverage it, despite contributing to the ambient sound and to the experience. Still, P1 referred how the opponent's voice assists in locating her position in the ring: "*The other coach's voice can be a bit annoying. But I think it's something you get used to and improve. It also helps you figure out where you are in the ring*". P4 further reflected if he could somehow leverage this secondary feedback:

> "*I could hear a low sound in the background, but I didn't really pay much attention to it. (...) I don't know if I could have improved my performance by paying attention to the opponent's instructions.*"

Despite prioritizing some elements, participants highlighted the importance of a complementary set of feedback types that contributed to the whole experience: "*The whole atmosphere, and maybe also the sound of the opponent, the sound of the punches, the movements, the punches, the sound of the audience itself. I think all of that is very important*" (P1). P3 highlighted that even apparently peripheral elements contributed to the realism of the experience: "*And the crowd is always... It might seem a bit insignificant, but it has its role of... well, it makes it feel like this is for real, you know?*"

5.6 Training and Rehabilitation

VR application with head and hand tracking are inherently physical activities, leading participants to comment on the usefulness of complex spatial audio experiences such as this one. Participants highlighted the potential to train specific abilities like spatial cognition, auditory focus, and coordination in a way that was both engaging and enjoyable. P1 exemplified this feeling by referring to the benefits it brings regarding spatial awareness and auditory training:

> "*What I liked the most. I think this is a game that helps, especially for people to have spatial awareness. To move around. To have a good level of concentration. Both auditory... as auditory training. And listening to whoever is giving you instructions. So, I liked it a lot. I would play it again.*"

P5 emphasized the experience's potential role in practicing orientation and directional instructions, referring to the difficulties she has in understanding those instructions and coordinating her movements, also pinpointing the importance of reference points:

> "*Yes, as I was saying, in my view, because for most of us who are blind, we sometimes struggle with directions (...) This helps. And I am very uncoordinated because of my dyslexia, right? And I think this game is not just about combat. At the coordination level, paying attention, and hearing the instructions (...) Normally we, who are blind, have to walk very straight, always with reference points. And since the game has its own reference points, we pay attention to the coach's instructions.*"

This type of multisensory training was also seen as a potential tool for rehabilitation, particularly in the context of orientation and mobility:

> "*Half joking, half serious, the first thing that came to mind when you asked the question was physiotherapy, haha. But in a rehabilitation context, and when I say rehabilitation, I mean for people who may have lost their vision later in life and need to rediscover their body and movements. This is essential for developing spatial orientation, mobility, and other skills. It could also apply to people who, during childhood or youth, were overly protected by their families, leading to a lack of body awareness*" - (P13)

P4, on the other hand, suggested that the experience could be used to further improve their boxing movements, by including real-time motion adjustments – e.g., by tracking and analyzing user's movements and providing immediate feedback for corrections:

> "*Well... I think it would probably be difficult. But... the application could have a camera that captures our movements. Then, that movement could be analyzed in terms of rotations and supinations, and provide instructions. For example, the hand needs to be turned upwards, or the angle is not quite right.*"

5.7 Real World Mapping

Real walking locomotion enabled participants to move virtually on a 1:1 scale, enhancing the realism of the experience. However, this technique also limited virtual movement to the physical boundaries of the space. This raised concerns, particularly when unfamiliar with the environment, which in turn can make participants less likely to move freely due to safety concerns: "*Because we can move around the space. But... I lose track of where I am. And if... Well, since you were here, there was no risk. But... Whether I would bump into something or not*" (P2).

Participants suggested different alternatives to either map the virtual and real-world or to support the VR experience, such as adding tactile references to the floor:

> "*What I liked less is that when I'm being told to go right, left, or back, I lose track of where I am (...) I think there could be some references on the ground for us to know if we're positioned correctly or not.*" - (P2)

On the other hand, participants also suggested to include mechanics to guide participants to stay within a safe boundary: "*...being free and getting feedback that you're about to hit a wall or the ropes would be great to feel comfortable in the room, and virtually, to be right in the middle of the ring*" (P10).

Participants also mentioned that the real-virtual world mapping could be easier in a familiar environment – e.g., their own home – where they have a mental map of the space, decreasing fears of collisions. Still, the application could also assist in further understanding their orientation. P10 mentioned:

> "*If I had the game available, I would definitely use it at home. Because, you see, even at home, we're limited; we always walk without a cane or anything because we know the house. But, if I were in a room with this technology, I wouldn't need any guidance, I wouldn't need a radio on to know where I am, whether I'm facing the door or the window, because the game would give me feedback.*"

6 Discussion

In this section, we answer our research questions based on the participatory design process and study findings. We then discuss the main lessons learned and how they may inform the design of more inclusive and engaging VR experiences for blind people.

6.1 Answering our Research Questions

Our work explored the design features and elements that support creating an accessible VR Boxing experience for blind people (RQ1) and how these features can be integrated into a rich and immersive experience (RQ2).

