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A Boxing Experience for Blind People using Virtual Reality

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[1] Tech & People Team - https://techandpeople.github.io/team
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Dedicatória.

Resumo

A realidade virtual (RV) tem o potencial de oferecer experiências imersivas, interativas e inovadoras, mas as pessoas com deficiências visuais enfrentam desafios significativos no acesso a essas tecnologias devido à forte dependência de estímulos visuais. Embora existam alguns esforços para adaptar experiências de RV a utilizadores com deficiência visual, essas adaptações costumam ser limitadas em termos de funcionalidade e realismo. Este trabalho apresenta uma experiência de boxe em RV acessível a pessoas cegas, projetada através de um processo participativo e com o objetivo de criar uma experiência rica em funcionalidades, que vá além das adaptações simplificadas existentes.

O boxe foi selecionado como o contexto para a criação desta experiência de RV, principalmente por três razões: primeiro, o boxe é uma atividade física que aproveita bem o movimento oferecido pela RV; segundo, o boxe permite a criação de ambientes com áudios dinâmicos e ricos, fundamentais para a navegação e interação por utilizadores cegos; e, por último, a popularidade das aplicações de boxe em RV como um género desportivo já amplamente explorado para utilizadores sem deficiências, tornando-o um bom ponto de comparação para criar uma versão acessível.

O desenvolvimento desta experiência foi conduzido através de um processo de design participativo, envolvendo um ex-pugilista profissional que perdeu a visão. O desenvolvimento inicialmente começou pelos resultados obtidos de uma sessão de design do trabalho The Design Space of the Auditory Representation of Objects and Their Behaviours in Virtual Reality for Blind People [37], e, em seguida, uma segunda sessão com o mesmo ex-pugilista profissional. Durante esta sessão, foi recolhido feedback para orientar e guiar o processo de desenvolvimento. Estas duas sessões de design permitiram que o participante compreendesse as possibilidades oferecidas pela RV, especialmente em termos de seguimento de movimentos da cabeça e das mãos, e como esses mecanismos poderiam ser utilizados para criar uma experiência realista e envolvente. O projeto da aplicação foi desenvolvido na plataforma Unity3D, executada no sistema de RV Meta Quest 2, o que permitiu implementar um conjunto de funcionalidades imersivas, utilizando feedback auditivo e háptico.

A experiência de boxe em RV resultante é composta por três modos principais: treino com saco de boxe, sendo este um modo inicial e simplificado, onde o utilizador pode treinar golpes num saco de boxe virtual, recebendo feedback auditivo e tátil correspondente à força e à localização dos golpes; o treino com treinador, sendo este um modo mais dinâmico, onde o utilizador treina com um adversário que se move à sua volta, orientado por um treinador virtual que dá instruções

verbais sobre que tipos de socos o utilizador deve fazer e também a localização do adversário, se for necessário, podendo também utilizar a respiração e os passos do adversário para perceber a localização do mesmo; e, por último, o combate, que é o modo mais complexo, onde o adversário também se move pelo ringue, e o utilizador deve seguir as instruções do treinador para atacar e defender. Neste modo, são também introduzidos sons de uma audiência e do treinador do adversário, para aumentar a imersão e criar um ambiente mais competitivo.

Após o desenvolvimento da experiência, foi realizado um estudo com 15 participantes cegos, com idades entre os 20 e os 64 anos, para avaliar a sua perceção e as suas experiências com os três modos da aplicação. A maioria dos participantes não tinha experiência prévia com RV, embora alguns estivessem familiarizados com tecnologia e desporto. O estudo foi realizado em locais apropriados, com espaço suficiente para garantir a segurança durante os movimentos físicos.

Durante o estudo, os participantes experimentaram os três modos da aplicação, e as suas interações foram registadas. Em seguida, foram realizadas entrevistas semiestruturadas para recolher feedback qualitativo sobre as suas experiências e para compreender as suas preferências e sugestões de melhoria. Também foram utilizados questionários para medir a satisfação geral e a perceção da facilidade de utilização.

Os resultados do estudo demonstraram que, de uma maneira geral, os participantes apreciaram a experiência de boxe em RV. O modo Combate foi o mais popular, devido à sua maior interatividade e complexidade, proporcionando uma sensação de realismo e desafio. O modo Treino com Saco de Pancadas foi visto como uma boa introdução, permitindo aos utilizadores familiarizarem-se com os movimentos básicos, enquanto o modo Treino com Treinador foi considerado o intermediário, proporcionando uma experiência mais dinâmica, mas sem a intensidade do combate total.

Os participantes apreciaram a progressão estruturada da experiência, desde um treino simples até ao combate completo. A introdução gradual de complexidade foi vista como fundamental para que os utilizadores ganhassem confiança nos movimentos e nas mecânicas do jogo. Muitos participantes expressaram o desejo de remover as instruções do treinador à medida que se familiarizavam com os movimentos, sugerindo que a autonomia e o controlo pessoal poderiam melhorar a experiência a longo prazo.

O uso de movimento natural, ou seja, a capacidade de andar e virar-se fisicamente no mundo virtual, foi amplamente elogiado. Esta forma de locomoção realista permitiu que os participantes praticassem a sua perceção espacial e coordenação de uma maneira intuitiva e envolvente. Os sons de passos e de respiração do adversário ajudaram a guiar os movimentos dos utilizadores, aumentando a imersão na experiência de combate.

O feedback auditivo e háptico também desempenhou um papel essencial na imersão. Embora o feedback tátil fornecido pelos controladores de RV ainda seja limitado, os participantes consideraram que as vibrações associadas aos golpes aumentaram o realismo da experiência. Além disso, os sons associados aos golpes, tanto recebidos como dados, ajudaram a criar uma sensação de impacto e interação física com o adversário.

O treinador virtual desempenhou um papel crucial na orientação dos participantes, especialmente durante os modos mais complexos. As instruções do treinador, que incluíam tanto orientações sobre os tipos de soco a realizar como ajustes de posição, foram vistas como valiosas para manter os participantes no fluxo do combate. No entanto, muitos expressaram o desejo de maior autonomia, sugerindo que, com o tempo, poderiam preferir reduzir a dependência das instruções do treinador, confiando mais nas suas próprias capacidades de navegação e ataque.

Os resultados deste estudo fornecem importantes orientações para o design de futuras experiências de RV acessíveis a pessoas cegas. Em primeiro lugar, a combinação de movimento natural, feedback auditivo rico e orientações bem cronometradas pode criar uma experiência imersiva e acessível, que também é desafiadora e envolvente. Em segundo lugar, a progressão estruturada é crucial para garantir que os utilizadores possam desenvolver as suas habilidades ao longo do tempo, começando com tarefas simples e progredindo para experiências mais complexas à medida que se tornam mais confortáveis.

Além disso, a importância da perceção espacial foi referida em várias partes do estudo. A capacidade de navegar no ambiente virtual através de pistas auditivas e táteis, sem depender de elementos visuais, poderá abrir novas possibilidades de treino e reabilitação para pessoas cegas. Os participantes destacaram como a experiência de RV os ajudou a praticar a coordenação e o posicionamento, habilidades que podem ser úteis em contextos do mundo real.

Por último, as escolhas de design relacionadas com a orientação e o feedback têm implicações significativas na forma como os utilizadores experienciam o ambiente virtual. A possibilidade de personalizar a quantidade de feedback ou de ajustar a frequência das instruções permite uma experiência mais ajustada às necessidades e preferências de cada utilizador.

Este trabalho demonstrou o potencial das tecnologias de RV para criar experiências envolventes e acessíveis a pessoas cegas. Ao desenvolver uma experiência de boxe rica em funcionalidades e centrada nas necessidades dos utilizadores, foi possível criar uma aplicação que não só oferece um desafio físico e mental, mas também abre novas possibilidades para a inclusão de pessoas com deficiência visual em ambientes virtuais. As lições aprendidas com este estudo oferecem um quadro importante para o desenvolvimento de futuras aplicações de RV que sejam acessíveis, imersivas e personalizáveis, proporcionando experiências mais inclusivas para todos os utilizadores.

Palavras-chave: RV acessível, Inclusão, Desporto, Interação Não Visual, Design participativo

Abstract

We developed a virtual reality (VR) boxing experience specifically for blind users, addressing the accessibility challenges posed by the heavy reliance on visual feedback. Using haptic and auditory cues, we created an immersive, feature-rich environment designed through a participatory process with an ex-professional blind boxer. The experience offers three modes: heavy bag training (for basic punches), coach training (with real-time feedback), and combat (a dynamic match against an opponent).

We did a study with 15 blind participants, where we evaluated the experience's accessibility and immersion. Most had no prior VR experience, but were familiar with boxing and technology. The study revealed that the combat mode was the most popular because of its complexity and interactivity, providing a sense of realism and challenge. The structured progression from simple tasks to more challenging ones allowed users to gain confidence and improve their skills over time.

The use of natural movement, such as walking and turning, was highly praised for enhancing spatial awareness. Auditory cues like footsteps and breathing helped guide users, while haptic feedback during punches added to the sense of realism. Despite current limitations in VR haptic technology, participants felt that it contributed positively to the experience. Many suggested that reducing reliance on the virtual coach's instructions would improve autonomy and engagement.

This study highlights the potential of VR to offer immersive, accessible experiences for blind users by combining natural movement, auditory and haptic feedback, and a gradual increase in challenge complexity.

Keywords: Accessible VR, Inclusion, Sport, Non-Visual Interaction, Participatory Design

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Chapter 1

Introduction

Virtual Reality (VR) shows promise in promoting novel and immersive experiences due to the new affordances provided, creating immersive and interactive environments in domains such as entertainment, education, and professional training. The features provided by recent technology, such as head and hand tracking, establish direct links between the physical and virtual worlds. These features allow users to rotate their heads and bodies to change direction and utilize hand gestures to interact with virtual objects, increasing the immersion of the experience [17, 86] and enhancing spatial awareness [27, 91]. However, despite these advancements, VR remains largely inaccessible to individuals with disabilities, particularly those with visual impairments, due to the technology's heavy reliance on visual feedback [23, 24, 80, 81, 87].

1.1 Motivation

Mainstream VR applications are usually designed around using visual interfaces, they do transmit information and stimuli across sensory modalities such as vision, sound, and touch, but they are build around visual information. This aspect presents significant challenges for blind users, as the majority of VR systems don't consider alternative sensory feedback that could provide accessible interactions for this demographic. Although previous research has focused on developing accessible VR experiences for blind users, these solutions tend to focus on isolated tasks, such as navigation [31, 94, 101], spatial awareness [38, 88], object manipulation [20, 70], or aiming [7, 28]. These studies often operate in controlled settings with limited stimuli [53, 100], providing valuable insights into VR accessibility but offering few comprehensive, feature-rich experiences equivalent to those designed for sighted users. Because of this, it makes visually impaired users excluded from fully participating in these experiences.

We are using the sport of boxing, that heavily relies on physical movement and spatial awareness. This sport presents an ideal opportunity to explore non-visual feedback designs for VR. The use of audio cues for locating an opponent and haptic feedback for simulating impact are very important to boxing, making it a suitable project for a VR experience that does not rely on sight. Boxing in VR could promote more physical activity among blind users, offering a lot of benefits beyond the usual entertainment aspect, such as improving coordination and spatial awareness.

The motivation for this project is to address these challenges by creating a boxing experience tailored to the needs of blind users, using spatialized audio feedback and haptic feedback to increase immersion of the experience and replicate a real world sport.

1.2 Objectives

Our focus in this project was on creating an accessible and immersive boxing experience for visually impaired users using Virtual Reality (VR). The goal was to take a common sport that's not typically accessible to blind people—boxing—and adapt it in a way that delivers information at just the right time, without overwhelming the user. Too much information at once can cause confusion, leading to poor decisions, which is especially critical in a fast-paced sport like boxing.

To achieve this, we relied on the headset to track the user's position and combined different types of feedback to relay information. Audio feedback, including both voice instructions and non-speech audio (sonification), was used to communicate essential information, while haptic feedback (vibrations in the controllers) helped the user feel when they were punching the opponent and also helped in the localization of the opponent and the ring. The challenge was to use these feedback methods in a way that gave the user enough information to stay engaged without causing an overload.

This project explored how to convey complex information in a dynamic, fast-paced environment using a combination of feedback methods. Our goal was to make the user feel immersed in the experience while keeping them physically active. Many VR experiences for visually impaired users tend to oversimplify interactions or focus on just one aspect of the sport, but we wanted to create something that felt comprehensive and realistic.

Throughout this thesis, we designed and developed a VR boxing experience that is accessible for blind users. This was done through a participatory design process involving visually impaired users, ensuring that the system met their needs. The final system integrated spatialized audio, sonification, and haptic feedback, that creates a responsive and immersive experience. We also carried out a user study with 15 blind participants to assess how usable, accessible and enjoyable the system was, their feedback has provided valuable insights for future improvements in accessible VR development. The project was developed using the Oculus Quest 2 VR system in

1.3 Contributions

The key contributions are as follows:

- **Learnings from a participatory design process**, where an ex-professional boxer provided critical insights on how to improve the VR experience. This study emphasizes how participatory design can offer solutions for enhancing accessibility in VR.

- **User study with 15 visually impaired participants**, comparing the different techniques used during the VR experience. This study examined the user preferences, and strategies that they used for interacting in the VR environment. Also, their overall opinions and effectiveness of our haptic and auditory feedback features for guiding user actions.

- **Development of a VR boxing application with three distinct modes**, including Heavy Bag Training, Coach Training, and Combat. Each mode was designed to progressively increase in complexity, allowing users to build confidence in their skills and movement while engaging with a feature rich experience.

1.4 Document Structure

This document is organized as follows:

- **Chapter 1: Introduction** – This chapter introduces the motivation behind this research, the objectives, and the significance of developing accessible virtual reality (VR) systems for blind users. It also provides a brief description of the methodology and scope of the study.
- **Chapter 2: Related Work** – This chapter reviews existing literature on accessible virtual environments, including prior research on haptic feedback, spatial audio feedback, and VR applications for visually impaired users. It also examines relevant studies on participatory design in VR and non-visual interaction mechanisms.
- **Chapter 3: Design Approach** – This chapter describes the design process of the VR boxing application. It includes the participatory design methodology employed with blind users, detailing the design decisions, iterations, and user feedback that shaped the development of the system.
- **Chapter 4: Implementation** – This chapter outlines the technical aspects of the VR boxing experience, focusing on how user interaction is achieved through haptic and auditory feedback. It also details the core components, such as the user movement, opponent movement mechanics, collision detection, and logging systems.
- **Chapter 5: User Study and Evaluation** – This chapter presents the methodology and findings of the user study conducted to evaluate the system's usability, accessibility, and user experience. It discusses the feedback gathered from participants and analyzes the system's performance in delivering an accessible boxing experience.
- **Chapter 6: Conclusion and Future Work** – This chapter concludes the thesis by summarizing the contributions made, the insights gained, and the challenges faced during the development of the VR boxing system. It also proposes directions for future research to further enhance accessibility in VR experiences for visually impaired users.

Chapter 2

Related Work

In this section, we discuss 1) accessible virtual environments for blind people with a focus on prior research on audio and haptic feedback, 2) more immersive VR experiences in different contexts, and 3) accessible virtual sports and sensory substitution.

2.1 Accessible Virtual Environments

From digital gaming [96] to virtual workspaces [85], 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) [65, 84], the primary focus on visual feedback for interacting with VEs poses a significant challenge for people with visual impairments [6, 35, 59, 106].

Prior research focused on exploring 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 [20, 46], and audio-based environments to enhance navigation in VEs [68, 98]. 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 [29, 57], transference of knowledge from the virtual to the real world [21, 36], or gaming [5, 82, 102]. Among these, customized devices or specialized equipment were often proposed for accessibility and interaction with VEs – e.g., by integrating a PHANTOM haptic interface with 3D audio [99]; customizing existing controllers, such as Wii hardware [55]; or developing new hardware, such as haptic gloves [112], or map creation tools [69].

These prior efforts provided valuable contributions to exploring and understanding virtual environments, typically through input systems such as the keyboard, joystick, or smartphone. More immersive virtual environments—e.g., through the use of Head-Mounted Displays (HMDs)—afford different interaction mechanisms that approximate actions in both the physical and virtual worlds.

Recent advancements in VR technologies, especially in spatial audio and more natural forms of locomotion, have further improved accessibility for visually impaired users. For example, the use of walking-in-place systems or treadmills in VR has allowed users to navigate more naturally, while tactile feedback through instrumented white canes provides blind users with enhanced navigation capabilities in virtual environments [53]. Additionally, haptic feedback devices such as gloves and tactile vests have made interactions with virtual objects more intuitive, enriching the experience for users by enabling them to ”feel” the virtual environment.

Audio-based solutions have also become more sophisticated, with applications utilizing advanced 3D spatial audio to provide directional cues and context. For instance, NavStick enables blind users to explore virtual environments by scanning directions using sound, while racing games like The RAD have employed sonification to create equitable gaming experiences for both blind and sighted players [102]. This growing trend in audio-centric solutions has extended to social and sports applications. For example, VR Bubble supports accessible social VR interactions by creating zones of auditory feedback2.1 that correspond to different levels of interaction, such as intimate, conversation, and social spaces [47].

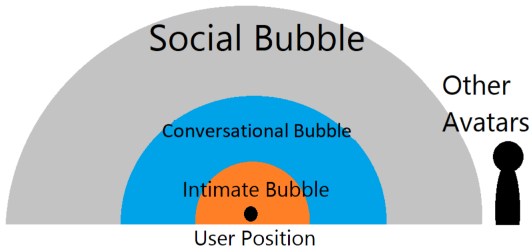

Figure 2.1: Conceptual diagram of bubbles [47]

Sports and exergames have also seen significant developments in accessibility. Applications that simulate real-world sports such as goalball or showdown have provided engaging experiences for blind users, making sports more accessible through the combination of auditory and haptic feedback [2, 72]. These developments show the potential of VR to provide more inclusive, physical, and immersive activities for the visually impaired community.

In conclusion, making virtual environments accessible for visually impaired users requires a multi-modal approach that combines audio, haptic, and sometimes physical feedback systems. Designers must prioritize accessibility in mainstream applications by considering alternative representations of visual stimuli. While much has been achieved through audio and haptic feedback, research continues to evolve, with studies like Kreimeier et al. explored new locomotion techniques and immersive feedback methods that could further bridge the accessibility gap in VR [53]. These advancements point towards a more inclusive future where virtual environments are accessible to all users, regardless of visual ability.

2.2 Virtual Reality for Blind People

As a result of Virtual Reality systems being mostly used for visual entertainment, they are not the most accessible equipment for people with visual impairments. However, there are other ways to transmit information to the user using audio and haptic feedback. There are studies and projects that have taken advantage of VR affordances to better perceive or interact with virtual environments, for example [26, 52, 88, 89, 99], where they made Virtual Reality accessible for blind people, but also leveraged the more natural movement abilities of VR to support O&M training [29, 60, 95, 100, 105]. These studies were considered to have good practices during the development of this project.

These interaction mechanisms have facilitated research on navigation, utilizing real-world locomotion and navigation skills in virtual environments, such as the use of white canes or actual walking [62, 94, 101, 114]. The capability to track hand movements has also inspired studies focused on aiming and object manipulation [7, 28, 70]. Additionally, the growing significance of social VR has led to developments aimed at enhancing social interaction [18, 47].

The work Blind Walk VR [52] is a study where they compared four types of VR locomotion to find out what has the best way to support egocentric VR locomotion in blind people. These types were two treadmills: the Cyberith Virtualizer and Virtuix Omni, the HTC Vive VR tracker (which is a tracker on an ankle), and a Windows Mixed Reality Joystick, as shown in Figure 2.2. The tests were made with seven blind and visually impaired people, and they were asked to move towards spatial sound sources using each of the devices. They found out, based on the perception of the participants, that the best option and safest was the joystick because it performed the best in terms of speed, and it did not require the physical demand that the treadmill required. Participants' feedback complemented those findings, saying that the treadmill felt unnatural and unsafe.

(a)

(b)

Figure 2.2: The joystick based locomotion using an Acer AH100 Windows Mixed Reality HMD and a Logitech G933 headset (a), the user's input regarding speed and direction of locomotion is adjusted by tilting the left controller's joystick (b) [52].

The work Remote Virtual Showdown [2] by Hojun Aan et al. developed an exergame, with the main purpose of creating the game Showdown, a Paralympic sport designed for people with visual impairments in a Virtual Reality environment. This game is a mixture of air hockey and table tennis; however, players need to be blindfolded so there is no visual advantage between them. They play the game only by recognizing the position of the ball with their hearing, and the objective of the game is to hit the ball into the opponent's goal pocket at the end of the table. It's also possible for the ball to ricochet off the walls.

Therefore, they implemented this sport in VR by using distinguishable 3D spatial sound depending on the position of the ball. They found that the best-suited technology for this was Google's Resonance Audio SDK, which provides HRTF, as it could differentiate the reaching time of audio in each ear. To create the sounds, they recorded the actual rolling of the showdown ball on the table at various distances, as well as the sound it makes when it hits the walls, so the player could have an accurate assessment of the ball's position.

They did tests in another paper [1], where they tested their exergame with sighted and visually impaired people and compared which group of people could more accurately hit the ball. They found that people with visual impairments could detect the ball 90.12 percent of the time, outperforming people without visual impairments, who could only hit the ball 55.97 percent of the time. They also asked the participants to play against AI, with the result being that people with visual impairments won 10 of 13 times, while sighted people won 9 of 13 times. The final user study involved the two groups competing against each other, as shown in Figure 2.3, and the results showed that people with visual impairments won 67.6 percent of the time. The conclusion of this study indicated that visually impaired people had better results in this game. It also concluded that they could experience similar exercise effects, with an intensity comparable to playing table tennis, as measured by heart rates during their user studies.

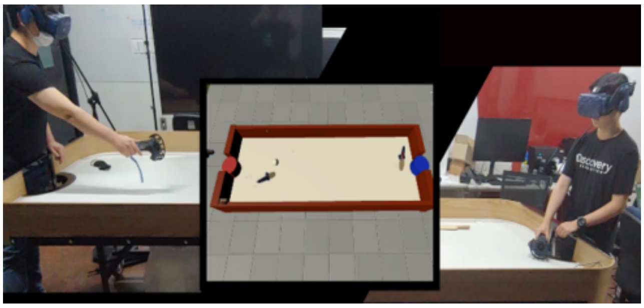

Figure 2.3: PVP showdown play [1]

Siu et al. [101] explored navigation in Virtual Reality for people with visual impairments using a novel white cane controller that enables navigation without using vision in large virtual environments with complex architecture. The cane has a three-axis brake mechanism to provide a large-scale shape of virtual objects. It conveys environmental information in the direction of the direct path of travel. The types of information are detection of obstacles, surface topologies like texture and elevation, and foot-placement preview.

They developed an application in Unity to interface with VIVE trackers and render the appropriate haptic and auditory feedback to the user based on their position and that of the cane. They used vibrations to differentiate textures of objects that resemble real-world sample surfaces, as well as sound effects generated from collisions and sweeping motions. Each virtual object is tagged with a recorded tapping texture and sweeping texture. When the virtual cane moves across the surface of a virtual object, the tapping texture is played back through the voice coil actuator, with its amplitude adjusted proportionally to the impact velocity. In addition, if the cane sweeps over the object, the sweeping texture playback rate is rendered and modulated based on the speed of the cane tip.

In the user study, they developed a scavenger hunt in VR to understand how participants could explore the virtual world using non-visual rendering. They had two tasks: 1) collect targets, and 2) avoid walking over hazards and virtual walls. Seven out of the eight participants could find all five targets in the game within the time limit set, and when four participants repeated the game for a second time, the average completion time decreased from 572.3 seconds to 218.2 seconds. They concluded that the system provides a compelling VR experience for visually impaired people through multimodal haptic cues and auditory feedback. Participants used kinesthetic force feedback to understand the architectural geometry, while tactile feedback and audio feedback conveyed more information about local surface properties and the geometry of materials.

Aaron Gluck et al. [34] discuss the inaccessibility of popular video games to players with visual impairments. While the technology in gaming has evolved, games are still not accessible, so they developed a racing game in Virtual Reality that is accessible to blind people. This fast-paced game has to provide useful information to the players in a quick way to allow them to make split-second decisions. This is a very good example for our project because it is fast-paced and requires quick information transmission to the user to make fast decisions, which is essential for our boxing project.

The objective of the game is to race against four artificial intelligence opponents using the Quest controllers to mimic a steering wheel, as shown in Figure 2.5, and to be the first to complete three laps around a three-and-a-half-mile-long virtual track without any visual information.

The primary source of information in this project is haptic feedback, because it was the best way to provide the player with constant information about how to steer the vehicle around the racetrack without any visual input. They did this by changing the haptic vibration's amplitude or intensity to provide additional information. For example, when a player starts to drift out of their path, gets too close to an opponent, or enters a turn, some haptic feedback is transmitted to the user to make corrections. If it's a big correction, the vibration is larger; if it's a slight correction, only a small vibration is sent, and as the correction occurs, the vibration amplitude decreases gradually. The player's speed also changes the vibration amplitude, and when it's triggered, it gives the player time to adjust.

Auditory feedback is also used to inform the player. For example, when the reactionary artificial intelligence pit crew speaks to the player, it uses vocal audio to give information to avoid crashing into an opponent. However, not all information is treated the same way. Some information requires an immediate response, while other information can be processed when convenient. Spatial audio is also used to provide the player with information about their surroundings in the virtual environment, but it is kept to a minimum to avoid information overload. It is primarily used in motor engines for the player to locate other opponents and to hear their own car, as there is a correlation between the car's speed and the sound it makes.

Additionally, the user can tilt their head upwards to replicate looking in a rearview mirror, providing information about the other racers behind the player. The player can also turn their head to the left or right to receive information if there are cars to their side, as shown in Figure 2.4. This information is provided using verbal feedback.

Figure 2.4: Using a head gesture to see what is on the player's left in Racing in the Dark [34].

Figure 2.5: Using hand gestures to make a left turn in Racing in the Dark [34].

Lorenzo Picinali et al. [88] discuss the ability to render individual sounds at the desired source localization or create complex spatial audio scenes without manipulating physical equipment.

They studied the possibility of assisting blind individuals in learning the configuration of a small space using 3D audio recordings and simulations. Their results found that passive listening to binaural recordings and 1st-order Ambisonic recordings were not efficient, but interactive VR navigation worked better by including head tracking and controlled displacement. Comparing the results of navigation between real and virtual environments found no significant difference in behavioral measures. Using a joystick to control the movement also helped users create a mental representation of the space they were in, better using realistic room sounds and simulations. This study concluded that visually impaired people could benefit from acoustic interactive VR systems because it would help them create a mental representation of the objects that surround them in future routes they need to walk by, all within the comfort of their homes.

The second design they explored was with echolocation, a useful mechanism for a visually impaired person to have an understanding of the environment they are in. This uses directional listening to the reflections of objects, sound waves off surfaces, and other objects, like the reflective sound footsteps make against objects surrounding them. This type of system must be built without simplifications because it could affect the accuracy of creating a mental representation of the place the users are in.

The results of participant feedback showed that they could locate the source of the sound and detect the reflected sound of the walls, creating a mental representation of the place they were in. The presence of controlled events, like finger snaps to locate objects surrounding them, was very useful. The finger snap was used a lot by the participants because listening to the reverberation generated by the noise helped in understanding the spatial configuration, as well as the footstep noise. They concluded that interactive virtual stimulation can be precise enough and can be generated solely through auditory exploration.

2.3 Virtual Sports for Blind People

There are a lot of difficulties that people with visual impairments face every day. One of them is doing sports, even though there are a lot of articles, like [30]. There is still little accessibility and security in certain sports, which is a big problem since physical activity or exercise can enhance health and reduce the risk of developing certain diseases, like obesity. To help them, we need to understand what they go through while doing these physical activities and how these difficulties can be addressed with new technologies.

Shin Kim et al. wrote the article [51] and developed an application called Sonic-Badminton, which is an augmented badminton game for blind people, with the end goal of improving people with visual impairments' quality of life and social interactions with sighted people.

In the development, they used audio augmentation to make the game's overall experience richer because blind people are familiar with audio-based interactions. The system they developed replaced the shuttlecock with localized audio output, so they could interpret the location of the ball and the way it was moving, as demonstrated in Figure 2.6. To do this, they attached audio output to the badminton racket, and the audio can be delivered through stereo headphones or speakers. However, this system can only detect if the racket is moving from one location to the right, left, or center.

They conducted a user study with three sighted people who had prior experience playing sports and three blind people who were athletes in table tennis. They were asked to play first a table tennis match, either blind versus blind or blind versus sighted, and then to play Sonic Badminton with each other in the same way. Afterward, a group interview was conducted with all participants.