Movement was a key factor in enhancing realism and engagement. The player's ability to move freely using real-walking made the experience more natural, while throwing punches and defending added a physicality that increased immersion and a better understanding of boxing. Additionally, the opponent's movement introduced a dynamic challenge, requiring players to track their positioning and react accordingly.

These dynamics further emphasised the role of **audio feedback**, as sounds such as the opponent's breathing and footsteps were very important for spatial awareness, while punch sounds were crucial to provide feedback about the user's actions —- although sometimes not distinctly enough to fully grasp its meaning (e.g., unsure about hitting the opponent's head or arms). We also learned that participants end up filtering the feedback to focus on the ones essential to the experience. Still, enriching the experience with meaningful feedback creates opportunities to progress in the game – e.g., the audience and the opponent's coach not only enriched the atmosphere but also provided subtle spatial cues that can potentially help users gauge positioning within the ring. Haptic feedback, on the other hand, served mostly as a complementary channel. While neglected by some participants, it was found useful by others for reinforcing the feedback of punches.

The **coach's instruction** played a crucial role in ensuring that blind participants could fully engage with the experience. Initially designed to assist with timing (when to attack or defend) it also became essential for orientation within the environment – an insight that emerged from Expert input and user feedback during the study. This guidance served as a scaffold for the VR Boxing experience, enabling participants to gradually rely on other cues (e.g., for orientation) if and when ready.

Another central element to support learning was **structured progression**, which allows users to gradually build their skills. The different modes provided a realistic evolution, starting with simpler tasks before advancing to more complex interactions.

By integrating movement-based mechanics, rich audio feedback (complemented by haptics), guided assistance, and structured progression, we created a feature-rich VR Boxing experience accessible to blind players. Thoughtfully combining these elements enabled the design of an immersive VR application that prioritized accessibility without compromising complexity or engagement.

These findings can inform the design of VR experiences with similar movement and feedback dynamics. Combat-based VR games are the most closely related, as they rely on movement, physical interactions, and feedback on the user's and opponent's actions. Structured progression and a coach's guidance also apply to these experiences. Some e-sports, like VR Tennis, may similarly benefit from movement and auditory cues (e.g., ball impact, opponent positioning), along with structured progression and coaching for timing and directional feedback.

In the following subsections, we further discuss the key lessons learned from this work, aiming to inform the design of accessible VR experiences.

6.2 Taking Full Advantage of VR Affordances

Immersive VR technology offers a range of interaction mechanisms from natural locomotion and spatial orientation to physical actions like pointing and punching, which were central to our design. The real-walking locomotion technique reflected the Expert's behaviour contributing to a more authentic boxing experience, which would hardly be the case with teleportation or joystick-based locomotion. Still, real-walking may not always be possible due to physical space constraints. Further exploring alternatives that resemble real walking but with fewer space restrictions, such as Redirected Walking [8] or Scaled Walking [33, 42], could assess if they offer a good compromise among realism, accessibility, and user experience. Additionally, while treadmills present an interesting avenue for future research, prior work [38] has found a reduced feeling of safety, precision, and intuitiveness in these technologies for blind people.

Head-tracking was another key VR affordance that participants found valuable, as it supported spatial awareness in ways that flat-screen experiences cannot. Participants highlighted how this ability, alongside a rich auditory feedback setting, enabled them to exercise their spatial awareness and coordination. The physical act of punching and defending, combined with audio and haptic feedback, was not only motivating in terms of physical exercise but also contributed to making the experience feel real. While auditory feedback was central and highly appreciated, haptic feedback, delivered through vibrations in the controllers, was seen as a complementary element. This is partially influenced by our own design choices and the limitations of current off-the-shelf VR systems, where haptic feedback is generally confined to simple vibrations. However, advances in VR haptics research promise to give a more prominent role to haptics as a way to improve immersion – e.g., by simulating physical barriers [46] or enhancing the sensation of impact with the own body [18, 45].

6.3 Building a Whole Experience with Seamless Progression

The first design session with the Expert highlighted the need to present the boxing experience as a cohesive, feature-rich journey that reflects the essence of boxing. While this aligned our experience with those that are commercially available, it also clearly demonstrated their lack of accessibility. For instance, boxing applications rely on the coach for narrative purposes or for encouragement but do not assist the user nor make the experience more accessible. Similarly, the audience is often used for encouragement, but our design augmented its role to provide additional orientation cues, by indicating proximity to the ropes. Other domains can draw inspiration from current mainstream applications – possibly even retrofitting them – but leverage existing elements for accessibility purposes.

The literature shows little to no guidance on how to structure different feedback types and sources into a whole, accessible experience. Our findings showcase the importance of not only offering a natural progression of experience and its mechanics – through three distinct experiences – but also grounding the experience in a well-guided introduction to essential and complementary feedback. For instance, Heavy Bag Training introduced participants to the main concepts of this experience – punching and its feedback – preparing them for the subsequent modes, while Coach Training introduced new concepts such as the coach and movement-based feedback, both with activities that fit the boxing domain. Future work may explore how structured progression may be applied in different contexts, such as education – e.g., could learners start with guided instructor feedback, advancing to peer-to-peer collaboration and finally to complex classroom dynamics? Where progression is harder to fit into the experience, prior research suggests in-context tutorials may be used to introduce key features and feedback [23].