The results of this experience concluded that the game was playable for both sighted and blind people, with the shuttlecock being exchanged an average of 8.11 times, which is a similar rate to table tennis. There were also no significant differences between games of blind versus blind and blind versus sighted, as the first pair (blind versus blind) scored on average 5:4, and the second pair (blind versus sighted) scored on average 5:3.66. The response to the game was positive, as participants enjoyed themselves and felt they could now play a game they couldn't before, at a

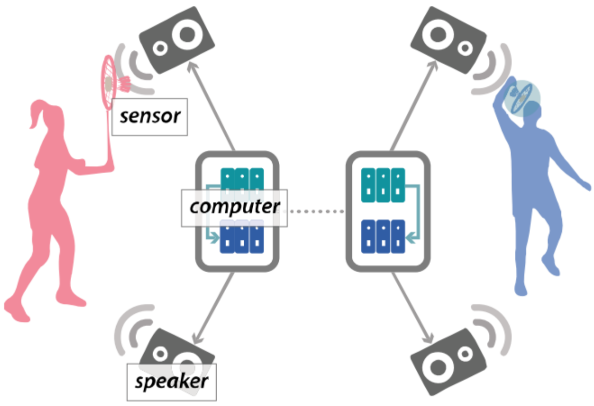

Figure 2.6: System Overview of Sonic-Badminton [51]

level similar to sighted people.

Takahiro Miura et al. wrote an article and developed an application aimed at making the game Goalball easier to practice without having to go on a court and play [72].

Goalball is an official Paralympic sport specifically designed for athletes with visual impairments. The objective is to throw a ball with bells embedded inside it into the opponent's goal. Similar to handball, players cannot kick the ball and must throw it by hand, using ear-hand coordination to guide it to the opponent's goal line as many times as possible. One challenge of this game is that players, due to their visual impairment, are sometimes afraid of being hit by a high-speed ball. However, with this application, GoalBaural, players can train their recognition of the ball's location without having to go to a court.

In the application, individuals can listen to randomized throwing conditions and learn to judge the ball's direction and distance using audio cues. These audio cues were made by recording the throwing sound binaurally and implementing the sound randomly in the interface.

They used 13 individuals with total or partial visual impairments, both with and without experience in goalball. The results showed that the application was usable for the participants and significantly improved their reaction time in determining the direction of the ball, whether they had experience or not, as shown in Figure 2.7. According to the participants' comments, this application effectively replicated various ball throws and provided a good simulation of a real game scenario.

Yancong Zhu et al. in their Running Guide work [115], discuss the information that people with visual impairments need to establish a sense of security while running a marathon, without the need for running guides. Runners with visual impairments need to perform well without the doubt of getting hurt or harming others.

First, they need to know when they are near a turning point, as well as whether they are running straight or deviating from the path. it is also important for them to understand the angle of any slopes they encounter, and to be aware of obstacles in their path. All of these factors are crucial for ensuring the runner feels safe.

One of the best ways to convey this information is through audio feedback, as visually impaired

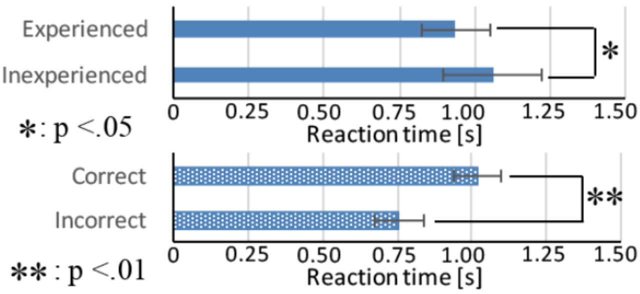

Figure 2.7: Reaction time of (upper) experienced and inexperienced participants, and (lower) correct and incorrect responses of the all. Error bars represent standard errors [72].

people are accustomed to using their hearing and speech to navigate their environment. To address these needs, the researchers developed a pair of wearable glasses. Using the information from their user research, these glasses can help people with visual impairments navigate a marathon more confidently and independently. The system uses GPS location data to create a virtual running track, providing vibrotactile and 3D spatial audio feedback (as shown in Figure 2.8) to inform runners if they are within the track.

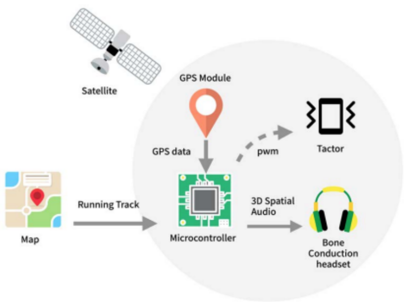

Figure 2.8: Marathon Navigation System [115].

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, which demands movement, includes opponents, and has peripheral elements such as audiences or a coach who either work as a storyteller or encourage the user. However, these are not accessible to blind people, as essential information needed to partake in the experience is conveyed visually (e.g., the opponent's position).

2.4 Sensory Substitution

Most of the information we receive is visual, but for people with visual impairments, this information is not available to them. To address this, sensory substitution can be used, which involves transforming the representation of one sensory input into another sensory form, enabling the individual to receive the needed information. For example, visual information can be transformed into audio feedback, or it can be converted into haptic feedback, where the person uses touch to receive information through vibrations.

People with visual impairments use this method every day. They use ambient sound to locate their position and the surrounding environment, and can also use a cane to feel the space for any obstacles. Therefore, learning from articles like [3], [49], and [16] on how to transform visual information into audio or haptic information is crucial for this project.

Tony Morelli, et al. article [77] talk about how gesture-based interactions are not accessible to people with visual impairments because these games use visual cues to indicate what gesture the user must make to progress in the game. However, these visual cues can be substituted with audio cues. Unfortunately, without the source code of commercial games, it's not possible to make them more accessible to blind people.

In a previous study, they found that exergames like *Dance Dance Revolution* and *Wii Sports*, when a human observer provided verbal cues to visually impaired children, allowed them to play the game. Based on this, they developed a solution that uses real-time video analysis to identify specific visual cues on the screen and substitute them with audio or vibrotactile cues.

In their user study, they had 28 sighted players and 7 players with visual impairments. They played a hurdle game, a timed-based game where sighted players could see on the screen when they needed to jump, and blind players had to rely on sound cues to know when to jump. In their results, they didn't find any significant difference in performance, as shown in Figure 2.9.

	Standard (σ)	RTSS (sighted) (σ)	RTSS(VI) (σ)
Time (s)	26.78 (4.76)	28.67 (8.41)	34.08 (3.79)
Success rate (%)	0.36 (0.32)	0.39 (0.26)	0.32 (0.12)
Avg. early jump	0.31 (0.75)	2.13 (1.02)	1.57 (0.78)
Avg. late jump	2.23 (1.36)	0.313 (0.48)	0 (0)

Figure 2.9: Kinect Hurdles combined results for both studies [77].

Arni Kristjánsson, et al. [54] presented an overview of techniques that have been developed for sensory substitution for people with visual impairments, including audio feedback and haptic feedback. However, they raised concerns that developers must take into account while designing sensory substitution devices, highlighting potential pitfalls in their design, which is very important for our project.

The main points they made in this article were that conveying unnecessary information about the environment to the user may cause an overload of information, leading the user to make incorrect actions. Another example they mention is that these technologies should not require extensive training to be used and should be simple and easy to use. However, this simplicity must not become a barrier to developing these technologies. Sensory substitution devices are best when task-focused and do not convey useless information to the user.

The auditory information conveyed should not interfere with the user's ability to sense the environment directly due to sensory overload, as people with visual impairments are used to environmental sounds and use them to locate themselves. These devices must not interfere with other perceptual functions, as it could lessen the performance of the user. Additionally, perception is a continuous process, not a snapshot of the environment, so these devices must provide continuous information without information overload, using different senses. They also discussed the possibilities of combining haptic and audio sensory substitution, speculating that haptic information may provide accurate directional data while audio information may be better at conveying distance more accurately. A combination of these two could be a very effective way of conveying environmental information to the user.

There are also first-person shooter games like *AudioQuake* [8] that use sensory substitution to make the game *Quake* accessible to people with visual impairments, replacing visual feedback with audio feedback. The audio feedback alerts the player to objects or events in the game, such as sounds informing the player of a wall nearby, with the sound increasing as the player approaches the wall. This project demonstrates that mainstream games can also be made accessible to people with visual impairments.

Ella Striem-Amit, et al. [103] explored the use of the vOICe, a visual-to-auditory sensory substitution device (SSD) that converts images into sound. Users wear a camera connected to a computer and stereo headphones, where the images are converted into "soundscapes" using an algorithm. The user listens to the audio and interprets it to form a mental image of their surroundings and objects in their vicinity.

In their user study, they enrolled all participants in a training program lasting several months with 2-hour weekly sessions, where they were taught how to interpret high-resolution visual information from the sounds generated by the vOICe. They concluded that people with visual impairments can retrieve detailed information at a much higher resolution than previously, and therefore, SSDs may be beneficial in restoring high-resolution functional vision.

Blind Hero [112] is an article about the video game *Guitar Hero* and how it was made accessible to people with visual impairments using sensory substitution, as this game relies heavily on visual information despite being about rhythm. To make it accessible, they substituted the visual stimuli with haptic stimuli using a glove they developed, equipped with small pager motors to provide haptic feedback. Each motor would represent one of five colored buttons in *Guitar Hero*. In their user study, they used sighted and visually impaired players, measuring performance and whether the sighted players had a similar gaming experience when using their vision to play *Guitar Hero*.

The results of this experiment were successful in translating visual stimuli into haptic stimuli, even though they had to compromise some elements of the game. Every participant enjoyed playing this version of the game. In conclusion, they mention that to make games accessible, compromises must be made, but the overall game experience should not be diminished. This project was successful in achieving that goal.

2.5 Discussion

The development of accessible virtual reality (VR) for visually impaired users has come a long way, as seen in the research covered in this thesis. Much of the earlier work has focused on turning visual information into non-visual cues, like spatial audio and haptic feedback [59, 68]. While these advancements have made it easier for blind users to navigate VR environments, there's still a challenge in creating experiences that go beyond basic navigation and move into fully interactive, engaging applications, such as VR sports or exergames.

Previous studies often concentrated on mobility training or object manipulation that didn't quite capture the full-body, physical nature of sports simulations [29, 57]. This project, on the other hand, integrates haptic feedback and spatial audio feedback to offer a more physically engaging experience. For example, Blind Walk VR [53] demonstrated the effectiveness of joystick-based locomotion compared with more natural locomotion for visually impaired users navigating towards spatial sound sources. Our work draws inspiration from this foundation, but to be closer to the real sport of boxing, it uses full-body physical movement. In doing so, it expands the potential of accessible VR to include more dynamic and demanding activities, like boxing.

Virtual sports adaptations have been successful in implementing both haptic and audio feedback. In one instance, localized audio was implemented in place of the shuttlecock's visual feedback in Sonic-Badminton, allowing blind players to compete with sighted players [51]. Similarly, players were able to compete using only 3D spatial sound cues when Showdown, a Paralympic sport, was adapted for virtual reality [110]. These examples highlight how VR can be used to help visually impaired people simulate competitive sports. By adding binaural audio cues (footsteps and breathing) to better locate an opponent's motions, our boxing experience builds on these ideas to offer users a more reactive and immersive environment.

Despite improvements, there are still many challenges in this sector. One such challenge, observed in numerous studies, is information overload, where users may become overwhelmed by auditory or haptic feedback, ultimately resulting in suboptimal decision-making [54]. Maintaining immersion while avoiding overload involves finding a balance between the quantity and speed of feedback. While developing this project, we gave significant consideration to how we organized the feedback systems, providing a steady rise in complexity so that users could become accustomed to it without feeling overwhelmed.

In conclusion, even though VR accessibility for people with visual impairments has advanced significantly, much work remains. Haptic feedback, combined with audio, makes for an effective toolkit for producing accessible, immersive experiences. However, these systems must be carefully planned to prevent feedback overload and to deliver clear, insightful guidance.

Chapter 3

Designing a VR Boxing Experience

3.1 Approach

The approach we took during this project is based on a prior research project [37] that explored how to augment objects and their behaviors in VR with non-visual audio representations and investigated how virtual reality (VR) could be made accessible for visually impaired users in the context of a boxing simulation. This project provided valuable information on how we should approach this project, and the foundation laid by the earlier work was critical in shaping the direction of this research.

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 will be referred to throughout the thesis as Expert. Collaborating with this Expert ensured we captured essential elements of the sport to explore before further testing the experience with non-experts in the domain.

While the previous project focused on laying the groundwork, the current work takes these ideas further, introducing more mechanisms and the integration of locomotion systems through Unity's XR Origin component. By building on the previous project's success, this thesis aims to deliver a more immersive and accessible VR boxing experience that closely mirrors real-world interactions.

The first session conducted in the previous project used a design probe with the objective to elicit knowledge and inform the design of the experience. Design probes help less tech-savvy people better understand unknown concepts and provide a proof-of-concept prototype to facilitate discussion and ideation [42]. This is particularly relevant for VR, as it enables exploring features that transcend what is possible in the physical world. The design probes and the final prototype were developed using Unity3D, running on a commercially available VR system (the Meta Quest 2 - headset and two controllers).

3.2 First Session: Initial Probe

The first session described in this section was not part of the current thesis, but rather a part of a prior research project [37]. This earlier work played a significant role in laying the groundwork for understanding how virtual reality (VR) could be used to create accessible boxing experiences for blind users. The objective of the prior project was to experiment with early-stage concepts of accessibility in VR, specifically focusing on methods to convey important environmental and interaction-based information without visual cues.

In the previous project, a simple VR boxing application was designed as a probe. The prototype utilized basic geometric shapes—cylinders representing body parts such as arms and the torso—to reduce visual complexity, allowing the research to focus on interaction and accessibility challenges. The design aimed to explore how blind users could detect and interact with their opponent's movements using non-visual methods like spatialized audio and haptic feedback.

This session involved working with a professional boxing coach with visual impairments, who had no prior experience with VR. The session helped demonstrate the potential of VR technologies such as head and hand tracking, as well as movement-based interactions that allow the user to engage physically in the environment. Different approaches for conveying the opponent's hand location were tested, including speech, sonification, and a combination of discrete and continuous cues. These insights guided further improvements in subsequent development.

The key insights from the earlier research project were centered around the use of real-time auditory feedback to guide the user during gameplay. It became clear that focusing on higher-level information, such as replicating a coach's vocal instructions during a match, was more practical than trying to convey detailed, continuous information about the opponent's hand position. As suggested by the expert participant, the emphasis should be placed on a holistic experience where the user receives more generalized guidance, such as defensive or offensive instructions (e.g., ”defend” or ”throw an uppercut”), to enhance immersion.

While the present thesis builds on these findings, it focuses on expanding the VR experience to incorporate more advanced systems, such as improved haptic feedback, enhanced auditory cues, and refined movement mechanics. The foundational work from the previous thesis provided invaluable insights into the design of accessible virtual environments and directly informed many of the design choices in the current project.

3.3 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 [37], 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 sometimes tied to the narrative or generic information.

We implemented a set of features that could be turned on/off independently. We wanted to understand the relative importance of each feature, how they could be improved, which new features could be added, and how these would integrate with each other. The latter was particularly important, as including further functionalities and feedback cues could negatively impact the experience due to the increasing cognitive load [13, 40, 108].

The implementation included a virtual boxing ring with a virtual opponent. The opponent's height is calibrated to match the user's height when the application is first launched, ensuring a realistic spatial alignment between the user and the opponent. This calibration helps users accurately gauge the position of the opponent's body parts, enhancing the realism and precision of punches. Additionally, the user is represented by a virtual body, showcasing the gloves that correspond to the VR controllers (i.e., the user's hands).

To increase immersion, the user has to use normal movement in the real world to move within the virtual environment. With this, users can freely navigate the virtual ring by physically moving in their play space, enabling repositioning without the need for complex controls or commands that would add unnecessary complexity to the environment. This design decision, inspired by the feedback from the expert, makes the experience more intuitive by aligning physical actions with in-game reactions. Because of this, players can focus on their boxing technique and strategy rather than using complicated control schemes, creating a more engaging experience. Furthermore, this natural locomotion promotes physical activity, contributing to the overall immersion and realism of the virtual boxing experience.

The session started with the most basic setup, where firstly the opponent is positioned directly in front of the user and remains stationary until the sound of a bell signals the start of the round. From this starting point, we progressively introduced a series of features, each building upon the previous ones, as shown in Table 3.1. These features were added step-by-step because it allows the participant to experiment freely with each of the functionalities at each stage without having to analyze all of them together. After each step, we paused the session to gather detailed feedback from the participant, focusing on how the newly introduced features were important to the user experience and if they worked as intended, also if they enhanced immersion, and how intuitive they were to use.

As we proceeded through the rounds, the complexity of the application gradually increased, making the opponent's movement more dynamic by adding rotation and movement through the ring, also making the interactions more responsive. At the end of the incremental feature introduction, the participant engaged in two full three-minute rounds with all features fully activated. During these rounds, we gradually increased the frequency and complexity of the instructions provided by the virtual coach, as well as the opponent's movement patterns. This increase in complexity was designed to simulate a more realistic and challenging boxing scenario, allowing us to assess how well the participant could adapt to the increasing pace and how effectively the system supported real-time feedback and interaction.

After the completion of all the rounds, a discussion was conducted to gather feedback on the entire experience. This included the participant's opinion of the application's usability, the balance between immersion and accessibility, and suggestions for further improvements. The session lasted approximately one hour and a half, with the expert spending the majority of the time—around one hour—actively engaging with the application, followed by 30 minutes of discussion to reflect on the experience and provide valuable insights for future iterations.

Table 3.1: 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.

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 increased in frequency and number during the final rounds. The Expert pointed out that as the game progresses and the frequency of coach instructions rises, it becomes harder to process and act on all the instructions quickly. This suggests that the experience could benefit from simplifying the instructions in some way. In particular, providing more concise guidance during intense moments could help the user stay focused on the boxing tasks.

In addition, the Expert expressed a desire for the opponent to move more frequently, making the experience more dynamic and challenging. However, he also noted that with increased movement, it became more difficult to locate the opponent, particularly during Step 7. To address this, he proposed that the virtual coach provide additional instructions to help reorient the user, especially in moments where the opponent's breathing and footsteps were not sufficient cues. For example, the coach could verbally indicate the opponent's position when necessary, helping the user adjust and maintain engagement in the fight. This was experimented by doing another round while movement instructions were provided verbally, simulating having the coach also say these instructions. This balance between increasing difficulty and providing adequate assistance sparked a discussion on designing different experiences that could align with real-world boxing scenarios—training sessions where more guidance is provided, and combat simulations where the user faces greater challenges with less help.

Another key point raised during the session was the difficulty in distinguishing between the different sounds and vibrations associated with punches. The Expert suggested that simplifying the feedback—by using fewer, but more easily distinguishable sounds and haptic patterns—would improve the user's ability to differentiate between the various types of impacts. This would enhance the user's responsiveness in fast-paced scenarios where immediate recognition of feedback is crucial.

While the realistic sounds of breathing and footsteps were appreciated, the Expert also recommended enhancing the spatial audio cues, even if it meant sacrificing some accuracy in the physical world mapping. Specifically, he proposed making the directionality of audio cues more pronounced by transmitting the sound only to the ear on the corresponding side (e.g., hearing the opponent's breathing exclusively in the left ear if the opponent is on the user's left). This change would make it easier to pinpoint the opponent's location, improving spatial awareness during the simulation.

Finally, the Expert expressed a preference for automatic coach instructions over those triggered manually. He found the automatic instructions more seamless and immersive, as they allowed him to focus on the experience without the need to actively request assistance. This insight suggests that future iterations of the application should prioritize the automation of helpful prompts to maintain immersion and reduce cognitive load on the user.

3.4 Three VR Boxing Modes

Based on feedback gathered from the design sessions with an expert blind user, we developed a VR Boxing Experience (Figure 3.1) tailored for accessibility, featuring three distinct modes. These modes were designed to cater to users with varying levels of boxing knowledge and experience. Each mode represents a key phase in a boxer's typical training and fighting routine: heavy bag training, coach training, and full combat. In all modes, users move within the virtual environment

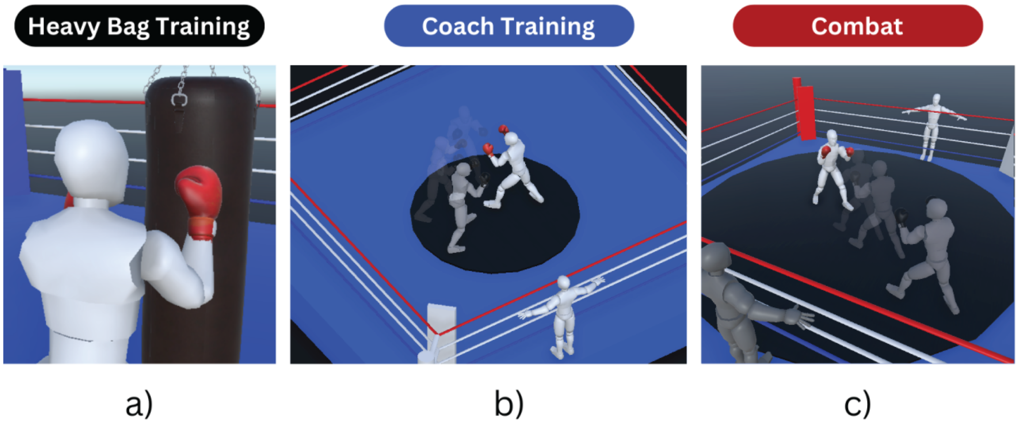

Figure 3.1: Three modes available in our VR Boxing experience: a) Heavy Bag Training allows the user to train different punches while perceiving the audio and haptic feedback on collisions; b) Coach Training places the user in a more dynamic training experience, with an opponent that attacks and defends while rotating around the user (conveying their location through breathing and footsteps), and a coach that provides both directional instructions of where the opponent is positioned and instructions of what actions to perform (type of punch or defense); c) Combat is the most complete experience which, besides the features presented in Coach Training, introduces a wider range of movement for the opponent around the virtual ring, an audience sound effect and a coach for the opponent.

by walking on a 1:1 scale, physically turning their heads and bodies, and using their hands to simulate punches. This approach ensures a more natural and immersive experience.

Heavy Bag Training

The first mode offers a straightforward, introductory experience where users start by punching a heavy bag. In this scenario, users face a virtual punching bag and focus on mastering basic punches such as the jab, cross, uppercut, and hook. This mode is designed to help users familiarize themselves with the fundamentals of boxing without the added complexity of a moving opponent and to understand the type of auditory and haptic feedback they will receive during this experience when they are punching something. This first mode is a good starting point for those new to VR or boxing itself, providing a low-pressure environment for physical activity.

The key features in this mode include auditory and haptic feedback. The intensity of the audio and vibrations is proportional to the force of the punches, giving users a clear sense of how hard they are striking. We incorporated realistic physics into the bag's behavior, so it swings when hit; but to prevent unintentional feedback (such as the bag swinging back and hitting the user), we made the bag slightly heavier, minimizing the swinging. This design keeps the interaction smooth, allowing users to focus on perfecting their punches without distraction.

Coach Training

This mode shifts the experience to a more dynamic level by introducing both an opponent and a coach into the virtual ring. The user practices sparring, where they face a virtual opponent

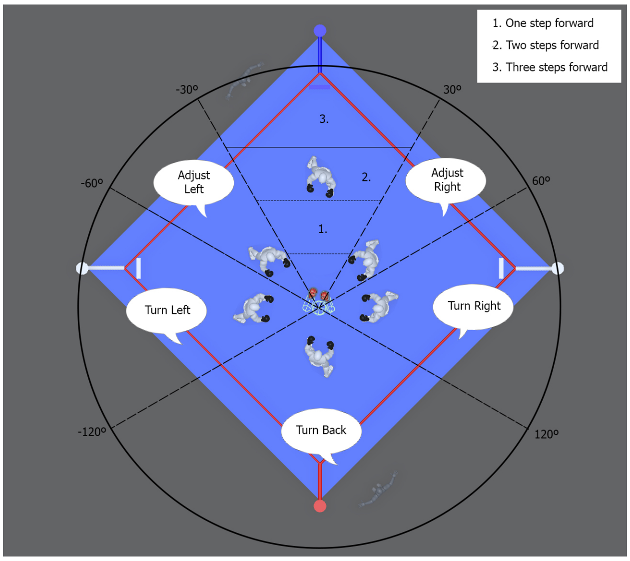

Figure 3.2: The angles and distance criteria for the coach to convey orientation instructions.

who moves around the user and occasionally attacks. The coach guides the user throughout the session, providing instructions on what punches to execute, when to defend, and how to respond to the opponent's movement.

We made significant adjustments to the audio and haptic feedback in this mode. For instance, we simplified the punch feedback into three distinct sounds to indicate whether the user landed a hit on the opponent's head, torso, or gloves/arms. These sounds are purposefully exaggerated—for example, a body punch might be accompanied by a grunt—making it easier for users to differentiate between types of strikes. Additionally, the same audio and haptic patterns are used whether the user is attacking or defending, but the feedback is softer and more muffled when the user gets hit.

To enhance realism and add more complexity to the environment, the opponent moves around the user during the session, and we incorporated audio cues such as the opponent's breathing and footsteps. This gives users a sense of the opponent's position and movement, making the experience feel more alive. The frequency and complexity of the opponent's movement can be customized based on the user's experience level, allowing for a more tailored session.

To further assist the user, the coach provides automatic instructions on what punches to throw and when to defend. These instructions are delivered at intervals, and the complexity of the commands (e.g., single punches vs. combinations) can be adjusted. An important feature is the coach's directional guidance (Figure 3.2). If the user is facing the wrong direction for more than three seconds (to give time for the participant to correct their position with the footstep and breathing sounds), the coach steps in with subtle guidance—like "adjust left" or "turn right" depending on how far off the user is from the opponent's position. This helps users stay oriented without overwhelming them.

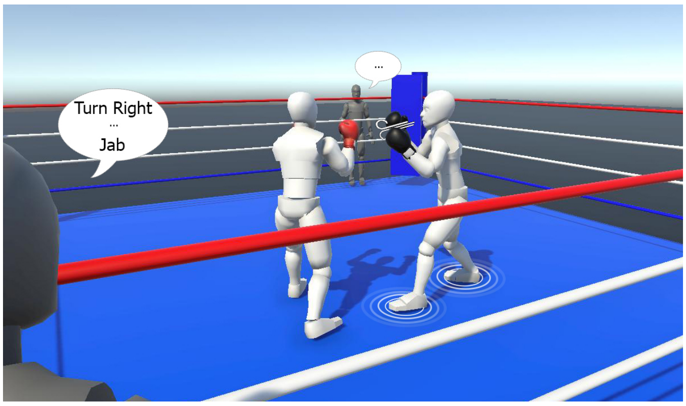

Figure 3.3: Simulation of combat mode in the virtual ring.

Combat

The Combat mode takes training to the next level, simulating a full boxing match. It incorporates many of the features from the Coach Training mode, such as the movement of the opponent around the user, automatic coach instructions, and feedback on punches and defenses. However, the Combat mode adds layers of complexity to create a more immersive and competitive experience.

In this mode, the opponent moves more through the ring (Figure 3.3), including retreating to specific locations, with the objective of making the user follow. If the user does not approach within ten seconds, the opponent will move back toward the user. The frequency and type of movement can be customized, ensuring that the experience adapts to the user's skill level. The coach also steps in with more detailed instructions, such as advising the user to take a few steps forward or guiding them to close the distance with the opponent if needed.

To increase realism, we have added additional sounds, such as the roar of an audience and the presence of the opponent's coach, whose voice can provide additional clues about the user's location within the ring. These subtle additions contribute to a more immersive experience. Another practical feature is the introduction of haptic feedback when the user touches the ropes, letting them know they are nearing the edge of the ring. This helps users stay within the fight zone and adds to the overall sense of spatial awareness.

Chapter 4

Implementation

The VR Boxing experience is implemented in Unity3D, where we used both auditory and haptic feedback to ensure accessibility for blind users. We also used natural locomotion, allowing participants to move freely within the virtual space without relying on complicated controls, which enhances immersion and reduces learning time. This approach makes the experience more intuitive for visually impaired users, creating a more natural and responsive virtual environment.

A very important component of this system is Unity's XR Origin from the XR Interaction Toolkit, which manages the user's movements. This toolkit adjusts to the user's physical height and actions in real time, allowing movements such as walking, turning, and dodging to be directly mirrored in the virtual boxing ring. The XR Origin system ensures that users' physical movements in the real world correspond seamlessly to the virtual environment, enabling smooth navigation and interaction during the boxing experience.

Spatialized audio plays a crucial role in enhancing realism, helping users locate their opponent through sounds like footsteps and breathing. Environmental audio, such as crowd reactions, further immerses users by providing non-visual cues about their surroundings. Haptic feedback also enhances the experience by offering physical sensations during interactions like punches or collisions with the ring ropes. The boxing environment itself consists of a ring, modeled in Unity, complete with key features like ropes and corner padding. For instance, the ring ropes vibrate when touched, giving blind users tactile feedback to help them stay oriented within the virtual space.