The richness of feedback and structured progression enabled participants to gradually use increasingly complex feedback as they became more experienced. For instance, participants reflected on leveraging peripheral elements such as the opponent's coach instructions, both as an orientation aid and to predict the opponent's actions. These different levels of feedback – both central and peripheral to the experience – led participants to feel the experience was real (e.g., P3 referring to the role of the audience). Future research may further investigate how to break down complex environments and experiences into different levels of feedback that fit the domain.

6.4 Guidance is Crucial, but so is Creating Opportunities for Independent Action

Guidance proved to be a key feature in the design of the VR Boxing experience. It was first proposed by the Expert during the design process – evolving from punch instructions to also include directional instructions – and was key to managing scenario complexity while enhancing realism and immersion. This feature was highly valued by participants who found it a facilitator to fully enjoy the experience. Providing guidance or some kind of assistance is not new in accessible virtual environments. For instance, in digital gaming, blind players are often assisted by automating or easing parts of the experience (e.g., in navigation or aiming), which in turn ends up reducing user agency [25, 55, 77]. In this study, participants relied heavily on instructions but were also given space to act independently, as the timing of the instructions inadvertently allowed users to execute their actions autonomously.

These findings can prompt research in other contexts where a virtual character fits the experience, such as a teacher or instructor in educational, sports, or training experiences. In social VR, this could represent an AI guide [13] providing the required assistance to partake in the experience, while allowing users to also act independently. More broadly, the concept of a (virtual) helper (e.g., a sidekick) [5, 6] is a common design pattern in mainstream gaming that makes use of Non-Player Characters that follow the user throughout the game. These helpers often play a narrative role and assist users with hints or resources to complete challenges. Still, this common design pattern has the potential to be further used for accessibility purposes, striking a balance between offering support and preserving user agency compared to solutions that overly constrain it.

Additionally, design choices incorporating guidance while giving room for independent action can support a smoother introduction to complex, feature-rich experiences. Still, it is crucial to ensure that other types of feedback can support users throughout the experience. In this study, movement and location were conveyed firstly through the opponent's breathing and footsteps. On the other hand, there was no indication (apart from the coach's instruction) of an incoming punch, meaning that fully removing instructions (even in the long term) could greatly impact the experience. This highlights the need and difficulty to carefully consider feedback in complex experiences – in the case of incoming punches this could mean, for instance, using a sonified sound or even the opponent's coach instruction.

6.5 Benefits of Movement-Based Rich Audio Experiences

Participants emphasized how combining movement and rich auditory feedback helped them practice and train their spatial awareness and coordination. This suggests that entertainment-focused experiences, in addition to those specifically designed to improve particular skills (e.g., O&M training [21, 41, 66, 72]), could potentially contribute to skill development. Prior work in keyboard-based interaction has shown advantages in game-like approaches to transfer navigation skills to the real world [15]. VR offers even greater potential to simulate real-world movement and interactions in engaging experiences, further enhancing this learning transfer. Researchers and developers may explore not only training programs that go beyond traditional methods but also how to purposefully design interactions that promote learning or training specific skills in playful experiences (e.g., sports, games, or cultural experiences).

Rich and realistic (3D) auditory feedback is the status quo in mainstream VR, which was also the case for most elements of our experience. However, the participatory design led us to manipulate the opponent's footsteps and breathing to more clearly indicate right or left rather than representing their exact position. On the other hand, accurate 3D audio can help introduce reference points to help users orient themselves in the virtual space and align themselves with the physical one. Participants noted that, at times, they felt disoriented in both the virtual and real worlds, despite the stationary location of the coaches, which could have served as landmarks. This suggests the need to make reference points more prominent and clearly defined within VR environments.

6.6 Limitations

This work focused on a specific domain, boxing, which includes a variety of interactions and feedback. While we derive lessons learned from the participatory design process and study findings that inform the design of other applications, some may not be directly applicable to other domains that involve, for instance, less physical movement or different interaction mechanisms. In addition, our study relied on a single session with eight rounds with non-experienced participants. While this enabled participants to progress along the experience, a longer exposure would inform how to further complement the application with more complex feedback and interactions.

7 Conclusion

VR's increasing popularity across a variety of domains makes it essential and timely to investigate the design of accessible VR experiences for blind people. In this paper, we described the participatory design process of a feature-rich VR Boxing experience for blind people and a user study with 15 blind participants.

We derived key lessons, including the importance of integrating natural movement, rich auditory feedback, and well-timed and integrated guidance, while balancing user agency. We also showcase how structured progression and immersive feedback can support users in an engaging experience that may, in turn, foster spatial awareness training.

This work highlights the value of exploring feature-rich applications that leverage VR's unique affordances, demonstrating their greater potential for accessibility. This encourages a broader perspective in future research and development, aiming to make mainstream VR more accessible to blind people rather than focusing mostly on specific applications or simplified scenarios tailored to this audience.

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