This approach to VR design aims to create a fully immersive and accessible experience, ensuring that blind users can engage with the environment in a way that feels natural and enjoyable while reflecting the real-world motions of boxing.

4.1 VR Prototype

Boxing Ring

The virtual boxing ring (Figure 4.1) was designed as a functional environment where the user could move freely. We used natural locomotion, allowing participants to walk and turn physically, which contributed to the navigation within the virtual space. This approach eliminated the need for complex movement controls that would increase the time for adaptation to the virtual environment and also increased accessibility by allowing users to rely on their body movements to navigate the virtual environment. The boxing ring serves as the spatial boundary for the user and the opponent, designed to keep the user within a defined area during the experience. Everything was built using Unity's 3D models.

The ring's dimensions are configured to resemble a standard boxing ring, providing enough space for both movement and combat while ensuring the user remains within the virtual environment's safe zone. The standard boxing ring is between 4.9 and 7.3 meters between the ropes and another 0.61 meters outside the ropes. The height of the platform is normally between 0.91 and 1.22 meters. For the participants to move more freely, it was decided to use the dimensions 7 meters by 7 meters inside the ropes with a height of 1 meter for the platform. The ring has a red corner where the participants started and a blue corner where the opponent started the combat.

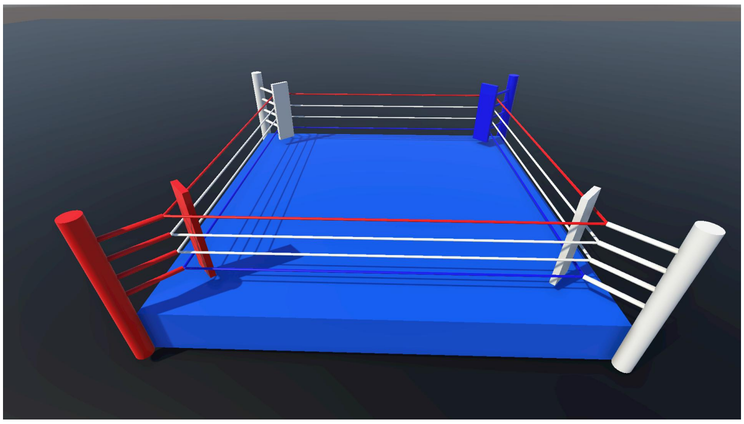

Figure 4.1: Ring design

Ropes/Corner paddings

The ring includes ropes and corner paddings, serving as haptic boundaries that vibrate the user's controller when they touch the ropes. This feature helps blind users stay aware of their position within the ring, without visual cues. These were made using Unity's 3D model of cylinders, and, contrary to real ropes, they don't move; they are always fixed in that position.

Audience

The ring also incorporates ambient audio feedback, such as the sounds of crowd reactions, to enhance the user's immersion. The sound of the crowd comes from four different places, which are the four sides of the boxing ring, with the intention that when the participant moves to one of the four sides of the ring, the audience on that side would get louder, giving the participant awareness of their position and indicating that they were getting closer to the ropes.

4.1.1 User's components and XR Origin

In the VR boxing experience, the user's movement within the virtual environment is managed using Unity's XR Origin, a component from Unity's XR Interaction Toolkit. The XR Origin is responsible for setting up the user's position, movement, and perspective within the virtual world, effectively aligning their real-world movements with in-game actions.

The XR Origin is a fundamental asset that defines the camera and movement setup for an XR (Extended Reality) application. It consists of a Camera Floor Offset object that allows the application to dynamically adjust the user's height and position based on real-world measurements. This ensures that the player experiences natural and immersive movement in the virtual space.

In our VR boxing application, the XR Origin is set up to:

- Adjust the user's height dynamically based on their real-world standing or sitting position.
- Allow full freedom of movement within the play area by tracking head and body movements through connected VR hardware (such as Meta Quest 2 that we are using).
- Map physical world movements (walking, crouching, turning) to corresponding in-game movements, allowing the player to dodge, punch, or navigate the boxing ring.

User Movement and Navigation

With XR Origin, the user's movement is not artificially simulated through controller inputs but is instead tracked in real-time via head and body movement. This allows for a highly immersive experience, where the participants can physically walk within their real-world play area, and those movements are mirrored in the virtual boxing ring.

The XR Origin consists of several key elements that support this:

- **Camera**: This component provides the player's perspective and tracks their head movement, allowing the player to look around naturally in the virtual world.
- **Character Controller**: This component ensures the player can physically move around the virtual boxing ring by translating real-world motion into game-space movement.
- **Tracking Input**: This system integrates with the player's VR hardware, tracking the position and rotation of the VR headset and translating it into in-game movement.

For example, when the user physically moves left, turns their head, or crouches in the real world, these actions are reflected seamlessly in the virtual world, allowing them to perform realistic boxing movements, such as dodging an opponent's punch or positioning themselves for a strike.

User Interaction: Haptic and Audio Feedback

To create a more immersive and responsive VR boxing experience, two scripts were used for each hand to handle haptic and audio feedback whenever the player interacts with some components of the virtual environment or the opponent.

The first script is responsible for delivering tactile feedback when the player's hand interacts with various elements in the virtual boxing environment. This is achieved by utilizing Unity's XRBaseController class to send haptic impulses to the player's left-hand VR controller. These impulses simulate the physical impact of punches and blocks, enhancing the realism of the gameplay. The script continuously monitors for collisions between the player's hands and specific tagged objects, such as the opponent's torso, head, gloves, arms, or the bag. This script also keeps track of key statistics, including the number of successful player hits, enemy defenses, and bag collisions. These counters provide valuable metrics for performance analysis and feedback using logs.

Through this haptic system, players experience the sensation of physical interactions, such as punches and blocks, directly through their VR controllers, offering a more engaging and realistic simulation of boxing.

The second script that deals with collisions also enhances the auditory feedback by playing context-specific audio cues upon collision. This script detects when the player's hands collide with various objects and triggers appropriate audio clips, providing an additional layer of immersion by simulating the sounds of physical contact.

- **Dynamic Audio Playback:** Upon collision with objects such as the opponent's Torso, Head, or the Bag, the script plays corresponding audio clips. These audio cues mimic the sound of punches landing, adding realism to the interaction.

- **Proximity-Based Sound Effects:** When colliding with objects like the opponent's Gloves or Arms, the script calculates the distance between the player's hand and the opponent. Depending on the proximity, different sound effects are played, to differentiate from defending or attacking.

- **Collision Control:** To prevent constant audio triggering from rapid collisions or when colliding with two components at the same time, the script incorporates a cooldown mechanism of 0.4 seconds to not use the function. This ensures that sounds do not overlap or become repetitive, maintaining an orderly auditory experience.

Together, the two scripts provide a cohesive multisensory experience by combining tactile and auditory feedback. This integration enhances player immersion in the following ways:

- **Haptic Feedback:** Provides physical sensations in the VR controller, simulating the impact of punches, blocks, and other interactions in the boxing environment.

- **Audio Feedback:** Plays relevant audio cues to simulate the sound of punches landing or being blocked, with variations based on proximity and object type.

- **Performance Logging:** Both scripts track and log collision events, allowing for detailed performance feedback and analysis, which can be used to improve the player's experience.

This system significantly enhances the player's engagement by using real-time sensory feedback to simulate the physical and auditory elements of a boxing match, thus offering a richer and more immersive VR experience.

Users model

For the users model only the boxing gloves model from the *Sketchfab website*[1] was used. Colliders were then applied with the XR Origin to represent the user's head, torso, gloves, and forearms (for defensive purposes), as shown in Figure4.2.

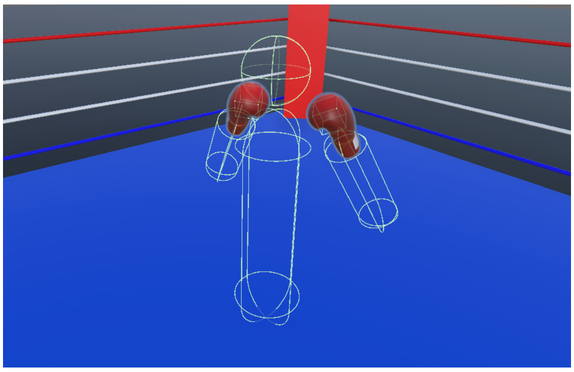

Figure 4.2: User's gloves and colliders

In the initial iteration, different sounds were played when the opponent punched the user's head, torso, or gloves/forearms, with distinct audio cues for each area. These sounds were also different from those triggered when the user landed punches on the opponent. However, after a session with the expert, this approach was modified. The sound effects for when the user is punched were made the same as those when the user punches the opponent, but with a lower volume and a more muffled tone. This adjustment allows the user to distinguish between being punched and punching, especially in situations where both the user and the opponent might punch simultaneously. By using these subtle audio differences, the user can better perceive who successfully landed the hit and what is happening during fast-paced interactions.

4.1.2 Boxing bag

The boxing bag provides a static training tool for users to practice their punches and movements before engaging with a dynamic opponent. The model that was used was from this website *Sketchfab website*[2] and it was implemented as a rigid body object in Unity using this with some mass, gravity and a spring point on the top to make it swing like a boxing bag, the bag responds to user punches with both haptic and auditory feedback to tell the bag was hit. It uses a sound from this website *Freesound*[3] that resembles a real punch in a boxing bag.

[1] Glove model - https://sketchfab.com/3d-models/boxing-glove-84424f446e7f4c3b8bf1c3204b581f28?sscid=71k8_h8zbb
[2] Bag model - https://sketchfab.com/3d-models/punching-bagboxing-bag-6b195883ada144d0a5d92f7ddcdfaf05
[3] Punch Sounds - https://freesound.org/

To ensure accessibility, the boxing bag also includes positional audio cues to help users orient themselves in the virtual environment. When users strike the bag, sound effects vary based on the force of the hit, giving real-time feedback about the effectiveness of their punches (Figure4.3).

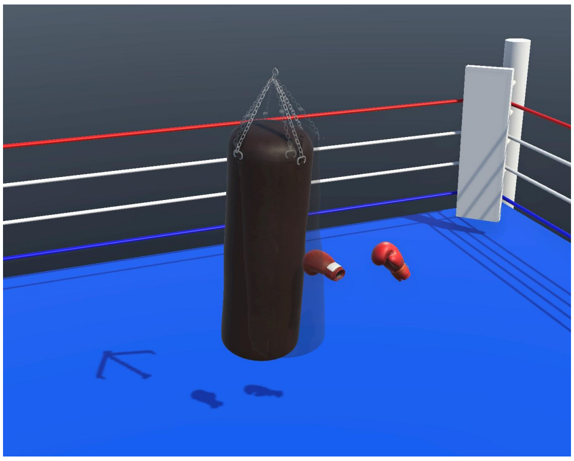

Figure 4.3: Boxing bag design and getting hit by a punch

4.1.3 The Opponent

The opponent is a core element of the VR boxing experience, designed to challenge the user both in terms of movement and timing. The opponent's movement is not visually represented but conveyed through audio cues such as footsteps and breathing, that rendered with 3D audio technology, helping users estimate the opponent's location which give users critical spatial awareness. The opponent's position and actions were crucially communicated through these sounds, allowing users to react by throwing punches or defending, simulating a real-world boxing match environment.

Model

The model for the opponent used was from the *Unity asset store*[4] and the gloves model used was from the *Sketchfab website*[5] and the color was changed to differentiate from the users glove, to allow the developer to differentiate better. After, the opponent's model was moved to resemble a boxing stance to make the punches come from a position more realistic than just standing straight and has the height of 1.80 meters. Lastly, it was used colliders for the opponent's gloves, forearms (for the defense), head and torso.

Punches

The opponent punches were made using Unity's animator, where we animated seven different movements, six of them are punches (jab Figure4.4, cross Figure4.5, right or left hook4.6, right or left uppercut4.7) and one defense Figure4.8.

[4]Opponent model - https://assetstore.unity.com/packages/3d/characters/humanoids/humans/3d-character-dummy-178395

[5]Glove model - https://sketchfab.com/3d-models/boxing-glove-84424f446e7f4c3b8bf1c3204b581f28?sscid=71k8_h8zbb

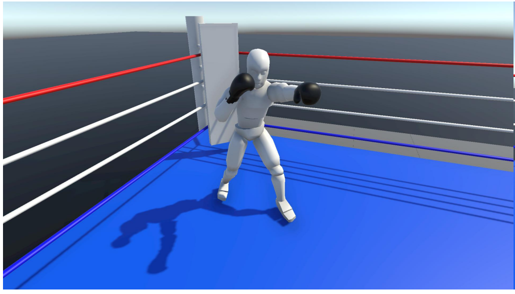

Figure 4.4: Opponent jab punch

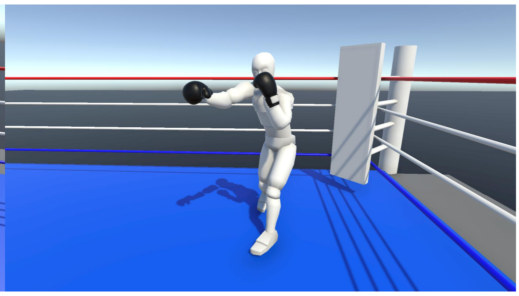

Figure 4.5: Opponent cross punch

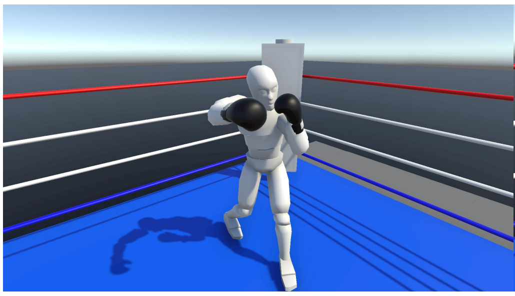

Figure 4.6: Opponent hook punch

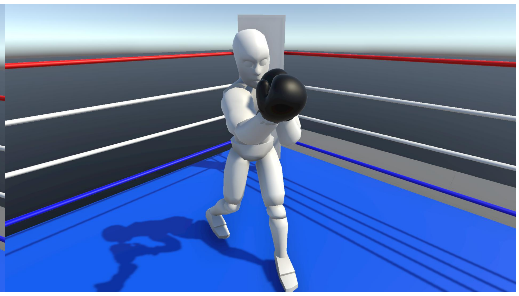

Figure 4.7: Opponent uppercut punch

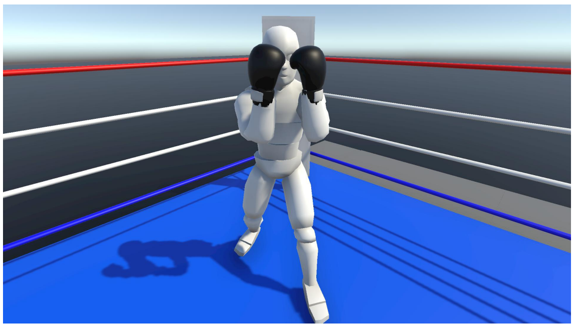

Figure 4.8: Opponent defense

In this study, we developed 11 distinct combinations of punches, such as jab and jab-cross, varying between 1 and 3 punches. These combinations were utilized sequentially during the experimental trials. These are the combinations used: Jab, Cross, Jab - Cross, Jab - Right Hook, Jab - Jab - Cross, Right Hook, Left Uppercut, Right Uppercut, Jab - Left Hook, Jab - Right Uppercut, Cross - Left Uppercut, Jab - Right Hook - Left Uppercut.

Movement

In the start of this project, the objective was to first make the opponent follow the user, so it was designed a script to control the behavior. This script utilizes player tracking and dynamic distance management to create interactions within the game environment. First, the opponent continuously adjusts its orientation to face the player to ensure the enemy's forward direction aligns with the player's position and also ignoring vertical height differences to ensure the opponent always stays on the ground. The distance management works by calculating the horizontal distance between the enemy and the player and making the opponent move forward with 0.7 meters per second, until reaching a distance of 0.9 meters, which is in the distance where it can punch the user. If the user steps forward, reaching the distance of 0.8 meters, it will move away from the player to maintain the 0.9 meters distance.

Then to make the experience more complex, we added 2 types of movement the first one was moving around the user where the opponent rotates around the user for 2 seconds and always maintaining the same distance as in (Figure4.9). In this version the opponent won't start rotating until 10 seconds of starting the round, then it will start rotating for 2 seconds, this rotation alternates right to left every two turns to introduce variability but maintaining the same experience for all the participants. After a turning event occurs, it will start a cooldown timer of 30 to 45 seconds, depending on what round the participant is doing.

The second type of movement is moving through the ring (Figure4.10) where the opponent moves to one of the four already determined locations. The objective of this type of movement is to make the user chase the opponent and try to reach him, to continue the combat, if the user didn't mange to reach the opponent he would start chasing the user again after waiting 10 seconds in the predetermined location. To ensure this happens, the other types of movement are put in pause until the opponent waits the full 10 seconds of the user manages to reach the user. This type of movement is used in a specific time in the experience depending on what round is being played like in this table5.1.

Sounds

We added footstep and breathing sounds to the opponent for the participants to be able to locate the opponent. For the opponent's sounds, it was used footsteps sounds from *Unity asset store*[6] this sound is always played when the opponent moves in any direction. For the breathing sound it

[6]Footsteps - https://assetstore.unity.com/packages/audio/sound-fx/foley/footsteps-essentials-189879

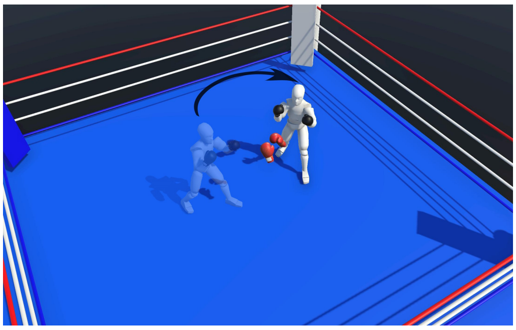

Figure 4.9: Opponent rotation

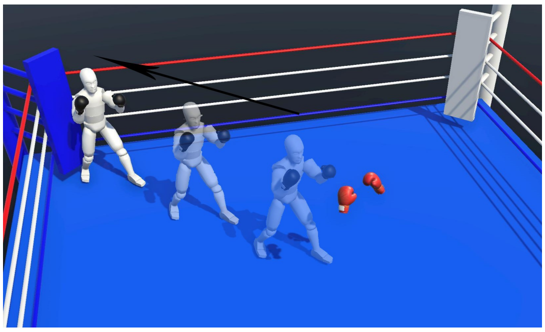

Figure 4.10: Opponent moves through the ring

was uses a sound from the website *Pixabay*[7] and then it was edited to have a better understanding where is the opponent location using the Audacity software, and it is always played during the round. Both these sounds are not used like 3D sounds, but they were used in a binaural audio way so when the opponent is on the right side of the user for example they will only hear in that side of the headset the sound will be gone on the left side of the headset and will also be gradually lower when the opponent is moving away from the user, with this method it will help the participants understand the opponent's position.

The opponent also has sounds of getting punched, these sounds were used from the website *Freesound*[8] and they were later edited using Audacity for our liking. In the start it was used different sounds depending on where the punch collided. We implemented six different sounds of the opponent getting punched, if the opponent was hit by the user's stronger hand (the hand that is positioned further back, which varies depending on whether the user is right or left-handed) it would play a stronger sound than if the opponent was hit by the users weaker hand, it would also change if the opponent was hit on the head, torso or gloves, on the head it was a sound resembling a person getting hit hard, in the torso it would be a sound resembling a pained grunt, while the sound of hitting gloves we used a real sound of two gloves colliding.

After the session with the Expert, we changed the sounds to fewer and more simplistic ones because there were too many sounds for the user to understand where they were hitting so we used only 3 sounds only depending on where the opponent was getting hit not depending if it is with the stronger hand or weaker hand.

Vibration

It was implemented haptic feedback when punching the opponent and in the start, similar to the sounds, there were 6 different levels of vibration demonstrated in table 4.1. The vibration depends on if it is the strong or weak hand hitting, the place it was hitting and the time of vibration.

After the session with the expert, this was also simplified, we used the same vibration for the stronger and weaker hand, now it only depends on the location of the punch and the time of vibration demonstrated in the table 4.2

[7] Breathing - https://pixabay.com/sound-effects/
[8] Punch Sounds - https://freesound.org/

Table 4.1: First iteration of the vibration levels and duration

Location	Left Hand	Right Hand	Duration
Gloves	0.1	0.2	0.25
Torso	0.35	0.5	0.5
Head	0.75	1	0.5

Table 4.2: Current vibration levels and duration

Location	Level	Duration
Gloves	0.1	0.25
Torso	0.5	0.5
Head	1	0.5

4.1.4 Coach

The user's coach acts as a guide throughout the experience, providing real-time instructions and feedback on the user's actions. The coach is an integral part of the interaction, offering verbal cues on when to punch, move, or defend. Positioned in the corner of the ring and never moves, so that the coach could potentially provide spatial orientation with their voice, as it could serve as an anchor to help the user stay aware of their location in the ring. The voice for the coach was created using Text-to-Speech from this website *Speechgen*[9].

The idea in the start of the project was for the coach only to convey the information about when to defend, attack and how to attack, only after we added the information about the opponent's location and if the user is too close to the ropes or one of the corners, because being in one of those places is a disadvantage to the user as it leaves the user with less space to escape the opponent.

The coach's audio feedback is closely linked to the opponent's actions, allowing users to anticipate and react effectively. Instructions like "move to your right" or "get ready to defend" are synchronized with the opponent's movement, offering the user guidance while maintaining a sense of independence and decision-making. The coach's feedback is designed to balance between being helpful and allowing users the space to make their own tactical choices.

Punch Instructions

The ways to convey information about what punches to throw are automatic, and they would activate when the opponent was in range to receive punches from the user, and the other way that the instructions were used was during the session with the expert in some of the rounds with a push of the "Trigger" button in one of the Quest 2 remotes (Figure4.11) when the expert felt the need of the coach punch instruction.

The expert advised us against using that button, suggesting instead that we grip the controller solely by its bottom part. This technique more accurately mimics a fist position and hand place-

[9]Coach voice - https://speechgen.io/

Figure 4.11: Trigger button of the Quest 2 controller

ment we would use if wearing a boxing glove. So the button we should use in the project is the ”Grip” button that should be under the index or middle finger (Figure4.12). At after the session, we chose to only the automatic instructions from the coach because it was the preferred way to convey the instructions to the expert and also to simplify the experience.

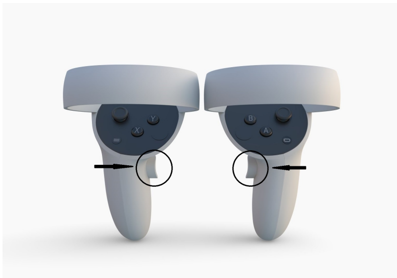

Figure 4.12: Grip button of the Quest 2 controller

For the automatic instructions, the coach follows a sequence depending on what mode and what round the user is in. To start the sequence, the user has to be in range of the opponent, which is 1 meter. It starts by giving the instruction for the user to defend, after a delay of 1 second the enemy starts attacking the user, when the attacking finishes it begins a delay of 3 seconds to see if the participants have the initiative to punch the opponent without the instruction of the coach. After that delay, the coach gives the first punch instruction, the instructions depend on what round the user is in, if it is the first or second round of coach training or combat it is always 1 punch if it is the third round it will be 1 or 2 punch combinations. After the last punch instruction is transmitted, there is a delay of 2 seconds and the sequence starts again with the user's defense. If at any point of the round, the user is not in the range, the sequence is paused until the user is in range again.

Movement Instructions

The coach has a script implemented that tracks the player's position in relation to the opponent, calculating the distance between the two and the angle at which the opponent is located relative to the player's forward-facing direction. The result from these calculations determine when and what type of auditory feedback should be given. Meaning, if the player is out of position for three seconds the coach is going to say first, which way the user should turn to and only after if needed how many steps he should take to reach the opponent.These correspond to a ”slight 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 is shown in (Figure3.2). For the forward movement, the coach is going to say ”One/two/three step forward” depending on if the opponent is 1 to 3 meters in distance of the user.

4.1.5 Opponent’s coach

The opponent’s coach serves as an additional audio source, providing indirect cues about the opponent’s actions. This character is implemented to offer real-time feedback similar to what a real coach would provide, guiding the opponent and offering tactical advice. The coach’s voice, located at a specific point outside the ring, serves as an additional orientation cue, helping users understand the spatial relationships in the environment. The audio cues from the coach complement the opponent’s actions.

4.1.6 Canvas

For this project, it was created four different canvas that are only used by person that is leading the experience don’t bother the participant during the gameplay. The first canvas function is to create the name of the log file, where it is put the name of the participant and choose the type of movement the opponent is going to have, Figure4.13.

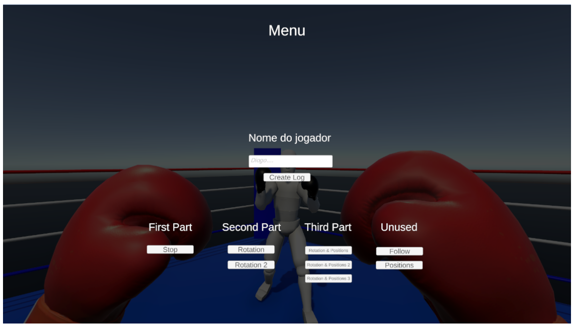

Figure 4.13: Initial canvas

After using the first canvas, automatically appears a second canvas Figure4.14, its purpose is to decide the type of instructions the participant is going to receive or to change to the first mode where opponent is substituted for the boxing bag. This canvas can also be turned on to disable or enable various features, for example the audience sounds or the footsteps. It is also used to start the experience or reset the experience.

The third canvas Figure4.15 appears after clicking start in the second canvas and stays on during the experience. Its use is to go to the second canvas with the purpose of resetting the experience or enabling/disabling a feature. There was another function of this canvas, by clicking the Audio Menu button another canvas Figure4.16 opened up that served to stop the coach’s automatic instructions, and we could click in buttons to say the next combination of punch instructions to the

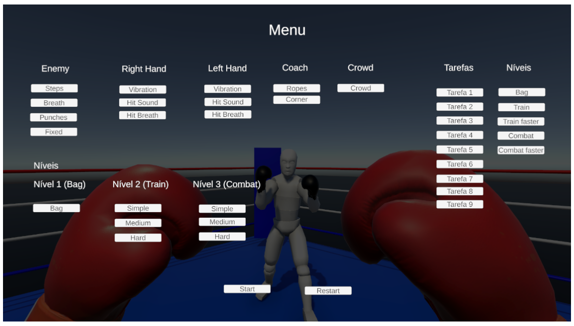

Figure 4.14: Second canvas

participant, but it was deprecated and never used.

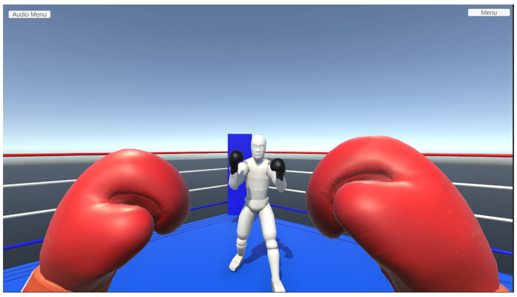

Figure 4.15: In game canvas

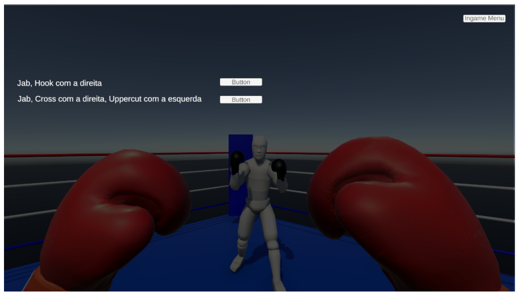

Figure 4.16: Deprecated canvas

4.1.7 Logs

The logging of collisions and interactions in this project is handled using a script in Unity. This script is responsible for recording various in-game events, such as when the player punches, defends, or interacts with the environment (e.g., hitting a punching bag or colliding with an enemy). This script relies on multiple components that handle different aspects of the project, such as:

- The components that create the vibrations on the left and right hand also tracks the player's right and left punches including successful hits on the enemy or bag, and when the user blocks the punches.
- The components that create the collision between the opponent's punches and the user also records them.
- The components that handle the coach's movement instructions and punch instructions also records them during each level

Then the logging system starts by defining a log file with the name chosen before the round starts where all the relevant data is stored. The logging is initially disabled by default when it is enabled, the script tracks collision events and logs detailed information about interactions between the player, enemy, and environment. This includes the time, type of collision, and the objects involved. The script uses Unity's OnCollisionEnter method to detect collisions in real time. Each time a collision occurs (e.g., a punch lands or is defended), the script logs the name of the objects involved and the timestamp of the event. The data related to collisions, such as the total number of hits, defenses, and instructions, are logged at the end of the game when the OnDestroy method is triggered.The log file is updated throughout the game session using StreamWriter. Each log entry is written in real time and immediately flushed to the file to ensure no data is lost during gameplay.

When the game ends, the script calculates and logs several metrics:

- Total player hits
- Total enemy hits
- Total bag collisions
- Total coach instructions and movement prompts

These metrics were useful for the analysis and can be used to assess some qualities of the project.

Chapter 5

User Study

The participatory design approach was very important in shaping the VR Boxing experience because of the feedback the Expert gave u, resulting in three distinct modes: Heavy Bag Training, Coach Training, and Combat. By involving the Expert in the design process, we ensured that the system met the needs for a broader group of blind people. This collaborative approach allowed us to refine both the technical aspects of the system and the overall user experience.

To understand the effectiveness of our final design and gain broader insights into the preferences and needs of blind users, we conducted a user study. The primary goal of this study was not only to evaluate how well the VR Boxing simulation performed across different modes, but also to derive actionable findings that could guide the development of future accessible VR experiences. Specifically, we aimed to address the following research questions:

1. How are the three distinct modes (Heavy Bag Training, Coach Training, and Combat) perceived by blind users in terms of usability, immersion, and engagement? What are the specific strengths and weaknesses of each mode from the perspective of the participants.

2. Which features of the system are most valued by blind users, and how do these features (e.g., auditory cues, haptic feedback, physical movement) enhance or worsen the overall VR experience? How do these features impact the user's ability to navigate, interact with, and feel immersion in the virtual boxing environment?

With this study, we aimed not only to evaluate our specific VR experience, but also to derive findings that may inform the design of other accessible, feature-rich, engaging, and immersive VR experiences for blind people. By focusing on feature-rich, immersive, and interactive experiences, we hope to contribute to the growing field of accessible VR, demonstrating how non-visual feedback can help blind users to engage with virtual environments. We also sought to understand how users responded to the increasing complexity of the different modes, and whether the progressive difficulty allowed them to build confidence and improve their skills over time.

5.1 Apparatus

We used the VR Boxing prototype previously described, running on a Meta Quest 2. To ensure an optimal performance and a smooth user experience, the headset was connected via a wired link to a laptop equipped with compatible system graphics (NVIDIA GeForce RTX 3060). The decision to use a wired connection was for the need for stability and performance consistency during the study. The wired setup allowed the researcher to oversee the sessions. This setup eliminated potential issues related to internet connectivity that could arise with wireless connections, that could make the VR experience less fluid for participants and potentially skewing the results of the user study.

Participants used headphones to enhance the spatialized audio. These headphones provided more immersive auditory feedback, helping participants locate better the virtual opponent and their own location in the virtual world. The choice of headphones ensured that the spatial audio cues remained clear and effective. The data from the study (e.g., instructions, punches given or received, among others) was logged locally.

The study was primarily conducted at a local institution, which provided a controlled environment with minimal distractions and ample space for free movement. However, for participant P4 the session was completed at our university and participants P13 to P15 were in locations of their convenience. In each case, we ensured that the locations had enough physical space for participants to move safely and freely within the VR boxing ring and maintaining low noise levels to avoid interference with the spatial audio cues.

5.2 Methodology

The study started tasks were structured around the three modes, organized in order of complexity – starting from Heavy Bag Training and finishing with Combat (detailed in the following section). We performed brief questions after each mode (to assess how much they liked it) and at the end (e.g., miniPXI [39]), and a semi-structured interview after completing all tasks to gather further insights about their experience.

5.2.1 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 rounds, each with a duration of one minute. 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 – intending to cover the four punch types and defense as many times as possible.

Table 5.1: 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

Mode	Round	Circles Around	Moves Away	Punch Instructions	Punch Combinations
Coach Training	1	Every 45s	-	Every 7s	1
	2	Every 30s	-		
	3		-		1 or 2
Combat	1	Every 45s	Every 45s		1
	2	Every 30s			
	3		Every 30s		1 or 2

Coach Training. This part has three rounds, each with a duration of two minutes. 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 5.1). 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, also with increasing complexity over time. The punch instructions are the same as in Coach Training, with 1-punch instructions in the first two rounds, and some 2-punch combinations in the third round. The opponent also 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.

5.2.2 Questionnaire and Semi-Structured Interview

To gather immediate feedback from participants, we asked two questions right after they completed each mode, one exception is the boxing bag mode where we asked after the first round. These questions were aimed at capturing their immediate reactions to the experience. We asked participants to rate how much they enjoyed each mode using a 7-point Likert Items (from 1- I didn’t enjoy it at all, to 7- I enjoyed it very much). This allowed us to pinpoint the participants levels of enjoyment at the end of each mode. Additionally, we asked them to share what they liked and disliked the most about their experience in that mode, whether positive or negative.

Once participants had interacted with all the modes, we moved on to the miniPXI questionnaire [39]. This validated tool includes eleven items, each designed to assess different dimensions of the player experience. Participants rated each on a scale from -3 (Strongly Disagree) to 3

(Strongly Agree). In addition to the miniPXI, we also asked participants to rate the importance of all the features presented, using a 7-point scale where 1 meant ”Not Important” and 7 meant ”Very Important”. This allowed us to identify what features participants found most valuable within the virtual environment. By comparing these ratings, we could pinpoint which features contributed most to creating an enjoyable and immersive experience, as well as those that might have been less impactful.

Finally, we conducted a semi-structured interview to dive deeper into participants' experiences. This interview gave us the opportunity to explore not just what they liked or disliked, but also why they felt that way. We asked about their specific interactions with the system, any challenges they encountered, and how they adapted to the VR environment. Participants were also encouraged to share any suggestions for improving the system.

5.3 Procedure

All sessions were conducted by at least two researchers. The first researcher led the study, while the second researcher took notes and provided support throughout the experience and interview. The last researcher participated in two sessions, mostly as an observer and assisting with the interview. The study protocol was approved by our University's Ethics Committee.

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 to sign (or approve verbally, if preferred). 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 all components with their hands (e.g., the headset and the controllers). Next, the researcher explained the four basic types of punches and in the case of the hook shot and uppercut with the left and right hand, also how to defend, and the fighting position, similar to a boxing mitt/pad work format. After completing the boxing fundamentals, participants were assisted in wearing the Meta Quest 2 hardware, the headphones and the respective VR controllers. Participants were then assisted to position themselves at a specific location (marked on the floor to assist the researcher), ensuring they had enough space to move around the room.

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. Finally, we thanked participants for their time and insights. All participants received a gift voucher for their participation.

Table 5.2: 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. We also asked how many times they have interacted with immersive VR.

ID	Age	Gender	Boxing	Technology	Virtual Environments	VR Experience
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

5.4 Participants

We recruited 15 blind participants (Table 5.2) 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 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.

5.5 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 thematic analysis [11]. 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.

5.6 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.

5.6.1 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 to lowest mean values are Immersion (M=2.7, SD=0.5), Audiovisual Appeal (M=2.7, SD=0.6), Clarity of Goals (M=2.7, SD=0.6), Enjoyment (M=2.5, SD=0.8), Curiosity (M=2.5, SD=0.8), Meaning (M=2.4, SD=0.9), Ease of Control (M=2.3, SD=0.6), Autonomy (M=2.2, SD=1.1), Progress Feedback (M=2.1, SD=1.4), Challenge (M=2.1, SD=1.0) and 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 even scores, Combat was preferred by ten participants, while four preferred Heavy Bag Training and one preferred Coach Training, respectively. For ten participants, Coach Training was second, while Heavy Bag Training was the least preferred for eleven participants like it is shown (Table5.3).

Table 5.3: Participants' order of preference for each mode

Ranking	Heavy Bag	Coach Training	Combat
First	4	1	10
Second	0	10	5
Third	11	4	0

Participants were generally positive about most features, when asked to assess the importance of each feature experienced during the study (Figure 5.1). 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. 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.

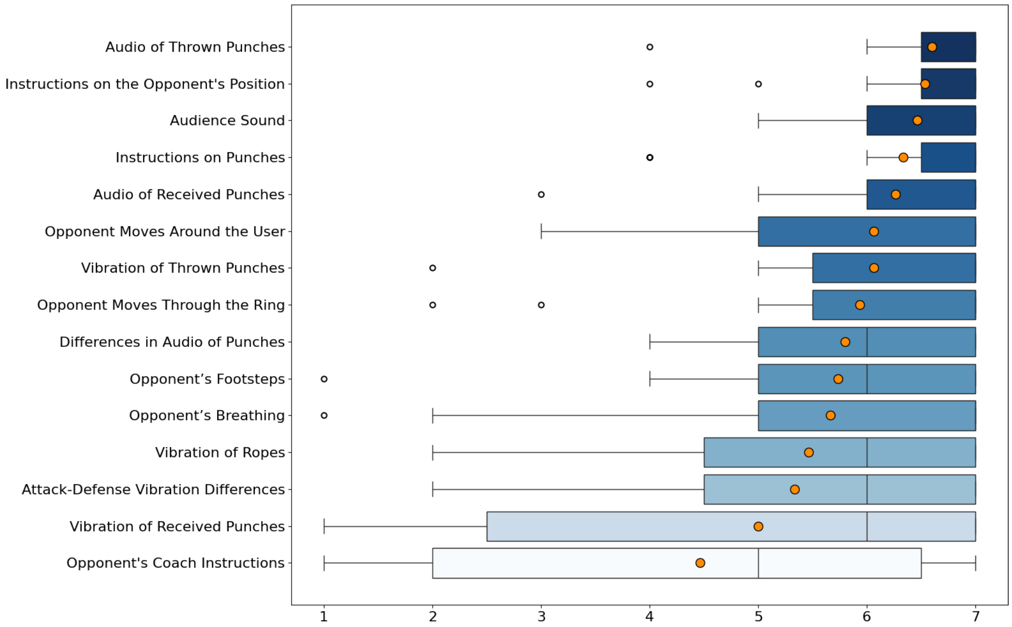

Figure 5.1: The Box Plot Graph demonstrates the variation of the answers to the Likert Items, from 1 (Not Important at All) to 7 (Very Important), about the importance of each implemented feature.

The recorded performance data showed in (Table5.4) during the VR boxing experience shows a trend of participants excelling in defense. Early in the rounds, participants displayed low agency in hitting the opponent as the mean values for the first two rounds of coach training are (M=11.4, SD=7.2) for the first round and (M=13.9, SD=12.5) for the second round, but as the experience progressed, they gained more agency increasing the number of punches that connected with the opponent with a similar number of the coach's punch instructions.

Despite this increase in offensive actions, participants managed to maintain a relatively low average for being hit by the opponent starting in the first round of coach training with the mean values of (M=10.5, SD=5.1) and ending in the third round of combate with (M=5.1, SD=2.8), indicating that their defensive skills got better throughout the session. The average of movement coach instructions suggests that participants needed some guidance for movement adjustments. This overall data suggests that participants became more proficient in managing both offense and defense over time.

5.6.2 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*

Table 5.4: Descriptive statistics of user actions during the VR boxing experience, encompassing metrics such as average, standard deviation, median, mode, maximum, and minimum values for five types of actions. These actions include hitting the opponent, defending, and responding to coach punch and movement instructions, providing insights into participants' performance across different rounds.

Round	Action	Average	Standard deviation	Median	Mode	Maximum	Minimum	Variance
1st Round Training	Hit the opponent	11.40	7.15	10.00	10.00	24.00	2.00	51.11
	Defended well	21.33	8.33	21.00	20.00	39.00	2.00	69.38
	Opponent hit the user	10.47	5.07	11.00	18.00	18.00	3.00	25.70
	Trainer Instructions	13.47	0.52	13.00	13.00	14.00	13.00	0.27
	Movement Coach Instructions	4.79	2.81	4.50	3.00	12.00	1.00	7.87
2nd Round Training	Hit the opponent	13.87	12.45	10.00	9.00	49.00	2.00	154.98
	Defended well	24.67	7.58	26.00	29.00	36.00	9.00	57.52
	Opponent hit the user	9.07	5.09	9.00	14.00	17.00	2.00	25.92
	Trainer Instructions	13.47	0.52	13.00	13.00	14.00	13.00	0.27
	Movement Coach Instructions	3.93	3.08	4.00	4.00	12.00	0.00	9.46
3rd Round Training	Hit the opponent	21.47	15.13	19.00	#N/A	54.00	4.00	228.84
	Defended well	25.53	6.46	25.00	30.00	35.00	11.00	41.70
	Opponent hit the user	8.00	3.63	7.00	5.00	18.00	4.00	13.14
	Trainer Instructions	16.33	1.29	16.00	16.00	21.00	16.00	1.67
	Movement Coach Instructions	4.43	3.23	3.00	3.00	11.00	1.00	10.42
1st Round Combat	Hit the opponent	14.87	11.62	13.00	4.00	48.00	4.00	134.98
	Defended well	23.40	8.20	25.00	25.00	37.00	5.00	67.26
	Opponent hit the user	8.80	4.38	8.00	8.00	18.00	3.00	19.17
	Trainer Instructions	11.53	0.64	11.00	11.00	13.00	11.00	0.41
	Movement Coach Instructions	6.00	3.21	5.00	4.00	13.00	3.00	10.31
2nd Round Combat	Hit the opponent	21.80	21.00	15.00	35.00	81.00	2.00	440.89
	Defended well	24.47	7.41	23.00	32.00	35.00	12.00	54.84
	Opponent hit the user	8.07	4.03	9.00	9.00	17.00	2.00	16.21
	Trainer Instructions	12.27	0.59	12.00	12.00	14.00	12.00	0.35
	Movement Coach Instructions	5.46	2.40	5.00	3.00	10.00	3.00	5.77
3rd Round Combat	Hit the opponent	20.07	17.59	19.00	3.00	50.00	1.00	309.35
	Defended well	22.33	8.67	21.00	21.00	41.00	10.00	75.24
	Opponent hit the user	5.13	2.77	5.00	4.00	10.00	1.00	7.70
	Trainer Instructions	13.73	1.28	13.00	13.00	18.00	13.00	1.64
	Movement Coach Instructions	8.14	2.44	8.00	6.00	13.00	5.00	5.98
Full Experience (per round)	Hit the opponent	17.24	14.97	13	5	81	1	224.14
	Defended well	23.62	7.72	24	25	41	5	59.65
	Opponent hit the user	8.26	4.43	8	4	18	1	19.61
	Trainer Instructions	13.47	1.73	13	13	21	11	2.99
	Movement Coach Instructions	5.46	3.12	5	3	13	0	9.76

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 and the physical challenge it offered, as participants appreciated the freedom of movement and the dynamic engagement it provided:

"*I liked Combat because it was more interactive. I was interacting with a dummy... the dynamic of it... The most fun part was moving from side to side and everything*" (P9).

Combat also 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 is 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 is what stimulates us the most, right, it is 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 in enjoying 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 between the other two modes, but 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 less 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 – also seen in its real-world counterpart of punching a bag – that helped them release built-up tension:

"*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).

5.6.3 Progression and Experience

Participants appreciated the progression of the VR boxing experience, noting how the gradual increase in difficulty 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).

Likewise, P3 remarked how passing through all stages, starting with the Heavy Bag Training, added extra excitement to the experience:

"[...] competing without going through that phase [Heavy Bag Training] probably wouldn't have had the same appeal. I found it very exciting because there was always feedback. And when you can't see and you get feedback, it adds a different kind of thrill to the game." (P3).

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.*"

Similar to P14, P10 reflected on the progression, attributing the final stage of the game as the most valuable for learning:

"Because, considering that I came into the unknown, an unfamiliar game, I believe I evolved, and that's why I'm placing more importance on the final stage of the game. it is in that order that I define the final instructions and the final combat as the most important for me." (P10).

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 is all part of it, you see. Because the first round is a bit calmer, the second starts... And the third, it seems like it is meant... It was made on purpose to motivate us (...) I started to get more excited in the third round (...) I think it is well-designed for us to... Get excited about it"* (P5).

5.6.4 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. And that's very important*" (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*".

In addition to these cues, P1 referred to the opponent's coach voice as – although potentially distracting – a potential aid in locating their 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 had a similar reflection during the interview, as he had not realized the coach remained in a fixed position and wondered if he would be able to use it as a reference point.

5.6.5 Priority and Complementary Feedback

The previous theme is a good example of how the different feedback types were sometimes prioritized over or complemented by others. Despite some participants' initial focus on breathing and footstep sounds to quickly detect the opponent, for others the coach's instructions were key to guiding them through the experience.

Another example is related to 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 like P5 said:

"*I could understand when it was in the head and when I was defending*"

But others were not able to like 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, during the interview, P4 reflected if somehow this secondary feedback could actually transmit relevant information:

"*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. That's something I didn't explore.*"

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?*"

5.6.6 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 (...) like left, down, up, 90 degrees, half-turn, full-turn. 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.*"

This was especially relevant as most participants had no prior boxing experience, meaning they did not know the punch's names or techniques before starting the experience.

5.6.7 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 real-world space. This raised concerns, particularly when unfamiliar with the environment, which in turn can make them 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. One specific comment was to add tactile references on the floor as a way to orient them:

"*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... Something more prominent to help us know if we're in the right spot*" (P2).

On the other hand, participants also suggested that the VR application could include mechanics to prevent collisions in the real-world and 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 the chances 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.*"

5.6.8 Perspectives of multiplayer boxing

In the realm of VR boxing, adding the feature for multiple players to join in raises key points about making sure everyone gets a fair shot and feels included. This is essential for ensuring that blind individuals enjoy the experience as much as everyone else. So, we asked the participants their opinions on adding multiplayer, and some of the participants were keen on adding this option because it would motivate them even more:

"Because there would already be a competitor and I would be more motivated to win the game. And then, since we both have the same difficulty, even our mistakes and successes would be interesting. And then I would start to focus more on hitting." (P8)

One participant mentioned that adding another person would increase motivation because it would increase the unpredictability, making it more interesting:

"I think it could be even more interesting because, probably, this person would introduce more spontaneity into the game. Here, in some way, the opponent's actions are, let's say, predefined, and with a person, the unpredictability would likely be greater. And that, in itself, would create more interest." (P4)

Another participant, when asked about adding multiplayer and playing alongside the participant's family, expressed the desire to be more involved with their family during these gaming sessions, rather than feeling left out:

"This game itself is really about individual study, right? Very good, yes. But also, if you practiced with two or three people, with two external people, right? Or a match with an enemy. I think it would be more interesting if two different people played. You see? And only they play at home. And I'm left out. You see? That's why I'm not motivated for this. And maybe that would motivate me to interact with all of them at home. You see? And not be left out." (P5)

The same participant further emphasized how being more engaged in such experiences with their family would be highly motivating:

"At least I would like to be more involved in this part with them, watching a game like this. I think it would motivate me a lot to interact with them or with someone else in any of the games you invest in. I think we wouldn't be left out. That's my view." (P5)

We also asked about the fairness of the experiment if they played against a sighted person, and participants had a variety of perspectives. Some thought the application would be fair if they played against a sighted person and, in that case, would feel more included:

"It would be fair. It would be very fair. For me, it would be ideal. The ideal situation. Because I see that in many cases, in many games, we are excluded, right? And I think, without family, it would be very...." (P5)

Other participants thought it would be very hard for a blind player to compete against a sighted player and suggested that matches between two blind players would be fairer:

"Well, I don't see it that way... We have to understand one thing, a blind person will never be on the same level, no matter how much information they have, as a person who can see, right? I still think it would be better for two blind people to play against each other. That's my opinion." (P15)

P12, who shared the same opinion that sighted players would have an advantage, suggested leveling the playing field by adding constraints for the sighted players, such as blindfolding them:

"It would reduce the advantage that the person has. Yes, the person who can see has more advantages, maybe they don't even need instructions. And I can't see, I need instructions, and they can easily dodge me. And I can only dodge them with instructions. What could make it more equal is... putting a blindfold on them. Yes, maybe that."

We also asked about multiplayer in a more cooperative manner where the blind user would be fighting against a bot, but instead of receiving information from the virtual trainer, they would receive it from a sighted person who would give them instructions about the location of the opponent and what punches to throw. Some of them liked this idea:

"That could also be fun, so in the team, one person would be fighting, and the other would be giving the tips. It could be fun, even if it's a blind person giving them." (P14)

Expanding on this idea of cooperation, one participant mentioned the possibility of having a more complex setup where it would be two players against another two players, with each sighted trainer guiding their blind partner. This would require distinct sounds for each opponent to ensure clear communication and effective teamwork:

"Yes. So, imagine, if it were two against two, there would be a team, right? For example, the trainer with me would give instructions to the partner playing with me, and there would be another trainer also giving instructions to the others. And in that case, there would need to be distinct sounds for opponent A and opponent B. And maybe the movement in the room would be different because there would be other opponents next to me defending. So there would need to be more audio from the trainer(...)." (P14)

Moreover, the concept of multiplayer VR boxing was also seen as a potential tool for team-building activities, adding a social and collaborative aspect to the experience:

"That would even be cool for team building, for example." (P9)

5.7 Discussion

We present the main lessons learned from both the participatory design process and the user study, highlighting how these insights can inform the design of more inclusive and engaging VR experiences for blind users. Overall, the results indicated that most participants enjoyed the experience and found it immersive and accessible.

5.7.1 Leveraging the Power of VR

Virtual reality offers an opportunity to create immersive, interactive experiences, and this study highlights how VR's inherent capabilities, such as natural movement, spatial audio, and tactile feedback, were essential in engaging users. The dynamic interaction with a moving opponent allowed users to experience a sense of realism that would have been difficult to achieve with other forms of locomotion, such as joystick, used in some works [53]. The use of the full body achieved through real-walking provided the participants with a more authentic experience of boxing, closely mirroring real-world interactions.

However, as effective as real-walking was in enhancing immersion, we also recognized the limitations imposed by physical space constraints. Many users might not have access to the large areas required to move freely within a VR boxing ring. This points to the need for future research and innovation in alternative movement methods like P4 talked about having the opponent move in a certain way to make the user not collide with anything in the real world, so the user has space to move freely in similar applications that have somewhat large area requirements.

Head-tracking was found to be yet another essential component for improving the interaction. This feature that allowed them to better orient themselves based on their physical movements was highlighted by the participants as improving their spatial awareness. Rich auditory feedback combined with head-tracking enabled users to efficiently improve their coordination abilities, fostering a skill-enhancement atmosphere.

VR also allows punching and defending in real time, and these were not just physical exercises; they added considerable value to the total immersion of the experiment. The controllers' haptic feedback reinforced the experience, and users expressed appreciation for this. However, we discovered, that haptic feedback sometimes is not perceived and used more in terms of a complementary feedback and could be improved upon. More complex haptic experiences using other technologies that more accurately represent the effects of punches or the existence of obstacles in the environment are needed for a better use of this type of feedback.

5.7.2 Balancing Guidance and Customizing Feedback for User Autonomy

As users progressed through the experience and became more comfortable with the VR environment, many expressed a desire for greater control over the feedback mechanisms. In particular, verbal instructions from the virtual coach were vital in helping participants navigate in the more complex modes like the Combat. These instructions ensured users were aware of their opponent's location and what actions to take, yet the timing of the guidance allowed them to act independently when they felt ready. While the coach was helpful, participants also desired the ability to rely more on their own instincts and auditory cues as they gained confidence.

As they became more familiar with the system, participants wanted the option to reduce or even turn off the coach's instructions in future rounds. This desire for customization underscores the importance of offering adaptable feedback systems that cater to the different needs and preferences of users. Some participants preferred frequent updates, while others wanted to rely on their abilities once they had become more accustomed to the environment.

Incorporating customizable levels of guidance into future VR boxing experiences would significantly enhance user engagement by allowing participants to adjust the amount of help they receive. For example, beginners may prefer detailed instructions, while advanced users might rely more on non-verbal cues, like the sound of their opponent's breathing or footsteps. Providing this level of personalization would not only give users more control but also help foster a sense of independence, boosting confidence and engagement as they progress through the experience.

5.7.3 Enhancing Realism through Multisensory Feedback

One of the most significant contributors to the sense of realism in the VR boxing experience was the combination of auditory and haptic feedback. Participants noted that the spatialized audio, such as the sound of the opponent's footsteps and breathing, was crucial in helping them orient themselves within the ring. This auditory feedback allowed users to pinpoint the location of their opponent and anticipate movements, simulating the sensory cues a boxer would rely on in a real match. Similarly, haptic feedback—delivered through the VR controllers—provided users with a tangible sense of impact when delivering punches, adding to the overall immersion.

While auditory feedback was clearly the most dominant and appreciated sensory input, haptic feedback also played a complementary role, though some users mentioned that it became less noticeable during fast-paced sequences. This points to a potential area for improvement in future VR designs: enhancing the precision and responsiveness of haptic feedback could further elevate the realism of such experiences. For example, more sophisticated force-feedback systems could simulate the resistance of an opponent's body or the jolt of a powerful punch, offering users a more physically engaging experience.

5.7.4 Complexity Progression

One of the findings from our study was the positive reception of the structured progression in the VR experience. Users started with simpler tasks, like punching a heavy bag, and gradually moved towards more complex challenges, such as facing an opponent in coach training and lastly combat mode that had more information being sent to the participants, increasing the complexity and immersion. This gradual increase in complexity was not only appreciated, but essential for building user's confidence and engagement during the experience. Participants mentioned that starting with the basics helped them familiarize themselves with the environment and the feedback they were going to receive before moving on to more dynamic and challenging scenarios.

The smooth transition between modes also lessened cognitive overload because it allowed participants time to get used to each new level of complexity. This is important for VR experiences, especially for users who might not be accustomed to fast-paced action or multisensory feedback. Similarly, structured experiences that ease users into increasingly complex tasks by gradually introducing new elements and complexity could be beneficial for future VR experiences, especially those intended for blind users. This progression also offers a framework for creating more accessible sports simulations, where adding layers of tasks and feedback could help simplify challenging environments.

5.7.5 Limitations

This work focused on a specific domain, boxing, which includes a variety of interactions and feedback mechanisms. While we've gained valuable insights from the participatory design process and user study, some findings may not fully apply to other areas that involve less physical movement or entirely different interaction patterns. Additionally, the study was conducted with non-experienced participants, consisting of eight rounds. Although this format allowed users to make steady progress, longer exposure to the system would offer more insight into how the experience could be refined further, such as incorporating more complex or continuous movement.

Another aspect that could be improved is the realism of the opponents. Currently, the system doesn't utilize artificial intelligence (AI) to simulate more sophisticated behaviors. Implementing AI that adapts dynamically to the player's performance could make the experience feel more realistic and provide a better challenge, increasing overall engagement. Adding this level of complexity would deepen the immersion and make future iterations of the system more versatile for users with different skill levels.

A further limitation to consider is the integration of multiplayer, including sighted participants, into the experience. As it stands, the system is designed specifically for blind users, and incorporating sighted individuals while maintaining a fair and balanced experience poses a challenge. Ensuring that the experience remains fair for both groups without giving sighted users an inherent advantage would require additional design considerations, such as tailored feedback systems and level adjustments to account for different abilities. This is an area that warrants further exploration to promote inclusivity without compromising fairness.

Users may also not have sufficient space to fully take advantage of real walking in VR, which can limit the experience. Space limitations can also pose a problem because users might accidentally bump into physical objects while moving freely in the real world.

Chapter 6

Conclusions & future work

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 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.

The findings show the importance of progressive learning experiences, which allow users to build confidence and skills gradually. The participants appreciated the structured approach, which made the evolution of the complexity good for the experience. This progression was crucial in helping participants familiarize themselves with the virtual environment and in enhancing their spatial awareness and movement coordination, these skills could potentially be transferred to real-world applications, such as physical rehabilitation or daily navigation as some of the participants said.

This work also showed that, while movement guidance and the punch instructions from the virtual coach was essential in helping participants navigate and engage with the environment and the opponent, especially when they are complemented with other types of feedback like the sound of footsteps, breathing from the opponent and the audience, but there is a clear desire for more autonomy as users gain experience, especially as the complexity increases. This also suggests that future VR applications should include customizable feedback options that allow users to adjust the amount of assistance they receive, providing a more personalized and adaptive experience to meet the many needs that blind people have. To ensure ease of use and smooth integration into daily life, efforts should be made to develop lightweight and portable VR systems with built-in accessibility capabilities, such as gesture control and speech recognition.

In terms of future work, studies could explore how prolonged exposure to accessible VR environments affects user autonomy and the retention of skills over time. Additionally, the principles developed in this research could be applied to other sports or even non-sport activities. Future investigations could consider how lessons learned from this VR boxing experience—such as the integration of natural movement and auditory feedback—might be useful in other domains, like education or rehabilitation. Another promising area for future research is the development of systems that enable users to customize the level of guidance and feedback they receive, giving them more autonomy as they grow more confident and skilled in virtual interactions. Finally, with the rapid advancement of haptic and auditory feedback technologies, further studies could explore how these innovations can enhance the immersion and accessibility of VR experiences for blind users.

In conclusion, the highlights are the immense potential of virtual reality in providing feedback to blind individuals and 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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